An investigation of wearable and IoT technology for health applications: a user centered approach

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This report is submitted in partial fulfillment of the requirements for the degree of a Master of Engineering with endorsement in Software Engineering at The University of Waikato.

ENGEN593 (HAM)

Abstract

The convergence of wearable technologies and the Internet of Things (IoT) has opened new possibilities for health monitoring and older adults care. However, existing systems remain fragmented, often lack interoperability, and tend to overlook the unique usability needs of older adults. This research investigates how a user-centered approach can inform the design and development of a Unified Wearable Device Framework (UWDF) to enhance integration, accessibility, and data visualization across heterogeneous IoT devices. Drawing on qualitative research involving older adults, caregivers, healthcare professionals, and technical personnel, the study identifies key design requirements and develops a working prototype of the UWDF platform. The framework emphasizes simplicity, modularity, and human-centered computing (HCC) principles. Usability testing demonstrates that the platform improves ease of interaction, supports personalized health monitoring, and facilitates caregiver engagement. The research contributes both a practical solution for managing diverse wearable health devices and a methodological reference for designing inclusive healthcare technologies that support aging-in-place.

Keywords: Wearable technology, Internet of Things (IoT), older adults care, human-centered design (HCD), interoperability, security, health monitoring, platform design

Acknowledgements

I am deeply grateful to Dr. Jemma Konig, whose guidance was instrumental in completing this thesis. As an engineer approaching this project, I benefited immensely from Dr. Jemma Konig's academic perspective, which reshaped my methodology and mindset. Her transformative support will continue to influence my professional and academic journey. I am honored that, as my thesis nears completion, Dr. Jemma Konig's child is about to be born. I extend my heartfelt wishes for joy and fulfillment to Dr. Jemma Konig, her child, and her family.

I also extend my gratitude to Dr. Judy Bowen for her comprehensive support throughout the final stages of my Master's project, and other University of Waikato staff whose support enabled me to travel from China to New Zealand and successfully complete my Master's project.

I owe a debt of gratitude to the pioneers and practitioners of software engineering. Their talent and dedication have not only made my career as a software engineer possible but also inspired my research. Through their remarkable contributions, I have come to appreciate the elegance of software engineering and its profound impact on society—an influence that will undoubtedly endure.

My deepest thanks go to my parents and brothers, who have nurtured and supported me throughout my life. I am equally grateful to my wife and two children, who accompanied me from China to New Zealand. Their unwavering support during this year of research, despite numerous challenges, has made this journey a cherished part of our family's memories.

Over the past year, New Zealand's people, landscapes, and culture have profoundly inspired me. My travels from University of Waikato to New Zealand's coasts, though not always smooth, have been filled with joy and rewarded with beauty, making every effort worthwhile. I look forward to continuing the exploration in the future.

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Chapter 1

Introduction

In recent years, the convergence of the Internet of Things (IoT) and wearable technology has transformed the landscape of healthcare. Wearable devices, such as smartwatches, fitness bands, and biosensors, have emerged as essential tools for continuous health monitoring, early disease detection, and preventive care. These technologies allow for real-time tracking of physiological signals, such as heart rate, blood pressure, and sleep patterns, offering opportunities for improving individual well-being and reducing the burden on healthcare systems.

Among the populations that can most benefit from these advancements are older adults. As global aging accelerates, the need for innovative, accessible, and user-friendly health technologies becomes increasingly urgent. Wearable IoT solutions offer the potential to support aging-in-place, improve safety, and enable timely interventions. However, these devices are often designed with general consumers in mind, and may not adequately address the specific needs, preferences, and limitations of older adults.

1.1 Motivation

Despite the potential of wearable and IoT-based health technologies, several challenges persist.

Firstly, the wearable device ecosystem is fragmented, with devices from different manufacturers operating on incompatible systems, lacking unified data standards, and often requiring separate applications for monitoring and configuration. For instance, studies highlight that proprietary protocols and non-standardized data formats hinder seamless integration, resulting in a disjointed user experience [5, 34].

Secondly, older adults face usability barriers due to cognitive, sensory, and motor limitations. Complex interfaces, small screens, and inconsistent interaction models significantly reduce accessibility and adoption rates [16, 29].

Moreover, caregivers and healthcare providers struggle to access meaningful, integrated data from wearable devices, limiting their ability to support clinical decision-making or remote care. Research indicates that fragmented data streams and lack of compatibility with electronic health record systems are major obstacles [26].

These challenges underscore the need for a unified platform that integrates wearable devices, simplifies interaction, and provides clear, actionable health information for older adults and their support networks.

1.2 Research Aim and Questions

The aim of this research is to develop and evaluate a Unified Wearable Device Framework (UWDF) that supports the integration, management, and visualization of multi-source health data from wearable IoT devices, with a specific focus on older adults.

To achieve this aim, the following research questions guide the investigation. These questions will be revisited in Chapter 7 to evaluate how well the research addressed them:

1. What types of IoT-based wearable devices are currently being used by older adults in healthcare?
2. How could Human Centered Computing (HCC) principles be applied in the design of IoT-based wearable devices for older adults?
3. What features and strategies are essential for IoT platforms to effectively support wearable devices in older adults healthcare?

To ensure the platform aligns with real-world needs, this research adopts a HCC approach, which prioritizes the needs, capabilities, and contexts of users, particularly older adults, caregivers, and healthcare professionals. Within this HCC framework, human-centered design (HCD) is employed as a practical methodology to engage end users throughout the design and development process. This approach includes early-stage needs assessment via surveys, informed design based on user feedback, and usability testing to validate the final solution.

By embedding user perspectives, this research aims to produce a framework that functions effectively and incorporates user-centered design principles to enhance usability, accessibility, and contextual relevance for older adults. This design philosophy is especially crucial in healthcare settings, where trust, ease of use, and accessibility are critical to adoption.

1.3 Structure of the Thesis

This thesis is structured as follows. Chapter 2 explores prior work in wearable technologies, IoT platforms, and user-centered design for older adults healthcare. Chapter 3 details the qualitative and technical research methods employed, including participant recruitment, data collection, and analysis. Chapter 4 presents the conceptual and logical architecture of the Unified Wearable Device Framework. Chapter 5 describes the system realization, including hardware integration and interface design. Chapter 6 provides the results of usability testing and technical validation. Chapter 7 and Chapter 8 synthesize the findings, discuss implications, and suggest future directions for research and development.

Chapter 2

Literature Review

Globally, populations are aging rapidly, placing immense pressure on healthcare and older adults care systems. According to the World Health Organization (WHO) and the Organization for Economic Co-operation and Development (OECD), the older adults stage begins at age 65 [10, 36]. In New Zealand, adults over 65, currently 15% of the population, account for 42% of health services use, a proportion projected to rise as nearly one-fourth of the population reaches this age by 2035 [42].

While not all older adults require technological assistance, this work focuses on those who can benefit from IoT-based wearable devices for health monitoring and safety enhancement. The most significant challenge for this population subset is the decline in physical functions, often necessitating wearable devices for continuous monitoring (e.g., heart rate, blood pressure) and safety assurance (e.g., fall detection). These health challenges underscore the importance of IoT-based solutions tailored to older adults' needs [42].

2.1 Introduction to Literature Review

This literature review is structured to address the three research questions introduced in Section 1.2, which guide the investigation into IoT-based wearable devices and platforms for older adults' healthcare. These questions focus on: (1) identifying the types of IoT-based wearable devices currently used in older adults' healthcare, (2) exploring how Human-Centered Computing (HCC) principles can enhance device design, and (3) determining the essential features and strategies for IoT platforms to support these devices effectively.

The review is organized into three main sections: Types of IoT-Based Wearable Devices and Applications (Section 2.2), Applying HCC Principles (Section 2.3),

Table 2.1: Application types in older adults healthcare

No.	**Application type**	**Data types**
1	Smart home	Activity, Movement, Fall detection
2	Telecare	Video and audio streaming, ECG, Vital signs
3	Telemonitoring	Vital signs
4	Telemedicine	Vital signs, ECG, Blood glucose
5	Internet of Things	Weight, Diet, Activity

and Essential IoT Platform Features (Section 2.4). Each section synthesizes existing literature to provide a theoretical foundation for the proposed Unified Wearable Device Framework (UWDF), addressing gaps in usability, interoperability, and accessibility for older adults. Subsequent chapters will build on these findings through participatory studies, framework design, and evaluation to develop a user-centric, interoperable, and secure solution.

2.2 Types of IoT-Based Wearable Devices

To address RQ1 — *"What types of IoT-based wearable devices are currently being used by older adults in healthcare?"*— this section investigates a range of IoT and wearable devices used in older adults healthcare.

2.2.1 IoT Applications for Older Adults

IoT applications with wearable devices have emerged as vital tools in older adults healthcare, enabling continuous health monitoring and safety enhancement in diverse settings, such as homes and care facilities [53]. These technologies include wearable sensors, smart home systems, and telecommunication-based platforms, designed to track health parameters, promote independent living, and support caregiver oversight. To provide a clear overview, this section categorizes IoT-based devices into five key types based on their primary functions and application scenarios, as identified through a synthesis of recent literature [28, 42, 53].

Table 2.1 summarizes these device types and their data types, derived from their core monitoring capabilities as reported in the literature (each of which is described below).

2.2.1.1 Smart Home Systems

Smart Home Systems provide a comprehensive picture of a subject's health status by monitoring mobility and interactions with their environment [53]. These systems are designed to support the safety of older adults residents, for instance, by detecting activity, movement, and falls, and automating tasks such as operating appliances or issuing emergency alerts. Smart home systems are particularly suited for home environments, enabling independent living while reducing the burden on caregivers [40].

For example, Chan et al. describe a smart home system that integrates motion sensors and smart lighting to monitor older adults' activity patterns and detect falls, enabling automated alerts to caregivers while supporting independent living [6].

2.2.1.2 Telecare

Telecare leverages telecommunication technologies and IoT to monitor and assist the older adults in home environments [28]. Applications include remote support via video and audio streaming, heart rate, and vital signs data, allowing the older adults to live safely and independently. Telecare systems can notify family or healthcare providers upon detecting vital signs monitoring, enhancing safety.

For example, Van den Berg et al. propose a telecare system that uses wearable sensors and video streaming to monitor heart rate and facilitate real-time communication between older adults and caregivers, enhancing safety in home settings [54].

2.2.1.3 Telemonitoring

Telemonitoring supports long-term health monitoring for older adults, enabling independent living through continuous tracking of vital signs, such as heart rate and blood pressure [28]. These systems rely on wearable devices, such as wrist-worn sensors, to collect data and provide time-efficient oversight for caregivers. Telemonitoring is a critical component of older adults healthcare, offering real-time insights into health status [1]. Telemonitoring differs from telecare by focusing primarily on continuous health data collection, such as vital signs, without the interactive telecommunication features (e.g., video streaming) typical of telecare systems. While telecare emphasizes caregiver communication, telemonitoring prioritizes automated data tracking for long-term health management [28].

For example, Alsadoon et al. describe a telemonitoring system using wrist-worn sensors to track heart rate and blood pressure, enabling caregivers to monitor older adults' health remotely with minimal direct interaction [1].

2.2.1.4 Telemedicine

Telemedicine uses IoT and telecommunication technologies to monitor older adults' health remotely, supporting continuous tracking of vital signs, e.g. heart rate and blood glucose [1]. It integrates wearable devices, such as wrist-worn sensors for heart rate and ambulatory blood pressure monitors (ABPM) for 24-hour blood pressure tracking, enabling real-time data sharing with healthcare providers to support independent living [50]. Telemedicine extends beyond telemonitoring by integrating real-time health data with virtual consultations, enabling direct interaction between older adults and healthcare providers. Unlike telemonitoring, which focuses solely on data collection, telemedicine supports diagnosis and treatment remotely [1].

For example, Perera et al. propose a telemedicine system incorporating wrist-worn sensors and ambulatory blood pressure monitors to enable real-time data sharing and virtual consultations, supporting chronic disease management for older adults [35].

2.2.1.5 Internet of Things (IoT) systems

Internet of Things (IoT) systems encompass various aspects of older adults healthcare, addressing diverse needs through remote monitoring systems [53]. These systems integrate wearable devices, such as smart insoles for activity tracking, with smart home systems and mobile applications to provide comprehensive health monitoring.

For example, An IoT system integrating smart insoles and mobile applications monitors activity levels [3] and diet, encouraging older adults to maintain healthy behaviors through real-time feedback [42].

Smart Homes, Telecare, Telemonitoring, and Telemedicine are typically IoT systems, as they leverage interconnected devices and sensors for data collection and communication. However, non-IoT implementations, such as standalone telemedicine systems without sensor integration, may exist in resource-constrained settings [53].

2.2.2 Wearable Devices for Older Adults

Wearable devices are embedded with sensors and algorithms to track and monitor health parameters and movements, supporting older adults' health and safety [53]. Biometric sensors measure physiological data, including body temperature, blood

Table 2.2: Common wearable devices in older adults healthcare

No.	Function type	Data Types	Integrated IoT System
1	Biomedical Monitoring	Vital signs (e.g., heart rate, blood pressure, ECG)	Telemonitoring, Telemedicine
2	Sleep Monitoring	Sleep patterns (e.g., EEG, EOG, EMG)	Telecare, IoT Systems
3	Gait Analysis	Step count, gait patterns	Smart Home, IoT Systems
4	Fall Detection	Fall alerts, movement tracking	Smart Home, Telecare

pressure, respiration rate, blood glucose, heart rate, blood oxygen saturation, and so on, enabling continuous or on-demand health monitoring [11, 53].

Table 2.2 summarizes common wearable device types, as reported in the literature [1, 11, 28, 41, 50, 53], including their functions and their integration with IoT-based systems from Table 2.1. Each is described below.

2.2.2.1 Biomedical Monitoring Devices

Biomedical monitoring devices track vital signs, such as heart rate, blood pressure, and blood glucose, to support continuous health monitoring [11]. These devices, like wrist-worn sensors or ambulatory blood pressure monitors (ABPM), integrate with Telemonitoring and Telemedicine systems to enable real-time data sharing with caregivers and healthcare providers, supporting independent living [1, 28].

Chi et al., for example, describe a wearable sensor embedded in textiles with conductive fibers to capture ECG signals, aiming to monitor cardiovascular health in older adults while prioritizing comfort and usability. Their system integrates with telemedicine platforms to enable real-time data sharing with healthcare providers, supporting early detection of heart conditions and promoting independent living [11].

2.2.2.2 Sleep Monitoring Devices

Sleep monitoring devices track sleep patterns using biomarkers like brain activity, eye activity, and muscle activity, providing insights into rest quality [17, 41, 45].

Often integrated with Telecare or IoT systems, these devices, such as wearable sleep trackers, support remote monitoring by caregivers to ensure older adults' well-being.

For example, Runnova et al. propose a wearable sleep tracker that monitors electroencephalographic signals to assess sleep quality, integrated with a telecare system to provide caregivers with insights into older adults' rest patterns [41].

2.2.2.3 Gait Analysis Devices

Gait analysis devices, such as smart insoles with pressure sensors and accelerometers, monitor step count and gait patterns to support safety and activity tracking [50]. Integrated with Smart Home and IoT systems, these devices enable caregivers to monitor mobility and detect irregular patterns, enhancing independent living [3].

Teixeira et al., for example, describe smart insoles with pressure sensors to monitor gait patterns, integrated with IoT systems to detect mobility issues and support caregiver oversight in home environments [50].

2.2.2.4 Fall Detection Devices

Fall detection devices track movement and detect falls, issuing alerts to caregivers or medical centers [12]. Integrated with Smart Home and Telecare systems, these devices, such as wearable accelerometers, enhance safety by providing real-time notifications, supporting older adults' independence [53].

For example, Dorri et al. propose a wearable accelerometer-based fall detection system that sends real-time alerts to caregivers via a smart home system, enhancing safety for older adults living independently [12].

2.2.3 Addressing RQ1

To address RQ1 — *"What types of IoT-based wearable devices are currently being used by older adults in healthcare?"*— this review identified a range of IoT-based wearable devices used in older adults healthcare, as summarized in Table 2.1 and Table 2.2.

The literature categorizes IoT-based device types into Smart Home, Telecare, Telemonitoring, Telemedicine, and IoT systems, as summarized in Table 2.1. Among wearable devices, key categories include biomedical monitors, sleep trackers, gait analyzers, and fall detectors, as detailed in Table 2.2. While each device type offers unique benefits, their suitability for older adults' healthcare varies based on usability, scalability, and alignment with ongoing health needs. Sleep trackers, for instance, focus on sleep quality but are less effective for continuous monitoring of vital signs, such as heart rate or blood pressure, which are critical for older adults [60]. Gait analyzers and fall detectors address mobility and safety but provide limited support for comprehensive health monitoring required by caregivers and healthcare professionals [38]. In contrast, biomedical monitoring devices, including heart rate, blood pressure, and carbon dioxide sensors, integrated with Telemonitoring and Telemedicine systems, enable real-time data collection essential for managing long-term health conditions, such as cardiovascular diseases, prevalent among older adults [1, 28].

Accordingly, this research prioritizes biomedical monitoring devices due to their versatility in addressing vital sign monitoring needs, as supported by their widespread use in IoT healthcare systems [42]. These sensors facilitate real-time data transmission and intuitive visualization, aligning with older adults' usability requirements and caregivers' monitoring demands, as identified in participatory studies [53].

2.3 Applying Human-Centered Computing Principles

To address RQ2 —*"How could HCC principles be applied in the design of IoT-based wearable devices for older adults?"*— this section explores how HCC principles enhance the usability and accessibility of IoT-based wearable devices for older adults' healthcare. It examines the theoretical foundations of HCC, its application to IoT and wearable technologies, and specific strategies for integrating these principles into the design of future frameworks, ensuring alignment with older adults' and caregivers' needs [23, 38].

2.3.1 Human-Centered Computing Principles

Human-Centered Computing (HCC) is a multidisciplinary approach that integrates human sciences and computer science to design systems that enhance user capabilities and experiences across diverse contexts [46]. Shneiderman describes HCC as bridging social sciences, cognitive psychology, human-computer interaction (HCI), and machine learning to create user-centric technologies that adapt to users' needs, preferences, and environments [46]. Shafto emphasizes that HCC focuses on amplifying human abilities through computational systems that account for personal, social, and cultural factors [44].

In the context of this research, HCC is applied specifically to older adults' healthcare, addressing their unique usability and accessibility needs due to cognitive, sensory, and motor limitations [24, 46]. HCC principles are particularly critical for designing IoT-based wearable devices for older adults, ensuring systems are intuitive, accessible, and supportive of independent living and caregiver oversight [59].

To implement HCC, robust design methodologies are essential. Woods advocates for involving human-factors engineers to capture real-world usage through field research, thereby ensuring reliable systems such as Telemonitoring for physiological data monitoring [56]. Clancey highlights human-machine integration, enabling seamless interaction between wearable sensors, smart home devices, and IoT platforms to support health monitoring and caregiver oversight [8]. HCC principles, as outlined by Wright and McCarthy [57] and ISO 9241-210 [23], prioritize user collaboration, accessibility, and adaptability, ensuring systems meet older adults' needs within their social and cultural contexts [24, 59].

A key standard in HCC is ISO 9241-210, which defines human-centered design (HCD) principles for interactive systems, emphasizing collaboration with all stakeholders, including users, caregivers, and professionals [23]. HCD, as outlined in ISO 9241-210, involves four phases [22]:

1. Identifying users and context.
2. Specifying requirements.
3. Producing design solutions.
4. Evaluating designs against requirements.

The standard specifies six core principles:

1. Understanding users and their environments.
2. Active user involvement throughout design.
3. Iterative design processes.
4. User-centered evaluation.
5. Addressing the whole user experience.
6. Multidisciplinary team collaboration.

In older adults' healthcare, these principles ensure IoT-based wearable devices are accessible, usable, and tailored to the needs of older adults and their caregivers [24, 59].

Table 2.3: HCD Principles Applied to IoT and Wearable Devices

No.	HCD Principle	Literature Application
1	Understanding users and environments	Perez et al. highlight the need for simple interfaces to address older adults' challenges with complex IoT systems [36].
2	Active user involvement	Sandhu et al. emphasize involving older adults and caregivers in co-design to ensure usability [42].
3	Iterative design	Petrocchi notes iterative prototyping with user feedback improves device accessibility [38].
4	User-centered evaluation	Yang et al. conducted usability testing with older adults to validate a wearable sleeve's interface [58].
5	Addressing whole user experience	Guo et al. advocate unobtrusive sensors in everyday objects to enhance user comfort [21].
6	Multidisciplinary collaboration	Ebadpour et al. stress collaboration among engineers, healthcare professionals, and HCI experts for culturally sensitive designs [13].

2.3.2 IoT-Based Wearable Devices for Older Adults

Older adults' healthcare monitoring uses IoT devices to track health status and support independent living [28, 40]. These systems aim to enhance safety and caregiver oversight through continuous monitoring [53]. However, many IoT applications focus on technical aspects, often neglecting user-centered design [53].

Table 2.3 provides a structured overview linking each HCD principle (Section 2.3.1) to relevant literature, summarizing their application to IoT and wearable devices.

Perez et al., for example, highlight challenges in IoT systems for older adults, including complex user interfaces, power dependency, security and privacy issues, device interoperability, context awareness, and long-term support [36]. Sandhu et al. emphasize that IoT development often overlooks older adults' usability needs, necessitating HCD involving users, caregivers, and professionals [42]. Petrocchi notes that low adoption of IoT healthcare services stems from a lack of social and human understanding, which HCD addresses by involving users as active participants throughout the design process [38].

HCD is exemplified by unobtrusive monitoring technologies, such as sensors in clothing or everyday objects (e.g., beds or steering wheels), which track physiological data or activity patterns without disrupting daily life [21, 49, 60]. Yang et al., for example, designed an electronic sleeve for health monitoring, using comfortable materials and co-design with older adults to ensure usability and engagement [58]. Ebadpour et al. summarize HCD principles, including user-centric design, accessibility, privacy, and cultural sensitivity, which are critical for IoT-based wearable devices [13].

Despite these advances, research on HCC in IoT-based wearable devices for older adults is limited, with few studies explicitly addressing HCC or HCD [25]. Kurnianingsih et al. note that many healthcare projects prioritize functionality over usability, leading to complex systems that pose usability challenges for older adults due to poor design [25].

This gap underscores the need for systematic HCD application, as defined by ISO 9241-210, which emphasizes stakeholder involvement (e.g., older adults, families, professionals) to create usable and accessible systems [23]. A notable example is Yu et al.'s SHfE smart home system, which integrates wearable devices for health monitoring [60]. Developed through collaboration with older adults and caregivers, this system aligns with HCD phases, particularly iterative design and evaluation, ensuring accessibility and supporting independent living. Such approaches demonstrate how HCD can address usability challenges and enhance adoption of IoT solutions for older adult healthcare.

2.3.3 Addressing RQ2

To address RQ2 —*"How could HCC principles be applied in the design of IoT-based wearable devices for older adults?"*—HCC principles have been investigated to guide the development of IoT-based wearable devices to meet older adults' usability needs [23].

This review outlines how HCC principles, specifically the six HCD principles of ISO 9241-210, guide the development of future IoT-based wearable device frameworks for older adults' healthcare. Future IoT-based wearable device frameworks can apply these principles as follows:

1. Understanding users and environments: Participatory studies with older adults, caregivers, healthcare professionals, and technical personnel are recommended to identify usability needs, such as simple interfaces to address older adults' challenges with complex navigation.
2. Active user involvement: Stakeholders are engaged through surveys and co-

design workshops to shape the sensor management and data visualization modules, ensuring accessibility.

3. Iterative design: Future IoT-based wearable device frameworks should implement iterative design by developing prototypes, collecting user feedback, and refining designs in repeated cycles to enhance usability.
4. User-centered evaluation: Usability testing with older adults and caregivers validates the platform's intuitive interface.
5. Addressing the whole user experience: The platform integrates real-time alerts and remote access to meet caregivers' monitoring needs.
6. Multidisciplinary team collaboration: Engineers, healthcare professionals, and HCI experts collaborate to ensure technical robustness and user-centric design.

These strategies address literature gaps where limited stakeholder involvement reduces usability [38], enabling the platform to support independent living and caregiver oversight through user-centric design and stakeholder collaboration.

2.4 Essential IoT Platform Features

IoT platforms are critical for integrating wearable devices and HCC principles in older adults' healthcare, enabling seamless data management, real-time monitoring, and user-centric service delivery to support independent living and caregiver oversight [2, 3].

To address RQ3 — *"What features and strategies are essential for IoT platforms to effectively support wearable devices in older adults healthcare?"*— this section investigates the architectural, technical, and user-centric requirements of IoT platforms. It explores platform architectures, example systems, technology stacks, and their alignment with HCC principles, providing insights to guide the development of future frameworks for scalable and accessible health monitoring.

2.4.1 Generalized Framework for IoT Platform

IoT platforms provide a scalable infrastructure for seamless communication, data management, and service provisioning in older adults' healthcare. A typical IoT architecture, as illustrated in Figure 2.1, comprises three layers: the Perception Layer, the Network Layer, and the Application Layer.

The Perception Layer manages wearable sensors like heart rate and carbon dioxide monitors to collect health data. It integrates sensors with micro-controllers, such

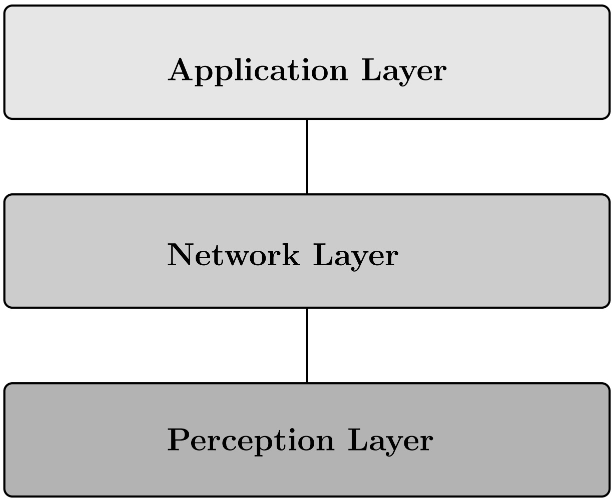


Figure 2.1: Typical IoT Architecture Layers

as the ESP32S2, to enable real-time data acquisition, as demonstrated in IoT healthcare systems [9]. The Network Layer ensures reliable data transmission via Wi-Fi to caregivers and healthcare providers. It facilitates secure connectivity, aligning with Wi-Fi-based data transmission modules [19]. The Application Layer supports personalized health monitoring through real-time data visualization and alerts. It provides intuitive interfaces and APIs, supporting user-centric design for older adults and caregivers. This layered structure is inspired by the general principles of IoT architectures outlined by [27] and others[18, 20].

A well-defined IoT architecture, as described by van Kranenburg, focuses on creating a dynamic global network infrastructure with self-configuring capabilities, where physical and virtual “Things” possess identities, physical attributes, and intelligent interfaces [55]. This architecture is highly applicable to older adults’ healthcare, enabling seamless integration of wearable devices, cloud services, and intelligent data processing through modular designs, as demonstrated in existing IoT systems [3, 27].

In the healthcare domain, IoT platforms support older adults by enabling wearable devices to perform three key functions: sensing (e.g., monitoring heart rate for heart-health management), storing (e.g., securely saving health data for caregiver access), and communicating (e.g., transmitting alerts to healthcare providers during emergencies). These functions are critical for real-time health monitoring, making IoT-based solutions ideal for older adults healthcare [1].

Through decoupling the fundamental building blocks of IoT such as identification, sensing, networking, computation, services, and analytics, a reference model can be adapted for specific healthcare applications, providing a layered approach that simplifies design while meeting the unique requirements of older adults healthcare solutions [3]. Thus, IoT platforms enable the deployment of wearable devices that improve the health and safety of older adults, integrating seamlessly into broader healthcare infrastructures.

Based on the literature, general IoT platform features for older adults' healthcare include:

1. Interoperability, enabling seamless device integration (e.g., wearable sensors) [3];
2. Real-time monitoring, supporting continuous health data tracking and alerts [1];
3. User-centric interfaces, ensuring accessibility for older adults and caregivers [42];
4. Security, incorporating encryption and GDPR compliance for data protection [38];
5. Scalability, allowing modular expansion to accommodate diverse devices [2].

These features align with the requirements for effective health monitoring and will be evaluated in subsequent comparisons of IoT platforms.

2.4.2 Examples of IoT Platforms

Several IoT platforms support older adults' healthcare monitoring by integrating wearable devices. Ali and Parveen proposed a framework using sensors (e.g., pulse oximeters, accelerometers) to collect health parameters, processed via microcontrollers and displayed on a user interface, with real-time notifications sent to caregivers via SMS or email [33]. Nandi and Ahmad's system enables remote monitoring through wearable sensors, allowing caregivers to access real-time health data via mobile devices [30]. Rani and Chauhan's distributed framework integrates sensors and cloud-based platforms to store and share health parameters, enhancing caregiver access [39].

This section describes three IoT platforms—Teladoc Health, ThingsBoard, and AWS IoT—commonly used in older adults' healthcare due to their support for wearable sensors and home-based monitoring. These platforms facilitate remote health monitoring by integrating wearable devices and providing real-time data access for caregivers and healthcare providers [3, 42, 53]. To compare their key features, Table 2.4 summarizes the capabilities of these platforms, highlighting their strengths and limitations in supporting older adults' healthcare needs.

Table 2.4: General IoT Platform Features in Three Commonly Used Platforms

No.	Feature	Platform Common Characteristics
1	Interoperability	Supports integration of wearable sensors but often limited by proprietary protocols or lack of universal standards like IEEE 11073.
2	Real-time Monitoring	Enables continuous tracking of health data and alerts, though responsiveness varies by platform complexity.
3	User-centric Interfaces	Provides dashboards, but complexity often hinders accessibility for older adults and non-technical caregivers.
4	Security	Incorporates encryption, but GDPR compliance and robust authentication are inconsistent.
5	Scalability	Supports device expansion, though setup costs or technical expertise requirements limit home use.

Teladoc Health is a telehealth platform that integrates wearable sensors and telecommunication technologies to provide remote health monitoring and virtual consultations. It enables continuous tracking of vital signs, such as heart rate and blood pressure, supporting older adults' independent living by connecting them with healthcare providers [31].

ThingsBoard is an open-source IoT platform designed for data collection, processing, and visualization from connected devices. It supports wearable sensors for activity and fall detection, allowing caregivers to monitor older adults' health and safety through customizable dashboards and real-time alerts [53].

AWS IoT is a cloud-based platform that enables scalable integration of IoT devices, including wearable sensors, for real-time data processing and storage. It supports health monitoring applications by providing secure connectivity and data analytics, suitable for home-based and clinical settings [3].

2.4.3 Technology Stack and Implementation Practices

The design of IoT platforms for older adults' healthcare depends on selecting appropriate hardware, software, and communication technologies to enable real-time monitoring, scalability, and usability. Table 2.5 summarizes common technologies

Table 2.5: Common Hardware and Software in IoT Platforms

No.	Type	Technologies	Literature Reference
1	Hardware	Arduino, ESP32, Raspberry Pi, STM32, Wearable Sensors, BLE-enabled Sensors	Support real-time data acquisition and sensor integration [3, 9, 18, 20, 53].
2	Software	C/C++, Python, Java, HTML/CSS/-JavaScript, Node.js, MQTT, SQL/NoSQL Databases	Enable low-level control and responsive web interfaces [3, 43, 9].
3	Communication	Wi-Fi, Bluetooth Low Energy (BLE), Zigbee, LoRaWAN	Ensures stable and scalable data transmission [9, 18, 53, 37].

used in such platforms, categorized into Hardware, Software, and Communication, with references to their applications in the literature. This section highlights the key features and advantages of these technogies for older adults' healthcare systems.

Hardware technologies, such as Arduino, ESP32, Raspberry Pi, STM32, wearable sensors, and BLE-enabled sensors, are widely used for their ability to support real-time data acquisition and sensor integration in IoT healthcare systems. ESP32 and STM32 microcontrollers offer low cost, built-in connectivity (e.g., Wi-Fi and Bluetooth), and low-power operation, making them suitable for wearable devices that monitor vital signs like heart rate and blood pressure [3, 9, 18]. Wearable and BLE (Bluetooth Low Energy) enabled sensors provide compact solutions for continuous health tracking, enhancing mobility and usability in home settings [20, 53].

Software, specifically programming languages, including C/C++, Python, Java, HTML/CSS/JavaScript, MQTT, and SQL/NoSQL databases, enable efficient system development and user interaction. C/C++ and Java provide low-level hardware control and robust performance for resource-constrained devices, while Python supports flexible prototyping [43]. HTML, CSS, and JavaScript facilitate responsive web-based graphical user interfaces (GUIs), allowing caregivers to access health data remotely [9].

Communication protocols, such as Wi-Fi, Bluetooth Low Energy (BLE), Zigbee, and LoRaWAN, ensure reliable data transmission. Wi-Fi is dominant for its stable, high-bandwidth connectivity, ideal for real-time monitoring in home environments [9, 18].

While these technologies are widely adopted, their selection depends on specific use cases, balancing cost, power efficiency, and scalability.

2.4.4 Human-Centered Computing and IoT Platforms

Many IoT platforms support healthcare monitoring, but their adaptation to older adults' needs is inconsistent. In addition, IoT platforms tend to address technical requirements but lack full HCC integration, with no evidence of user involvement throughout design and validation [4]. Perez and Zeadally also note the absence of universal interoperability and security standards, such as IEEE 11073 [37].

Systems like the smart door platform [9] and ESP32-based implementations [18, 20] demonstrate functional feasibility for real-time monitoring in older adults healthcare, leveraging cost-effective hardware and Wi-Fi connectivity. However, their lack of robust privacy protection mechanisms highlights the need for HCC-aligned security designs.

For example, Cobo et al. [9] describe a smart door system that enables remote control via a web interface but does not implement encryption or user authentication. This highlights a gap between technical implementation and secure, user-centered design, as emphasized by Sandhu et al. [42].

This section evaluates the three IoT platforms that were outlined in Section 2.4.2 —Teladoc Health, ThingsBoard, and AWS IoT—through HCC principles, specifically the six HCD principles of ISO 9241-210: understanding users and environments, active user involvement, iterative design, user-centered evaluation, addressing the whole user experience, and multidisciplinary team collaboration [23].

These platforms, while technically robust, often lack full alignment with HCD principles, limiting their effectiveness for older adults' healthcare. This misalignment with HCD principles, as summarized in Table 2.6, limits their effectiveness by reducing accessibility and usability for older adults and caregivers [23, 38].

Teladoc Health integrates wearable sensors to support remote health monitoring, enabling independent living [51]. However, its clinician-focused design restricts direct caregiver access to sensor data, conflicting with HCD's principle of active user involvement, as caregivers and older adults are not fully engaged in the design or data interaction process [13, 23]. Additionally, its limited focus on iterative design hinders adaptability to older adults' evolving needs.

Table 2.6: HCD Principles in IoT Platforms for older adults' Healthcare

No.	HCD Principle	Platform Shortcomings
1	Understanding users and environments	Limited user studies in platform design [4].
2	Active user involvement	No evidence of caregiver or older adult involvement [4].
3	Iterative design	Lack of iterative prototyping for usability [37].
4	User-centered evaluation	Minimal user testing for accessibility [4].
5	Addressing whole user experience	Complex interfaces hinder older adults' adoption [37].
6	Multidisciplinary collaboration	Absence of HCI and healthcare expert input [37].

ThingsBoard supports fall detection and activity monitoring through wearable sensors, enhancing safety [53]. Its complex interface, requiring technical expertise for customization, violates HCD's accessibility principle, making it challenging for older adults and non-technical caregivers to use effectively [22, 23]. The platform also lacks evidence of user-centered evaluation, reducing its alignment with older adults' usability needs.

AWS IoT enables scalable integration of wearable sensors for real-time health monitoring [3]. However, its high setup costs and technical complexity hinder adoption in home settings, misaligning with HCD's principle of addressing the whole user experience, which emphasizes inclusivity and ease of use [23, 38]. Furthermore, there is limited evidence of multidisciplinary team collaboration in its design for older adults' healthcare.

These platforms demonstrate technical capabilities but fall short in incorporating HCD principles, such as intuitive interfaces and stakeholder collaboration, critical for older adults' healthcare. Future frameworks should prioritize user-centric design and accessibility to address these gaps [23, 38].

2.4.5 Addressing RQ3

To address RQ3 — *"What features and strategies are essential for IoT platforms to effectively support wearable devices in older adults healthcare?"*— this review identifies essential features and strategies for IoT platforms supporting wearable devices in older adults' healthcare, focusing on biomedical monitoring devices like heart rate and blood pressure sensors.

Key features include: (1) interoperability, enabling seamless integration of devices like wrist-worn sensors with platforms like AWS IoT, as supported by standards like IEEE 11073 [37]; (2) user-centric design, ensuring intuitive interfaces for older adults and caregivers, as seen in ThingsBoard's customizable dashboards but limited by its technical complexity [53]; and (3) robust security, implementing GDPR (General Data Protection Regulation) compliant encryption to protect health data, addressing gaps in platforms like Teladoc Health [51, 31].

Strategies to enhance platforms include adopting modular architectures for scalability and integrating HCD principles to improve accessibility [2, 23]. These findings guide the development of future IoT platforms, which should prioritize interoperability and security to support real-time health monitoring while addressing usability needs through stakeholder collaboration.

2.5 Summary of Findings

This chapter reviewed IoT-based wearable devices and platforms for older adults' healthcare, addressing the three research questions introduced in Section 2.1.

For RQ1, the review identifies IoT-based device types—Smart Home, Telecare, Telemonitoring, Telemedicine, and IoT systems—and wearable devices, including biomedical monitors, sleep trackers, gait analyzers, and fall detectors (Tables 2.1, 2.2). Biomedical monitoring devices, such as wrist-worn heart rate and blood pressure sensors, are prioritized due to their critical role in managing and supporting independent living [1, 28].

For RQ2, HCC principles, specifically the six HCD principles of ISO 9241-210—(1) understanding users and their environments, (2) active user involvement, (3) iterative design, (4) user-centered evaluation, (5) addressing the whole user experience, and (6) multidisciplinary team collaboration—provide a foundation for designing accessible and usable IoT-based wearable devices, addressing gaps in stakeholder involvement [23, 38].

For RQ3, IoT platforms require interoperability, user-centric design, and robust security, with platforms like ThingsBoard and AWS IoT showing technical capabilities but lacking full HCD integration [3, 53]. Core features include: (1) interoperability, (2) real-time monitoring, (3) user-centric interfaces, (4) security, and (5) scalability. These features, aligned with the HCD principles, ensure platforms meet the usability, safety, and scalability needs of older adults' healthcare

[37, 42].

Based on these findings, this study proposes the Unified Wearable Device Framework (UWDF) to address identified gaps, such as limited usability and interoperability, by integrating biomedical monitoring devices with user-centric, interoperable, and secure IoT platforms. Future research should focus on participatory studies and user-centered evaluations to develop such frameworks, ensuring accessibility, scalability, and safety for older adults' healthcare [37, 42].

Chapter 3

User Behavior and Needs Study

As highlighted during the literature review, incorporating human perspectives from the outset is essential for designing effective IoT-based wearable devices for older adults healthcare (Section 2.2). Human-centered design (HCD) and computing (HCC) principles ensure systems are accessible and meet the unique needs of older adults and caregivers (Section 2.3) [23, 38, 42]. Furthermore, essential IoT platform features, including interoperability, user-centered design, and GDPR (General Data Protection Regulation)-compliant encryption (e.g., AES-256 encryption), underscore the need for secure and scalable systems (Section 2.4) [37].

To address this, this study begins with a qualitative investigation to capture the needs, preferences, and challenges of older adults, caregivers, healthcare professionals, and technical personnel before developing the Unified Wearable Device Framework (UWDF). By prioritizing stakeholder input early, the research aims to promote the platform fosters simplicity, trust, and engagement in older adults healthcare applications.

This chapter outlines the User Behavior and Needs Study, a stakeholder-driven investigation designed to explore user needs and behaviors in the context of wearable and IoT health technologies. The study was conducted to inform the design and implementation of the UWDF.

Guided by human-centered computing (HCC) principles, the study seeks to do the following.

- Identify the practical needs, challenges, and expectations of older adults and caregivers when using wearable health devices, such as interface usability and battery reliability, building on the device types discussed in Section 2.2.
- Provide empirical data to guide the design, technical optimization, and

usability of the UWDF platform, particularly for interface design, data privacy, and interoperability, as emphasized by HCC principles in Section 2.3.

- Collect professional feedback from healthcare providers and technical personnel regarding platform compatibility, security, and functionality, including data accuracy and system integration, informed by the platform features in Section 2.4.

The HCC approach, emphasizing iterative user involvement, accessibility, and usability, ensures that user needs drive the design and implementation process (as discussed earlier in Section 2.3). This study incorporates multi-stakeholder perspectives to balance usability for non-technical users with technical requirements for system integration. A multi-stakeholder questionnaire survey was conducted, targeting older adults, caregivers, medical staff, and technical staff, to achieve these objectives.

3.1 Methodology

This section details the research design, covering participant recruitment, research methods, tools, questionnaire design, and the implementation process.

3.1.1 Participants

Four key stakeholder groups were targeted: older adults, caregivers, healthcare professionals, and technical personnel.

Older Adults: Older adults were defined as individuals aged 65 and above. The age range of the older adult respondents was 66 to 85 years. All participants in this group were capable of living independently and did not require continual medical care, making them representative of active aging individuals. In addition to the older adults themselves, family members—often serving as informal caregivers—provided supplementary insights based on daily device use observations and challenges encountered in home care settings.

Caregivers: Caregiver participants included both professional and non-professional individuals responsible for supporting older adults' health management. Despite the relatively low number of caregiver respondents (5 out of 56), their responses were highly valuable. The smaller sample size reflects real-world demographics in both countries, where a significant portion of older adults live independently or are cared for by family members, reducing the availability of formal caregivers for participation.

Stakeholder Group	Participants Number
Older Adults	18
Caregivers	5
Healthcare Professionals	23
Technical Personnel	10

Table 3.1: Stakeholder Groups and Participants Number

Healthcare Professionals: This group included general practitioners, nurses, and physical therapists with direct experience in monitoring older adults' health or recommending wearable devices. Their clinical insights were crucial in evaluating the medical value of device features, the reliability of physiological data, and the practicality of device adoption in healthcare workflows.

Technical Personnel: Participants in this group included software engineers, hardware developers, system architects, and data scientists. Their role in the study was to provide feedback on device-platform compatibility, system scalability, data security, and desired framework features. Their responses were essential to aligning the platform design with contemporary IoT development practices.

Table 3.1 summarizes the participant distribution. As shown in the table, 18 out of 56 (32.1%) participants were older adults, 5 out of 56 (8.9%) were caregivers, 23 out of 56 (41.1%) were healthcare professionals, and 10 out of 56 (17.9%) were technology developers. This distribution ensured that the perspectives of all key stakeholder groups were adequately represented in the study.

Participants were recruited from both New Zealand and China. A multilingual format was adopted to accommodate participants' language preferences, ensuring a more accurate and inclusive data collection process. The surveys were distributed both online and offline. Online distribution allowed wide access across regions using electronic forms, while offline paper-based surveys were provided in local community centers and older adults care facilities to reach participants unfamiliar with digital platforms.

All participants joined the study voluntarily, and no financial incentives were offered. The final number of participants was not pre-fixed but emerged naturally from the response to recruitment outreach. Ethical approval shown in Appendix A was obtained through institutional procedures, and all data were collected under informed consent conditions.

3.1.2 Equipment

Online surveys only required participants to have access to a smartphone, tablet, or computer. This ensured that all groups-including older adults, caregivers, healthcare professionals and technical personnel-could easily participate in the survey using common devices. For offline surveys, the research team provided paper versions of the questionnaire and were responsible for subsequent data entry.

Various software tools were used for data collection and analysis, including Microsoft Forms for online questionnaire distribution and preliminary data collection. The collected data was then exported to Excel and analyzed.

3.1.3 Questionnaire Design

The questionnaires were tailored to the unique characteristics of the four stakeholder groups—older adults, caregivers, healthcare professionals, and technical personnel—to gather relevant feedback. These questionnaires used multiple-choice and rating questions to evaluate user experiences and identify specific functional needs for each group.

3.1.3.1 Questionnaire Design for Older Adults

This group mainly focused on the types of devices used by older adults in daily life, and their views on device functions. For example, whether they use smartwatches, fitness trackers, or blood pressure monitors, and which functions are most helpful for their daily health management (such as heart rate monitoring, step counting, blood pressure monitoring, etc.). The survey can be seen in Appendix B, while the questions are listed below.

1. Which of the following electronic products and wearable devices are you currently using?
2. What conveniences have you experienced while using wearable devices?
3. What inconveniences have you experienced while using wearable devices?
4. What health difficulties do you think wearable devices could help with in older adults daily life?
5. Have you used or been aware of wearable devices that address the following issues
6. How would you prefer to manage and control your health monitoring data?
7. Who would you like to share your health monitoring data with?

8. How concerned are you about data security and privacy when using wearable devices?

3.1.3.2 Questionnaire Design for Caregivers

For caregivers, the focus was on the challenges they encountered when helping older adults use wearable devices, as well as the caregiver's needs for the devices. The survey can be seen in Appendix B, while the questions are listed below.

1. What factors do you think influence an older adult's willingness to use wearable devices?
2. What information would you like to obtain about the older adult's health through wearable devices?
3. How do you think wearable devices can help you care for older adults?
4. What features would you like wearable devices to have?
5. What problems have you encountered with existing older adult physiological monitoring devices or platforms?

3.1.3.3 Questionnaire Design for Healthcare Professionals

For healthcare professionals, the questionnaire centered on how wearable devices can help them better monitor patient health. The survey can be seen in Appendix B, while the questions are listed below.

1. How do you think wearable devices can be applied to older adults health management and chronic disease prevention?
2. What data would you like to obtain from wearable devices to assist in diagnosis and treatment?
3. What concerns do you have about data security, privacy, and ethics with wearable devices?

3.1.3.4 Questionnaire Design for Technical Personnel

For technical personnel, the questionnaire focused on the technical implementation of wearable devices, especially device-platform compatibility, data security, and framework optimization. The survey can be seen in Appendix B, while the questions are listed below.

1. What types of IoT platforms do you have experience working with?

2. What challenges have you encountered while developing IoT wearable devices?
3. What improvements would you like to see in existing IoT wearable device platforms?
4. What features would you prioritize in the development of a universal IoT wearable framework like UWDF
5. What applications would you develop on the UWDF platform?
6. What factors would influence your decision to adopt a new IoT platform for wearable device development?
7. Based on your experience and expectations, what operation success rate do you believe a high-quality platform should achieve?
8. As a potential user, what level of satisfaction do you expect regarding the platform's technical usability?
9. How important is the feature of Data security and encryption when selecting an IoT platform for wearable devices?

3.1.4 Protocol

This section outlines the protocol followed for the user study, detailing the steps designed to engage participants and collect data effectively. The process includes participant recruitment, administration of the questionnaire, and data collection procedures, each structured to align with the study's objectives and ensure clarity in execution.

Pilot study: Before the formal questionnaire design, a small-scale pre-survey was conducted internally to ensure question clarity, conciseness, and coverage of stakeholder needs. Based on the feedback from the pre-survey, the question settings were further optimized to ensure that all participants could easily understand and answer the questions in the questionnaire.

Online and offline questionnaire distribution: The formal questionnaire was conducted simultaneously through online and offline channels. For the online questionnaire, participants could fill it out through a link, and the questionnaire platform would automatically collect and save the data. For the paper questionnaires distributed offline, researchers directly contacted participants to ensure that some older adults who are not accustomed to using electronic devices could also participate smoothly.

Data collection and processing: Online questionnaires were automatically recorded and saved through the questionnaire platform, while offline questionnaires were manually entered by researchers. All data was kept strictly confidential, and privacy protection measures were taken during processing. After data collection was completed, it underwent preliminary cleaning to ensure the accuracy of the analysis.

Data analysis: The collected data was analyzed using Excel, focusing on feedback from different groups regarding the functional requirements and pain points of wearable devices.

The analysis results were used for both quantitative analysis and qualitative feedback to comprehensively understand user experiences and device improvement directions.

3.2 Data Analysis

All collected questionnaire data were compiled into Microsoft Excel spreadsheets for cleaning, visualization, and analysis. Quantitative data from multiple-choice and scale-based questions were processed using descriptive statistical methods, including frequency counts and percentage distributions. For questions offering an "Other" option, participants could provide free-text responses. These open-ended inputs were analyzed using inductive content analysis. The process involved: (1) collecting all text responses, (2) reviewing responses to identify keywords and patterns, (3) categorizing responses into existing pre-defined options or new categories where applicable, and (4) summarizing findings to inform design implications. Due to the limited number of free-text responses (less than 10% of total responses across all groups), no new categories emerged, reinforcing the representativeness of pre-defined options.

Each stakeholder group's questionnaire consisted of two parts: Questions 1–5 collected personal and demographic information (e.g., age, health status, gender, occupation, or technology experience), providing context for participants' responses, and Questions 6 onward focused on experiences, preferences, and needs related to wearable health devices. To streamline reporting, the core questions (Question 6 and beyond) are renumbered starting from Question 1 in the analysis sections for each group. This renumbering is applied consistently across all groups for clarity, while the original questionnaire structure is preserved. Figures and tables visualize stakeholder feedback, facilitating interpretation and comparison across groups.

3.2.1 Older Adults

Older adults are defined as individuals aged 65 years and over. The actual age range of the older adult participants who completed the survey was 66 to 85 years old. In terms of health status, all participants were in a condition where they did not require long-term medical care, and their daily lives were not impacted.

Older adults with poor health conditions, such as severe cognitive or mobility impairments, were not included in this user survey due to their limited ability to participate effectively or use wearable devices independently. This study focused on older adults with health monitoring needs, such as those managing long-term health conditions or requiring mobility support, to ensure the collected data reflected the experiences and preferences of the primary end-users capable of engaging with IoT-based wearable technologies.

3.2.1.1 Results

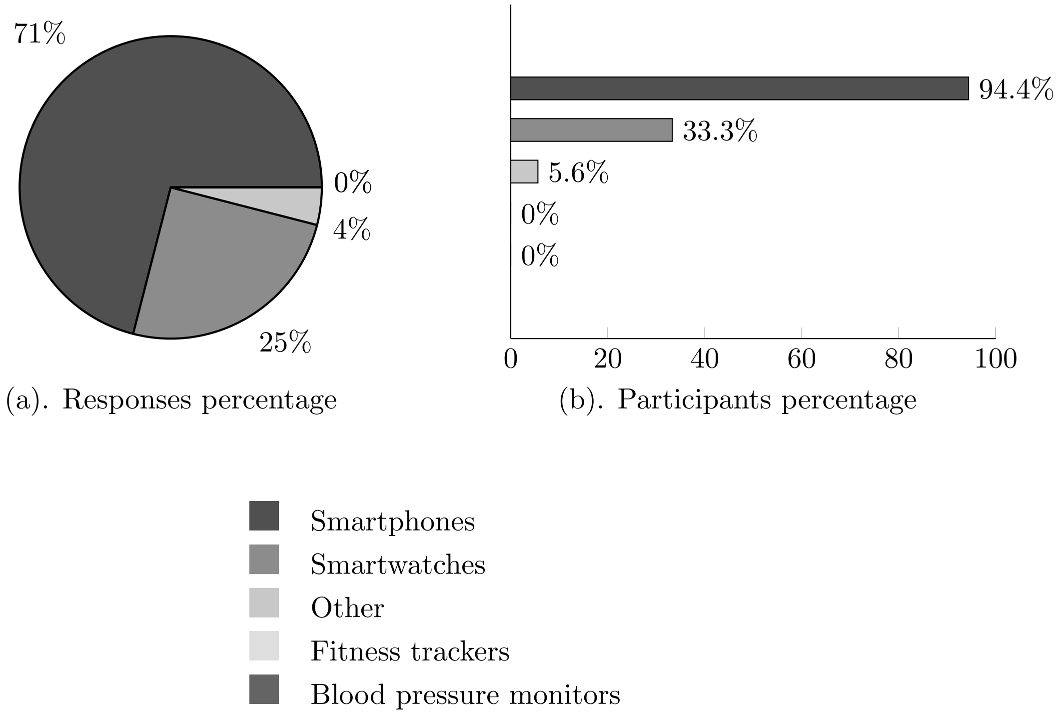
The survey of older adults consisted of six questions designed to understand their experiences, preferences, and concerns regarding wearable devices.

Question 1: "Which of the following electronic products and wearable devices are you currently using? (Select all that apply)". This question was constructed to identify the types of electronic products and wearable devices currently used by older adults, helping us understand the prevalence and preferences for these technologies among this user group.

As shown in Figure 3.1, Smartphones were the most commonly used devices, with 17 of 18 (71% of responses, 94.4% of participants) older adults selecting this option. Smartwatches were the second most used, selected by 6 participants (25% of responses, 33.3% of participants), indicating moderate adoption of wearable technology among this group. Other devices were reported by one participant (4% of responses, 5.6% of participants), suggesting limited use of alternative technologies. Neither Fitness trackers nor Blood pressure monitors were selected by any participants, indicating these devices may have lower relevance or accessibility for this population.

Question 2: "What conveniences have you experienced while using wearable devices? (Select all that apply)". This question was constructed to measure the benefits and positive experiences that older adults have encountered while using wearable devices, helping us understand which features are most valuable to this user group.

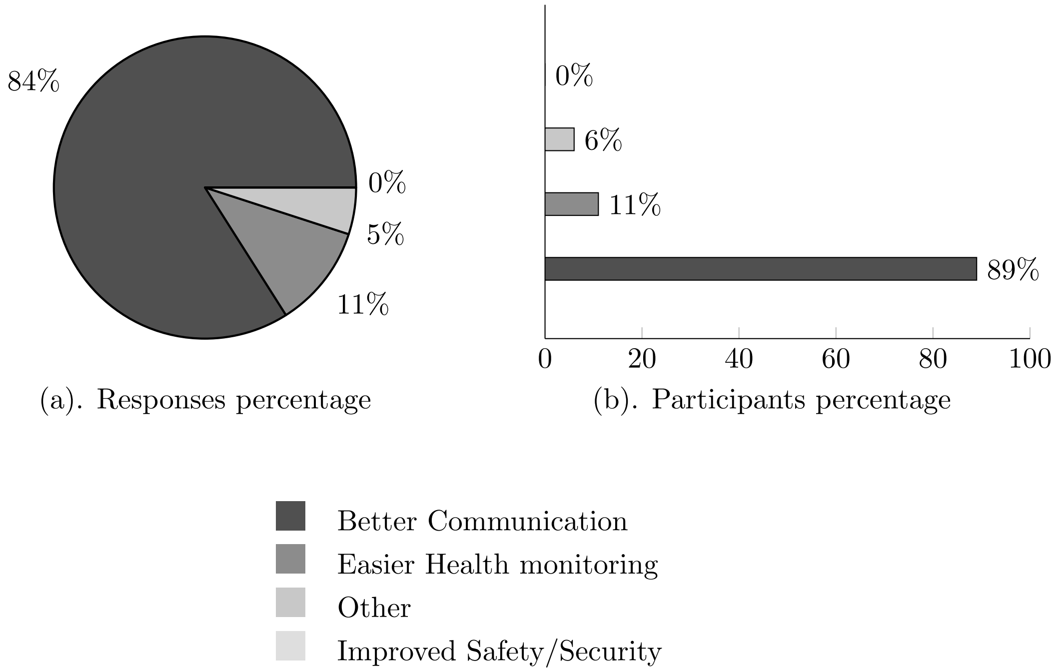
As shown in Figure 3.2, Better Communication was ranked the highest convenience, with 16 of 18 (84% of responses, 89% of participants) older adults selecting



(a). Responses percentage

(b). Participants percentage

Figure 3.1: Electronic Products and Wearable Devices Usage

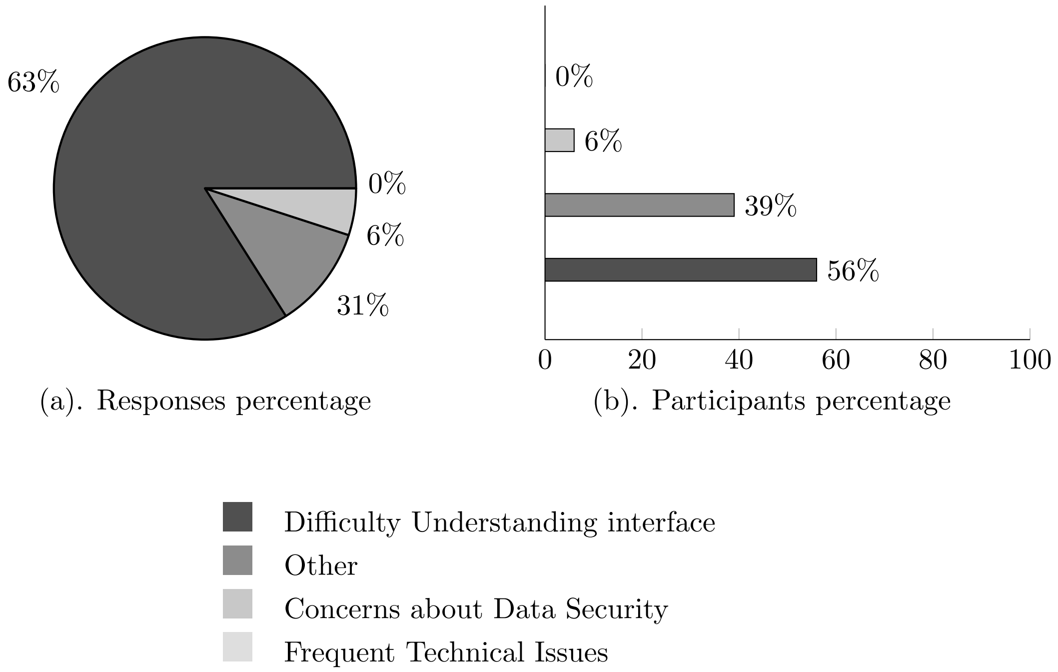


(a). Responses percentage

(b). Participants percentage

Figure 3.2: Conveniences Experienced by Older Adults

this option. Easier Health Monitoring was the second most reported convenience, selected by two participants (11% of responses, 11% of participants), indicating strong recognition of wearable devices' health tracking capabilities. Other functionality was valued by one participant, suggesting these features, while impor-



(a). Responses percentage

(b). Participants percentage

Figure 3.3: Inconveniences Experienced by Older Adults

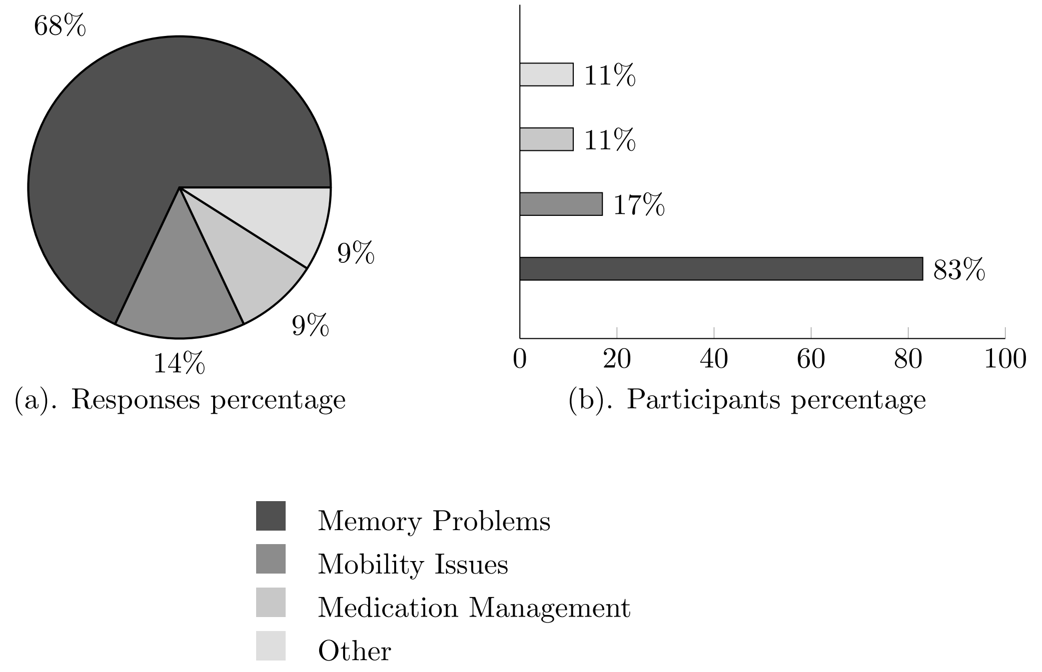
tant, may need enhancement to increase their perceived value.

Question 3: “What inconveniences have you experienced while using wearable devices? (Select all that apply)”. This question was designed to identify the primary challenges and barriers that older adults face when using wearable devices.

As shown in Figure 3.3, Difficulty Understanding Interface was the most significant challenge, reported by ten participants (63% of responses, 56% of participants), highlighting the need for clear UI and function solutions in the UWDF platform. Other Issues were problematic for five participants (31% of responses, 39% of participants), while Concerns about Data Security frustrated one participant (6% of responses and 6% of participants).

Question 4: “What health difficulties do you think wearable devices could help with in older adults daily life? (Select all that apply)”. This question aimed to identify the specific health-related challenges that older adults believe could be addressed through wearable technology.

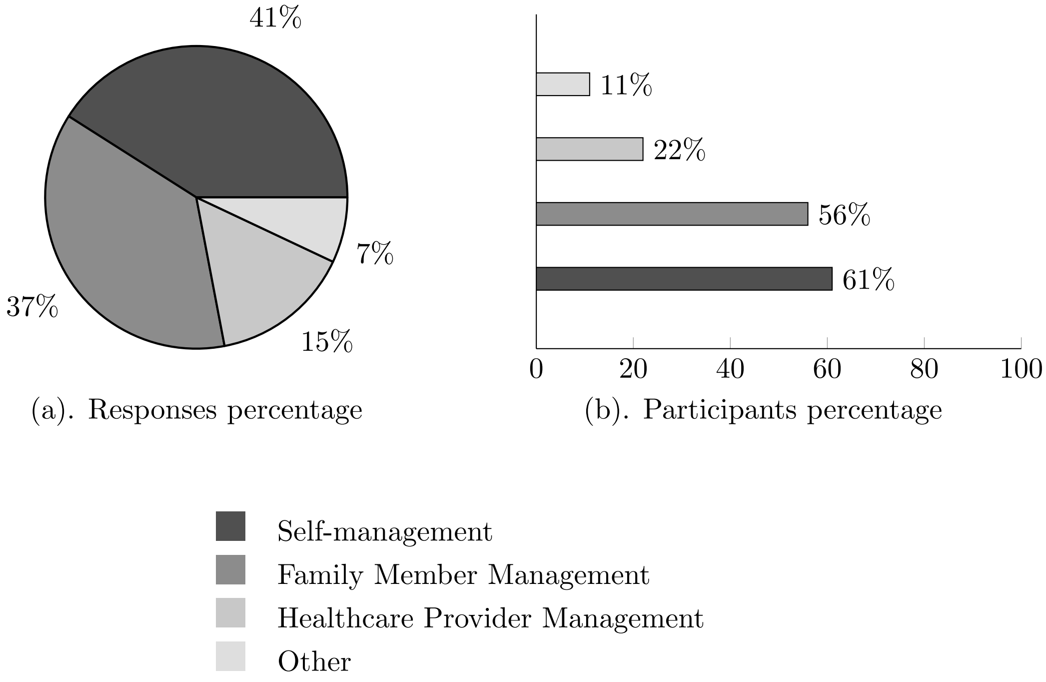
As shown in Figure 3.4, Memory Problems emerged as the primary concern, with 15 participants (68% of responses, 83% of participants) believing wearable devices could help address this issue. Mobility Issues was the second most selected option, chosen by three participants (14% of responses, 17% of participants), indicating a strong desire for mobility-related features. Medication Management and Other were each selected by two participants (9% of responses, 11% of participants),



(a). Responses percentage

(b). Participants percentage

Figure 3.4: Health Difficulties Addressed



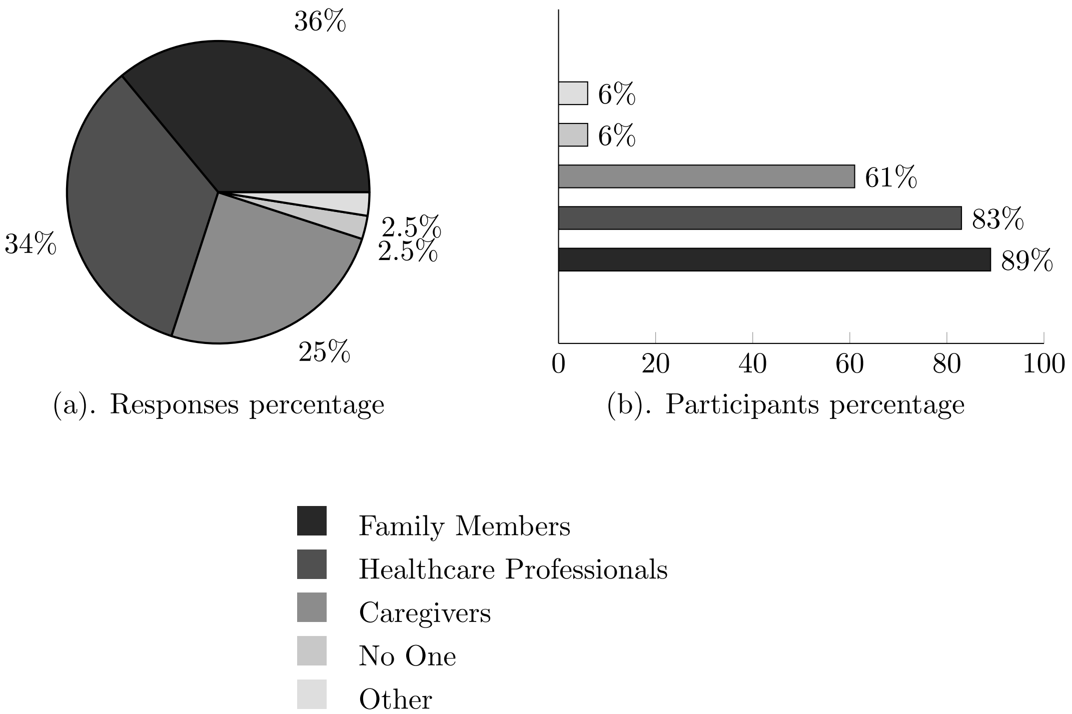
(a). Responses percentage

(b). Participants percentage

Figure 3.5: Preferred Methods for Health Data Management

suggesting a comprehensive range of health monitoring needs.

Question 5: “How would you prefer to manage and control your health monitoring data? (Select all that apply)”. This question was designed to understand older adults’ preferences for data management.



(a). Responses percentage

(b). Participants percentage

Figure 3.6: Preferred Recipients for Health Data Sharing

As shown in Figure 3.5, Self-management was the preferred option, selected by 11 participants (41% of responses, 61% of participants), indicating a strong desire for autonomy. Family Member Management was the second most popular choice with ten participants (37% of responses, 56% of participants), suggesting the importance of family support. Healthcare Provider Management was selected by four participants (15% of responses, 22% of participants), indicating varying levels of comfort with different management approaches.

Question 6: “Who would you like to share your health monitoring data with? (Select all that apply)”. This question was constructed to understand older adults’ preferences regarding data sharing.

As shown in Figure 3.6, Family Members were the most trusted recipients, with 16 participants (36% of responses, 89% of participants) willing to share their data with them. Healthcare Professionals were the second most selected option, chosen by 15 participants (34% of responses, 83% of participants). Caregivers were selected by 11 participants (25% of responses, 61% of participants), indicating varying levels of trust and perceived necessity for different stakeholders.

Question 7: “How are you concerned about data security and privacy when using wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Concerned, 5 = Very Concerned)”. This question aimed to gauge older adults’ level of concern regarding data security and privacy.

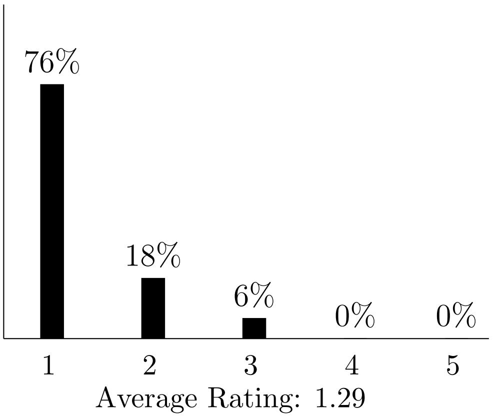


Figure 3.7: Level of Concern

As shown in Figure 3.7, most participants expressed no concern, with thirteen participants (76%) selecting level 1. Three participants (18%) indicated low concern (level 2), while one participant (6%) chose moderate concern (level 3). No one selected high levels (level 4 and level 5). This distribution suggests that older adults pay little attention to data security and privacy.

3.2.1.2 Discussion and Key Findings

Section 3.2.1.1 outlined the results from the survey of older adults. From these results, there are six key findings that can be extrapolated.

1. Most older adults participants reported experiencing improved communication as a benefit of using wearable devices.
2. The most frequently cited inconvenience was difficulty understanding the device interface.
3. Memory problems were the most common health difficulty that participants felt wearable devices could help with.
4. Most participants preferred to manage their health data themselves or have it managed by a family member.
5. Family members and healthcare professionals were the preferred recipients for data sharing.
6. Data security and privacy concerns were generally low among participants.

The findings from the older adults group emphasize the significance of user-centered designs and effective data management. Older adults preferred simplified device interfaces and autonomous or family-assisted data management, highlighting a need for intuitive features and clear instructions in wearable devices. This underscores the importance of prioritizing simplicity and accessibility in the design phase. Their relatively low concern for data privacy suggests that awareness campaigns or built-in secure systems that function seamlessly in the background could alleviate latent concerns.

These insights will guide enhancements in the platform interface, such as incorporating simplified navigation and larger, more readable icons. Additionally, automatic yet transparent privacy protection measures will be valuable to ensure ease of mind without complicating the user experience.

3.2.2 Caregivers

A caregiver refers to an individual who provides care and support to the older adults in various settings such as nursing homes, communities, and homes. Caregivers offered valuable perspectives on the practical aspects of wearable devices for older adults.

3.2.2.1 Results

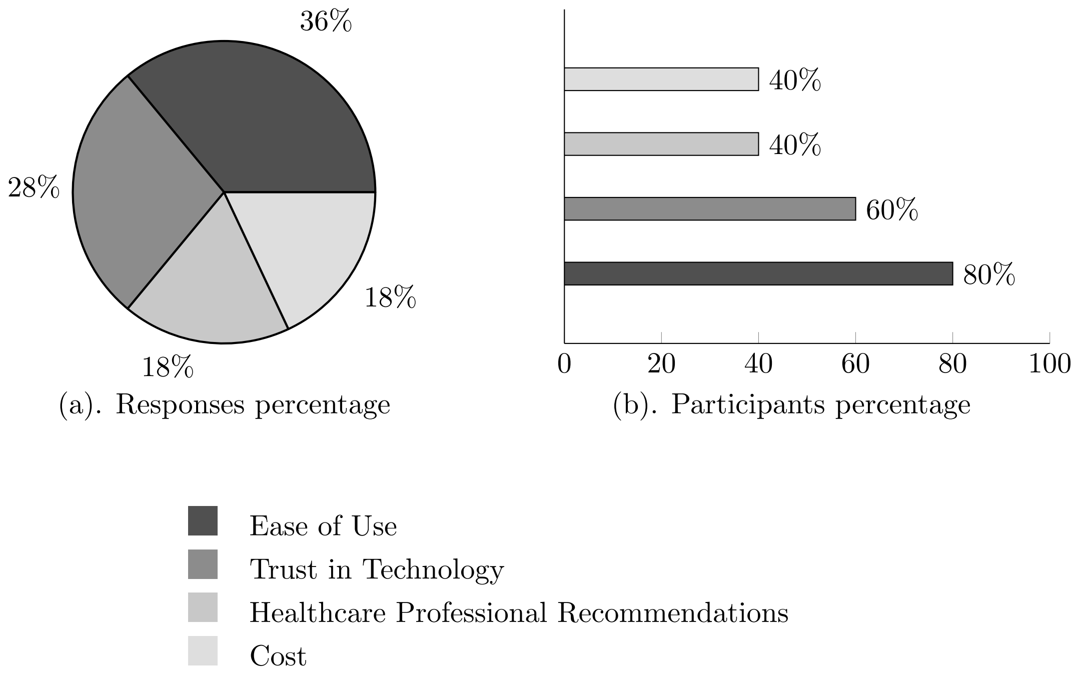
The survey for caregivers consisted of five questions to help us understand their perspectives on wearable devices for older adults care.

Question 1: “What factors do you think influence an older adults’ willingness to use wearable devices? (Select all that apply)”. This question was designed to understand caregivers’ perspectives on adoption barriers and motivators.

As shown in Figure 3.8, Ease of Use was identified as the most significant factor, selected by four participants (36% of responses, 80% of participants). Trust in Technology was the second most important factor, chosen by three participants (28% of responses, 60% of participants). Cost and Healthcare Professional Recommendations were each selected by two participants (18% of responses, 40% of participants). This distribution highlights the importance of developing user-friendly, affordable devices with professional endorsement.

Question 2: “What information would you like to obtain about the older adults’ health through wearable devices? (Select all that apply)”. This question aimed to identify the key health metrics that caregivers need to monitor.

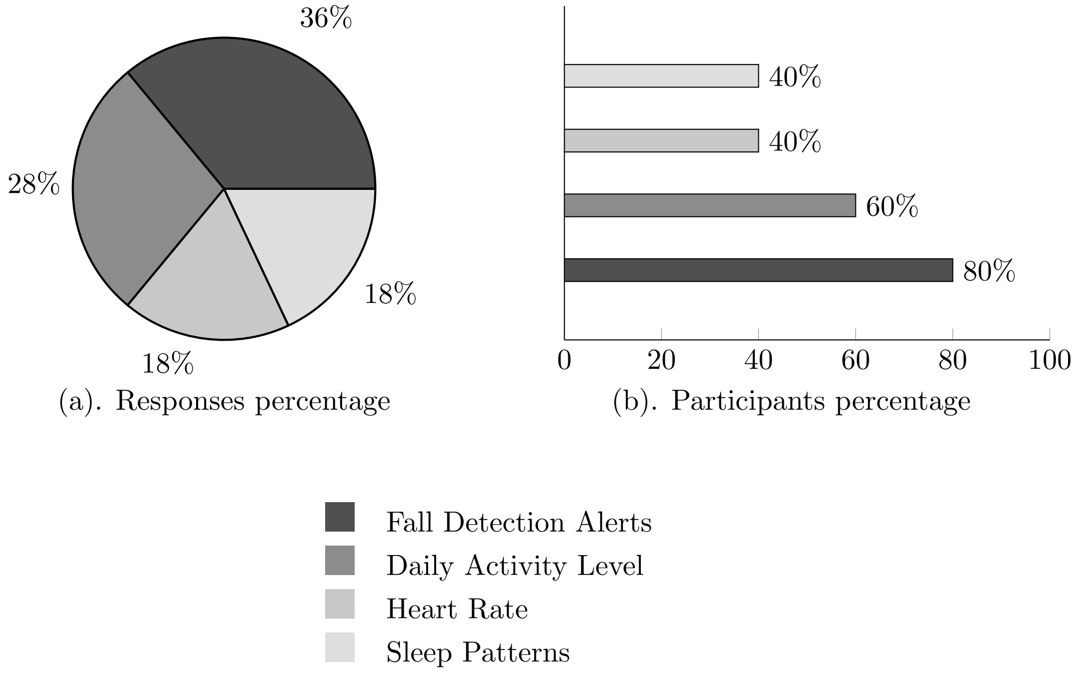
As shown in Figure 3.9, Fall Detection Alerts was chosen by four participants (36% of responses, 83% of participants), while Daily Activity Level was selected by three participants (27% of responses, 83% of participants). Heart Rate and Sleep Patterns were each selected by two participants (18% of responses, 83% of participants), indicating these as essential monitoring parameters. This suggests



(a). Responses percentage

(b). Participants percentage

Figure 3.8: Factors Influencing Older Adults Adoption



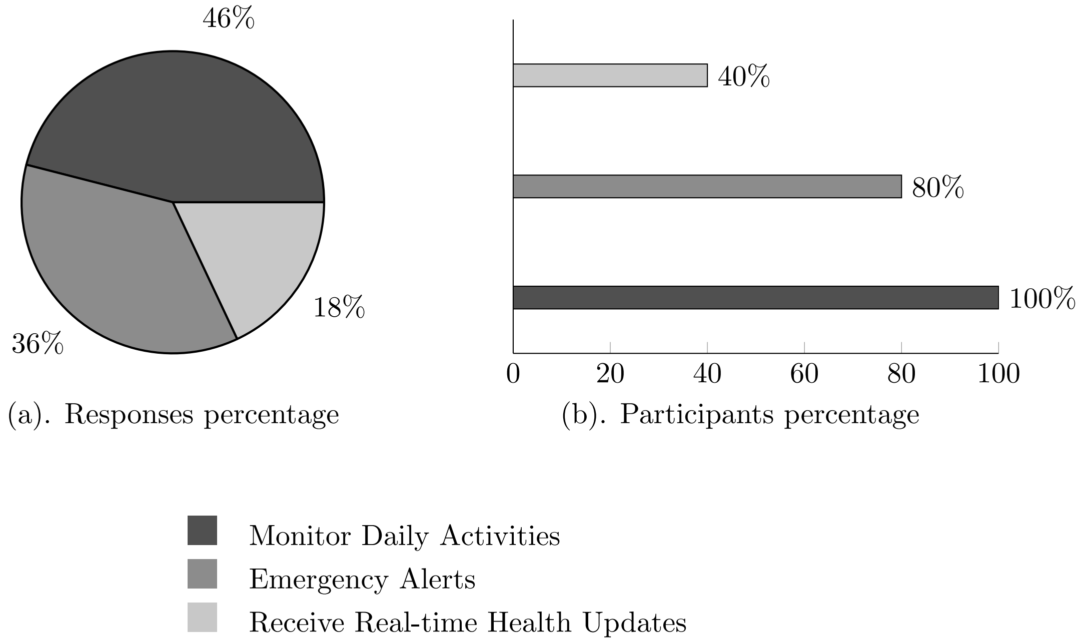
(a). Responses percentage

(b). Participants percentage

Figure 3.9: Desired Health Information

a need for comprehensive health monitoring, particularly for daily activities and sleep.

Question 3: “How do you think wearable devices can help you care for older adults individuals? (Select all that apply)”. This question was constructed to



(a). Responses percentage (b). Participants percentage

Figure 3.10: Potential Benefits of Wearable Devices

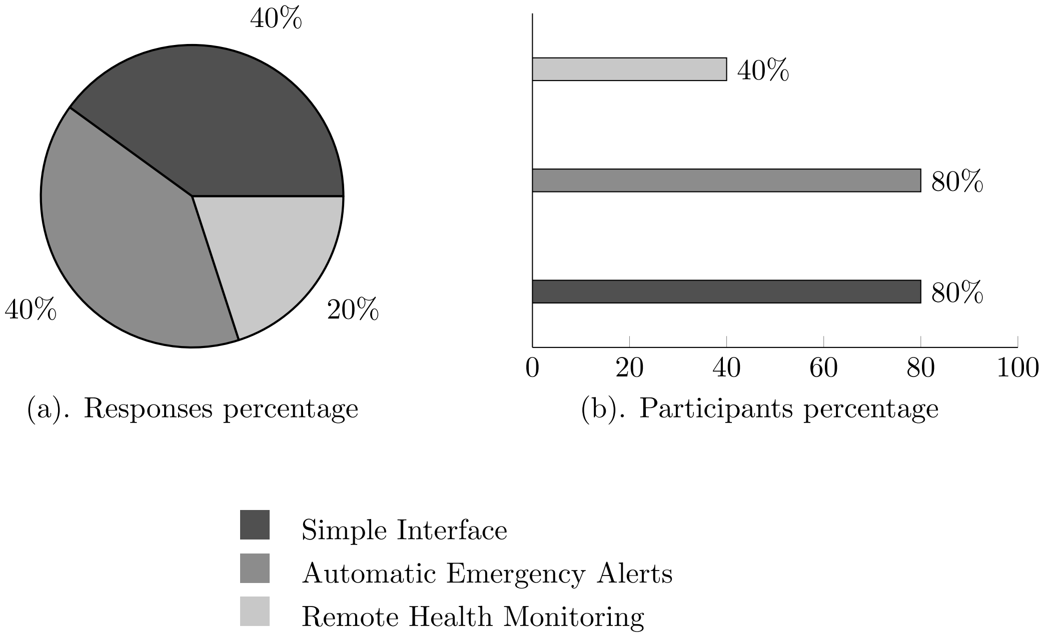
understand how caregivers envision using wearable technology to enhance their care delivery.

As shown in Figure 3.10, Fall Detection Alerts was chosen by four participants (36% of responses, 83% of participants), while Daily Activity Level was selected by 3 participants (27% of responses, 83% of participants). Heart Rate and Sleep Patterns were each selected by two participants (18% of responses, 83% of participants), indicating these as essential monitoring parameters. This suggests a need for comprehensive health monitoring capabilities with particular emphasis on daily activities and sleep monitoring.

Question 4: “What features would you like wearable devices to have? (Select all that apply)”. This question aims to identify specific features that would support caregivers in their role.

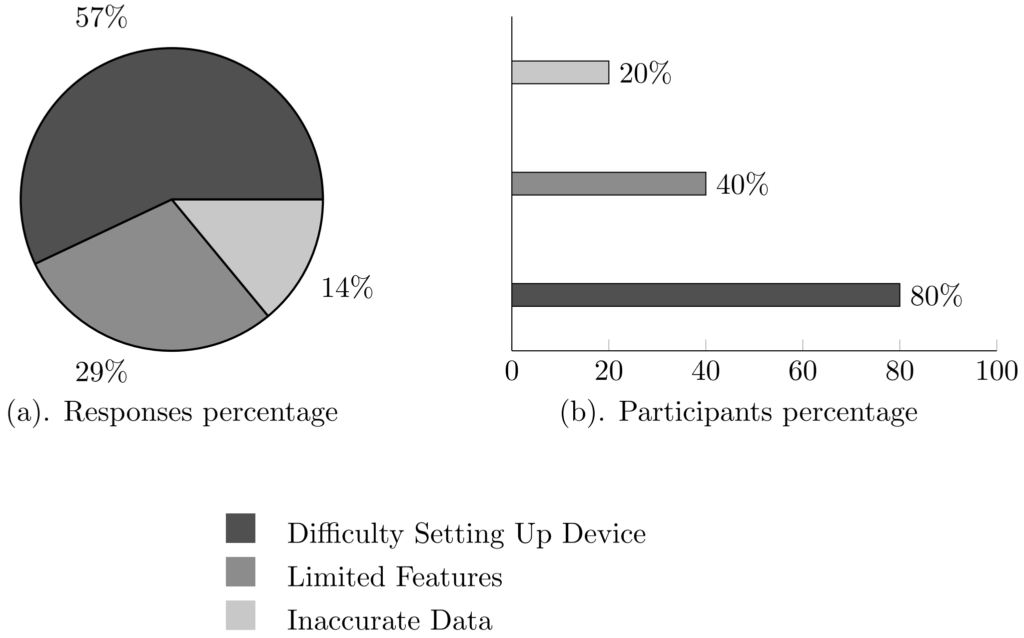
As shown in Figure 3.11, Simple Interface for Older Adults and Automatic Emergency Alerts were each selected by four participants (40% of responses, 80% of participants). While Remote Health Monitoring was selected by two participants (20% of responses, 40% of participants). This indicates a strong preference for automatic emergency alerts with user-friendly interfaces.

Question 5: “What problems have you encountered with existing physiological monitoring devices or platforms? (Select all that apply)”. This question was designed to identify current technology limitations.



(a). Responses percentage (b). Participants percentage

Figure 3.11: Desired Features



(a). Responses percentage (b). Participants percentage

Figure 3.12: Problems with Existing Monitoring Devices

As shown in Figure 3.12, Difficulty Setting Up Device was reported by four participants (57% of responses, 80% of participants). Limited Features was selected by two participants (29% of responses, 40% of participants), while Inaccurate Data was chosen by one participant (14% of responses, 20% of participants). These findings highlight the need for improved features and data accuracy in the UWDF platform.

3.2.2.2 Discussion and Key Findings

The analysis of the caregiver survey responses highlighted several critical factors. These results yield five major conclusions:

1. Caregivers believed that ease of use, cost, and recommendations from healthcare professionals were the main factors influencing an older adults's willingness to use wearable devices.
2. Caregivers expressed a desire to obtain information on daily activity levels, sleep patterns, and fall alerts through wearable devices.
3. Caregivers saw the potential for wearable devices to help them monitor daily activities, provide real-time health updates, and send alerts in case of emergencies.
4. Desired features included remote health monitoring, a simple interface for older adults, and automatic emergency alerts.
5. Reported problems with existing devices included difficulty setting up the device, limited features, and inaccurate data.

Caregivers' emphasis on ease of use, affordability, and trusted recommendations highlights the socio-practical considerations surrounding the adoption of wearable devices. Their desire for real-time updates, emergency alerts, and remote monitoring features aligns with the practical challenges they face in caregiving, while the issues with existing devices underscore the need for robust setup and operational support.

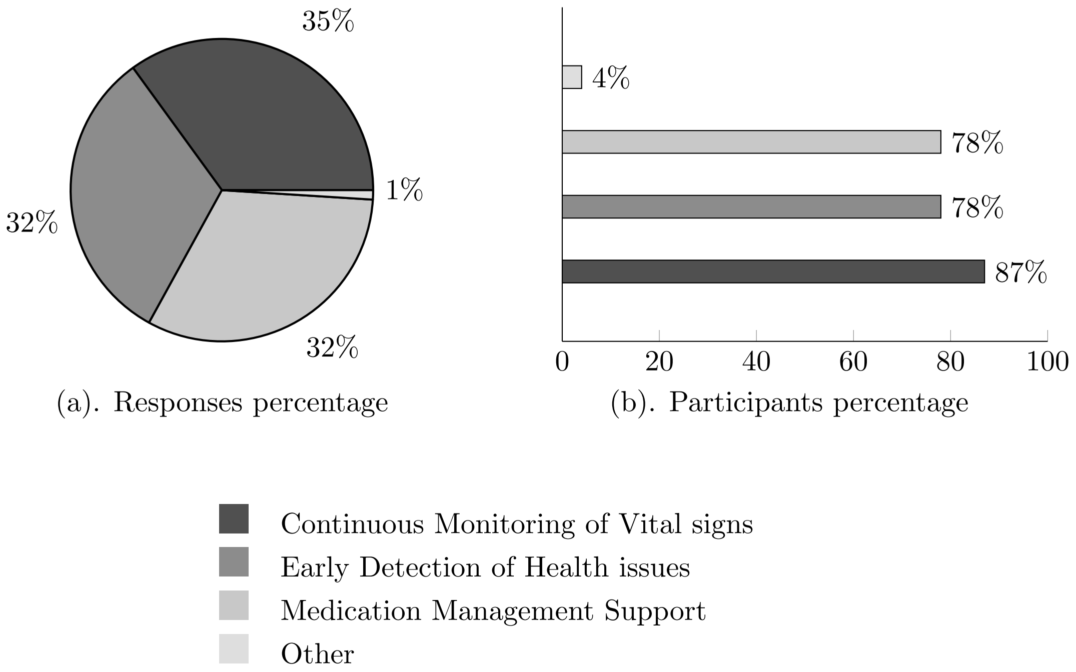
Based on these findings, the platform will prioritize incorporating remote monitoring capabilities, simplified setup processes, and fail-safe emergency alert systems. User manuals and customer support options tailored for caregivers will also be developed to enhance usability and trust.

3.2.3 Healthcare Professionals

The healthcare professionals participating in this survey had experience both in using wearable devices in medical practice and in assisting older adults with their medical needs.

3.2.3.1 Results

The survey for healthcare professionals consisted of three targeted questions designed to understand their clinical perspectives on wearable devices for older adults care.



(a). Responses percentage

(b). Participants percentage

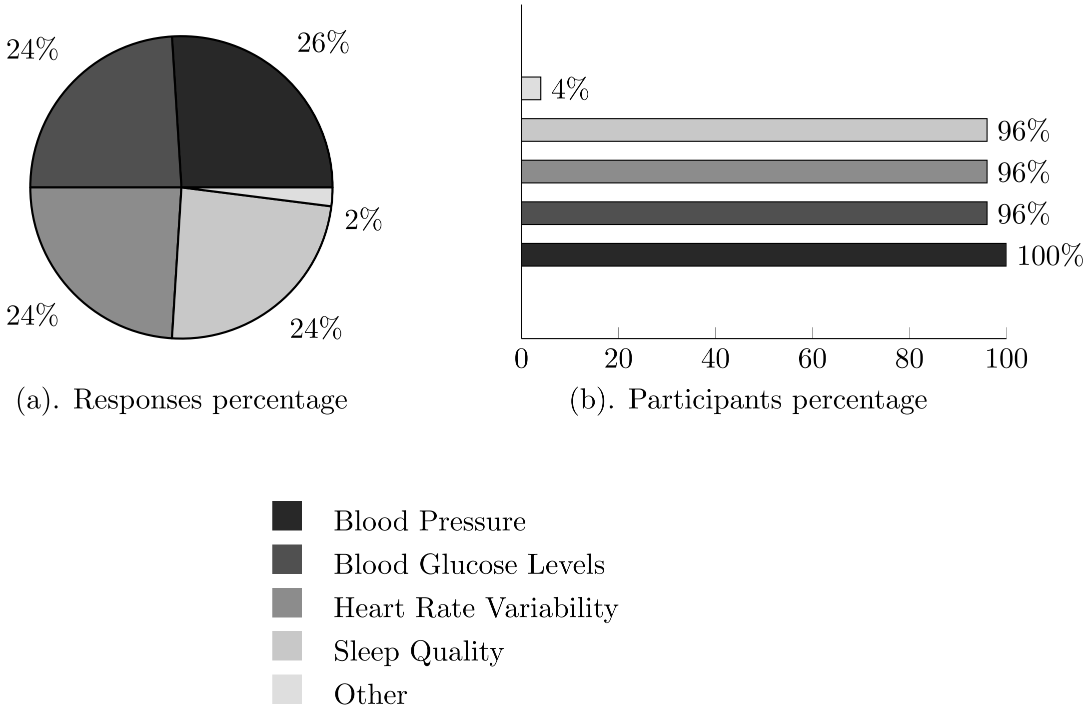
Figure 3.13: Healthcare Applications of Wearable Devices in Older Adults Care

Question 1: “How do you think wearable devices can be applied to older adults health management and chronic disease prevention? (Select all that apply)”. This question was designed to identify the most valuable healthcare applications of wearable technology in older adults care.

As shown in Figure 3.13, Continuous Monitoring of Vital Signs was selected by 20 of 23 participants (35% of responses, 87% of participants), indicating this as the primary healthcare application. Early Detection of Health Issues and Medication Management Support were chosen by 18 participants (32% of responses, 78% of participants), highlighting the preventive potential of wearable devices. These results emphasize the importance of comprehensive health monitoring capabilities with a focus on preventive care.

Question 2: “What data would you like to obtain from wearable devices to assist in diagnosis and treatment? (Select all that apply)”. This question aims to identify the specific health metrics that healthcare professionals consider most valuable for healthcare decision-making.

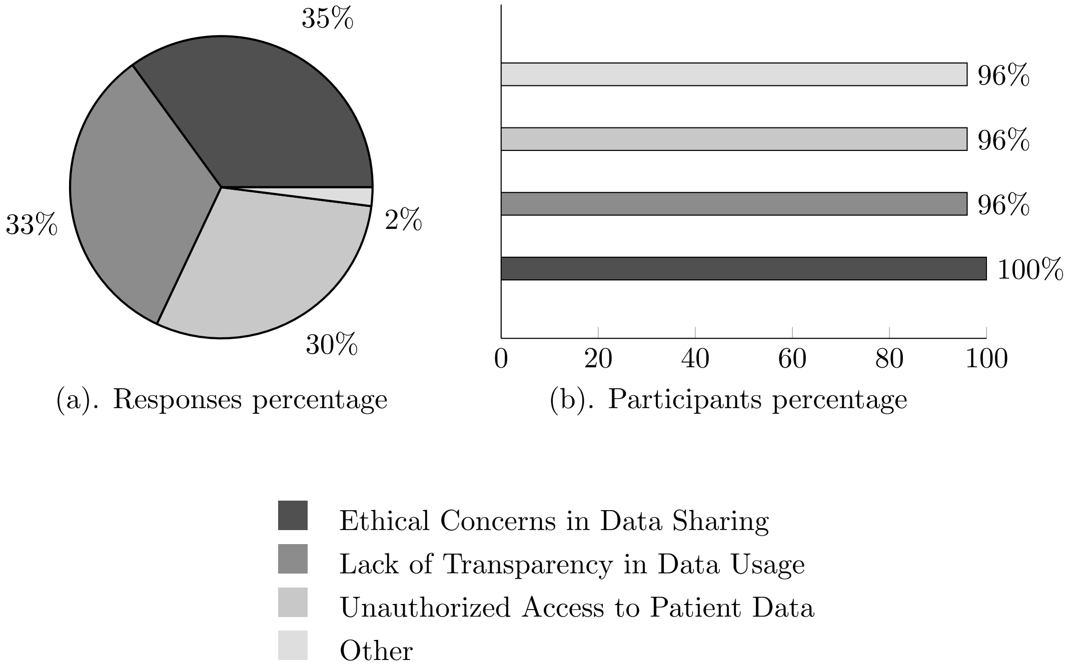
As shown in Figure 3.14, Blood Pressure Data was the most requested metric, selected by all 23 participants (26% of responses, 100% of participants). Blood Glucose Levels, Heart Rate Variability and Sleep Quality were each selected by 22 participants (24% of responses, 96% of participants), This distribution indicates the need for extensive physiological monitoring capabilities in the UWDF platform.



(a). Responses percentage

(b). Participants percentage

Figure 3.14: Desired Healthcare Data from Wearable Devices



(a). Responses percentage

(b). Participants percentage

Figure 3.15: Healthcare Professionals' Data Security and Privacy Concerns

Question 3: "What concerns do you have about data security, privacy, and ethics with wearable devices? (Select all that apply)" was designed to identify healthcare professionals' concerns about data management.

As shown in Figure 3.15, Ethical Concerns in Data Sharing was the primary concern, selected by 16 participants (35% of responses, 70% of participants). Lack of Transparency in Data Usage was chosen by 15 participants (33% of responses, 65% of participants), while Unauthorized Access to Patient Data was selected by 14 participants (30% of responses, 61% of participants). These findings emphasize the need for robust security measures and clear data governance policies in the UWDF platform.

3.2.3.2 Discussion and Key Findings

Section 3.2.3.1 outlined the results from the survey of healthcare professionals, who provided healthcare perspectives on wearable device implementation. From these results, three key findings emerge.

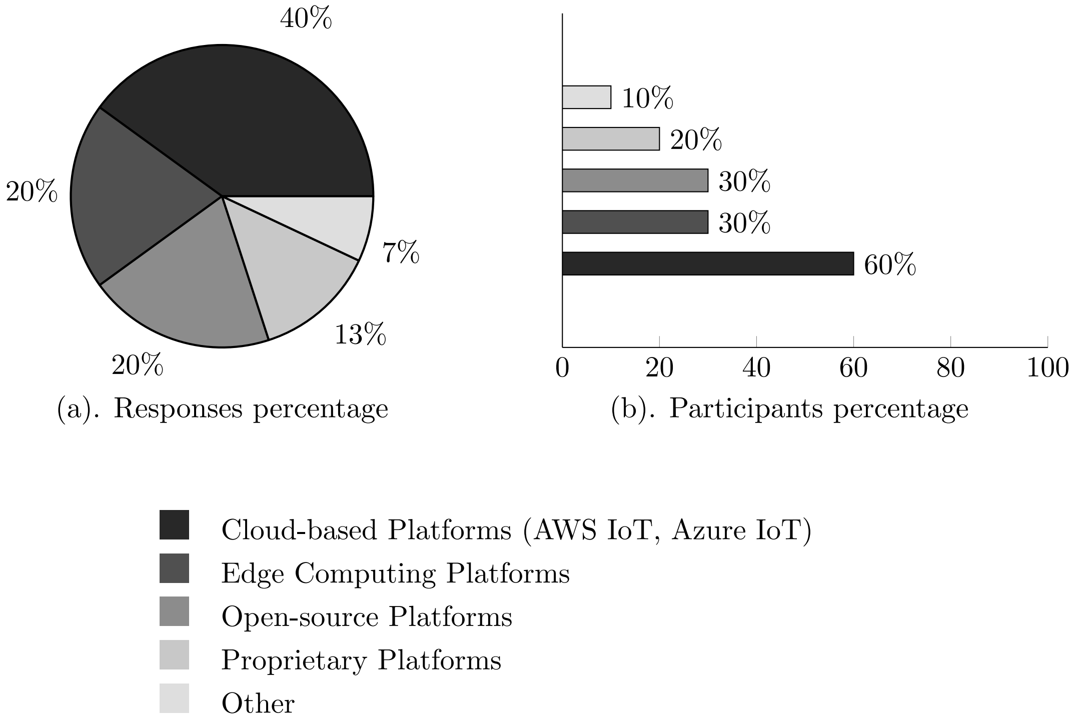
1. Medical professionals widely believed that wearable devices could be applied to continuous monitoring of vital signs, early detection of health issues, and assistance with medication management.
2. They desired data on blood pressure, blood glucose levels, heart rate variability, and sleep quality from wearable devices.
3. Unauthorized access to patient data, lack of transparency in data usage, and ethical concerns in data sharing were major concerns regarding data security, privacy, and ethics.

Healthcare professionals' focus on real-time health data for diagnostic and preventive care underscores the healthcare utility of wearable devices. Concerning data security, privacy, and ethical usage highlights the need for transparent and stringent security measures. The demand for comprehensive health data (e.g., blood pressure, glucose levels) reveals an opportunity to expand device compatibility with medical-grade sensors.

These findings will inform the integration of advanced security protocols, such as encryption and controlled data access, within the UWDF platform. Additionally, efforts will focus on establishing compatibility with relevant sensors and aligning the generated data adheres to healthcare standards for diagnosis and monitoring.

3.2.4 Technical Personnel

The technical personnel participating in this survey have experience in developing and implementing IoT-based wearable devices and platforms. Their expertise includes software engineering, hardware development, system architecture, and data science, making their feedback critical for the design and implementation of



(a). Responses percentage

(b). Participants percentage

Figure 3.16: IoT Experience with Different IoT Platforms

the UWDF. They provided valuable insights into technical requirements, such as device-platform compatibility, data security, and framework optimization, which are essential for creating a scalable and robust IoT wearable platform.

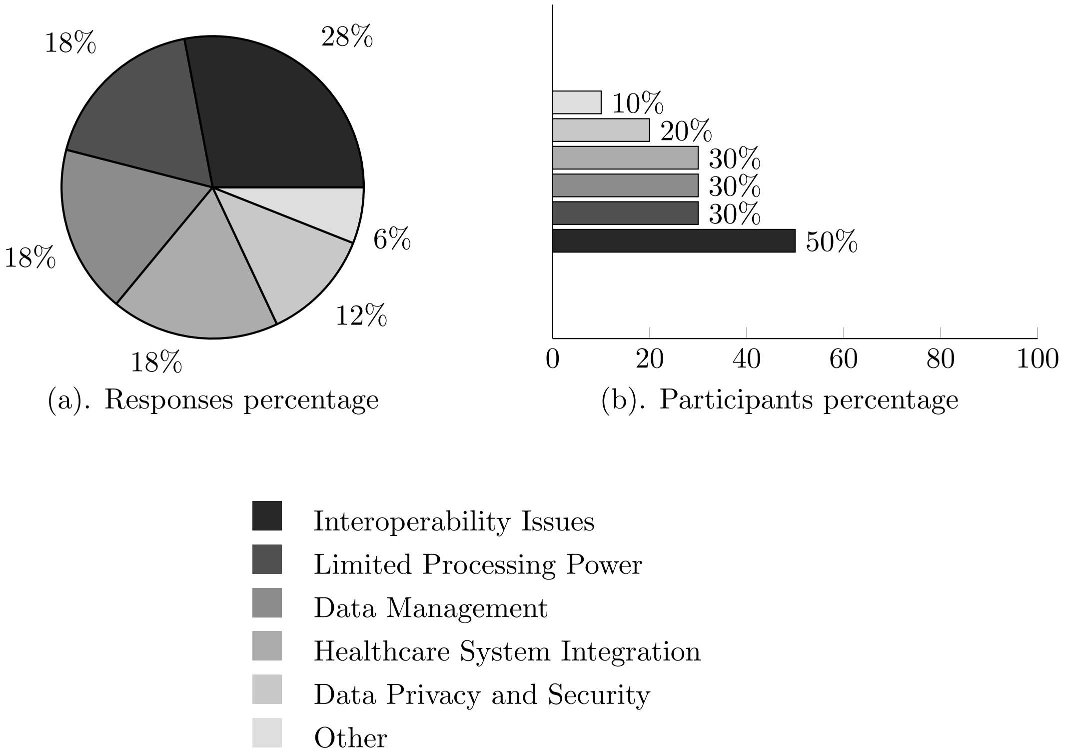
3.2.4.1 Results

The survey for technical personnel consisted of ten detailed questions. Each question was designed to gather specific insights about technical requirements, challenges, and expectations.

Question 1: “What types of IoT platforms do you have experience working with? (Select all that apply)”. This question aimed to identify the technical backgrounds and platform preferences.

As shown in Figure 3.16, Cloud-based Platforms (AWS IoT, Azure IoT) were the most common, with six participants (40% of responses, 60% of participants) having experience with them. Edge Computing Platforms and Open-source Platforms were each used by three participants (20% of responses, 30% of participants), while Proprietary Platforms were used by two participants (13% of responses, 20% of participants). This indicates the importance of cloud integration and compatibility with existing IoT ecosystems.

Question 2: “What challenges have you encountered while developing IoT wear-



(a). Responses percentage

(b). Participants percentage

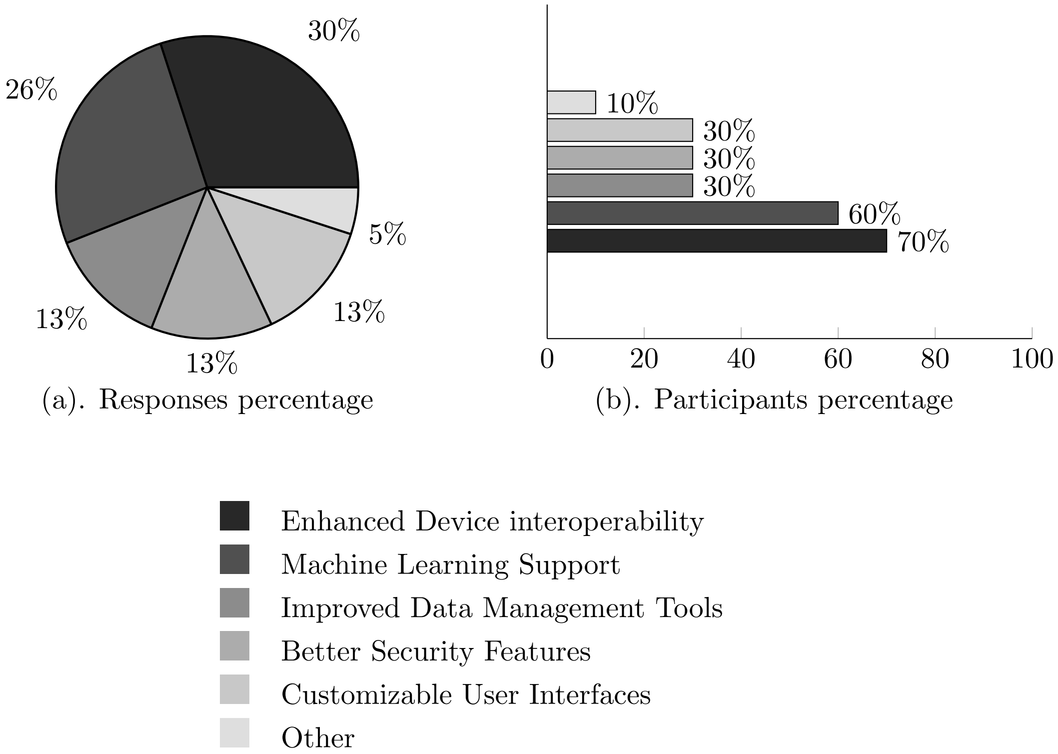
Figure 3.17: Challenges in IoT Wearable Device Development

able devices? (Select all that apply)". This question was designed to identify common technical obstacles.

As shown in Figure 3.17, Interoperability Issues were experienced by five participants (50% of responses, 83% of participants), Limited Processing Power, Data Management and Healthcare System Integration were each challenge for three participants (30% of responses, 83% of participants) each, Data Privacy and Security was the weakest challenge, reported by two participants (20% of responses, 83% of participants). These findings highlight that interoperability issues were the most common challenge faced by participants, while data privacy and security were the least reported concerns.

Question 3: "What improvements would you like to see in existing IoT wearable device platforms? (Select all that apply)". This question aimed to identify specific areas where current platforms fall short.

As shown in Figure 3.18, Enhanced Device Interoperability was the most requested improvement, selected by seven participants (30% of responses, 70% of participants). Machine Learning Support was desired by 6 participants (26% of responses, 60% of participants), while Improved Data Management Tools, Better Security Features and Customizable User Interfaces were each selected by three participants (13% of responses, 30% of participants). This once again confirms



(a). Responses percentage

(b). Participants percentage

Figure 3.18: Desired Platform Improvements

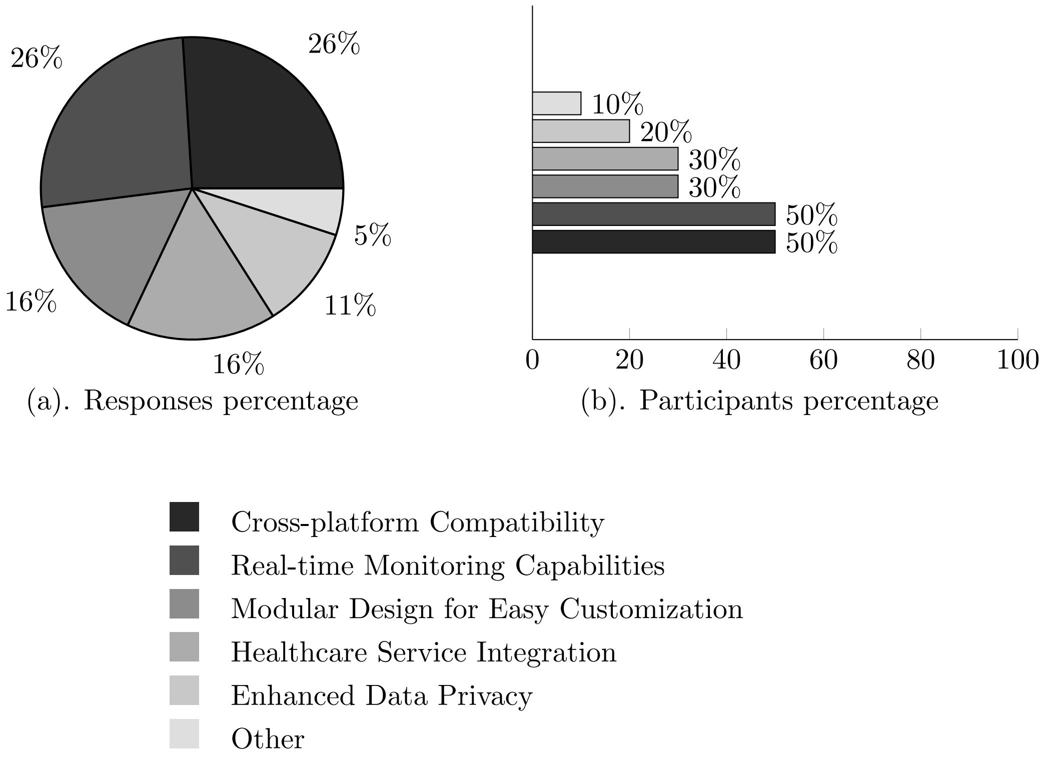
the importance of interoperability, consistent with question 2.

Question 4: “What features would you prioritize in the development of a universal IoT wearable framework like UWDF? (Select all that apply)”. This question was designed to evaluate which features technical personnel consider most critical for success.

As shown in Figure 3.19, Cross-platform Compatibility and Real-time Monitoring Capabilities were the highest priority, each selected by five participants (26% of responses, 50% of participants), while Modular Design for Easy Customization and Healthcare Service Integration were each selected by three participants (16% of responses, 30% of participants). Enhanced Data Privacy was selected by two participants (11% of responses, 20% of participants). This distribution emphasizes the Cross-platform compatibility and real-time monitoring capabilities were the top priorities for participants, while enhanced data privacy was the least selected.

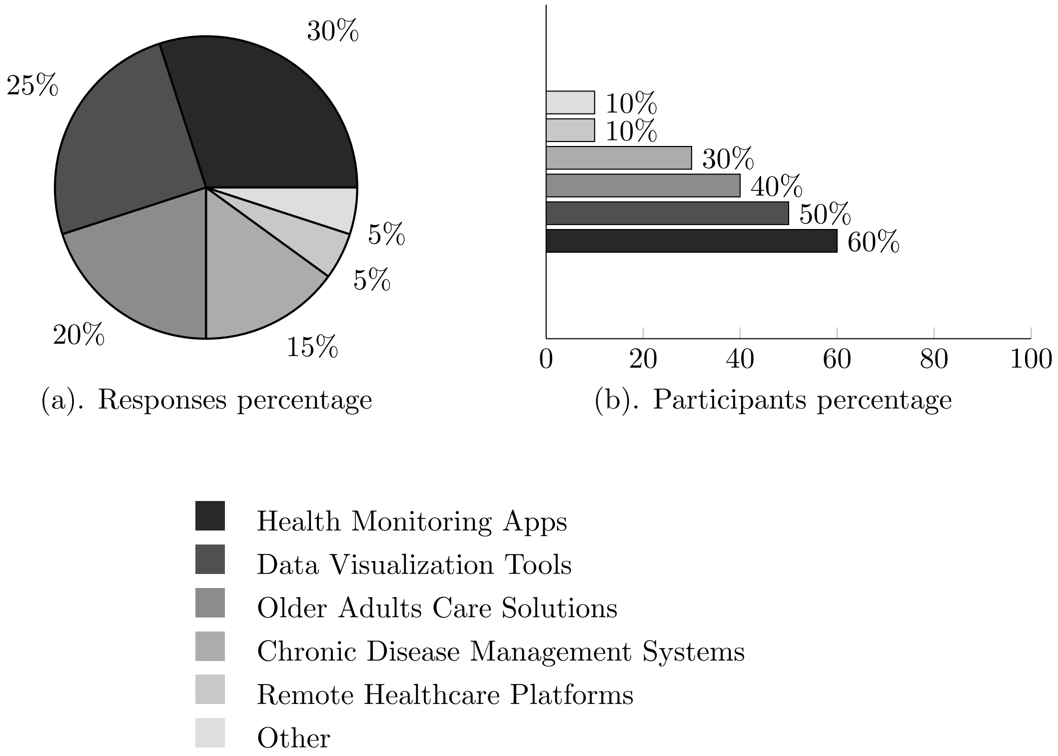
Question 5: “What applications would you develop on the UWDF platform? (Select all that apply)”. This question aimed to identify the types of applications developers plan to create.

As shown in Figure 3.20, Health Monitoring Apps were the most common planned


(a). Responses percentage

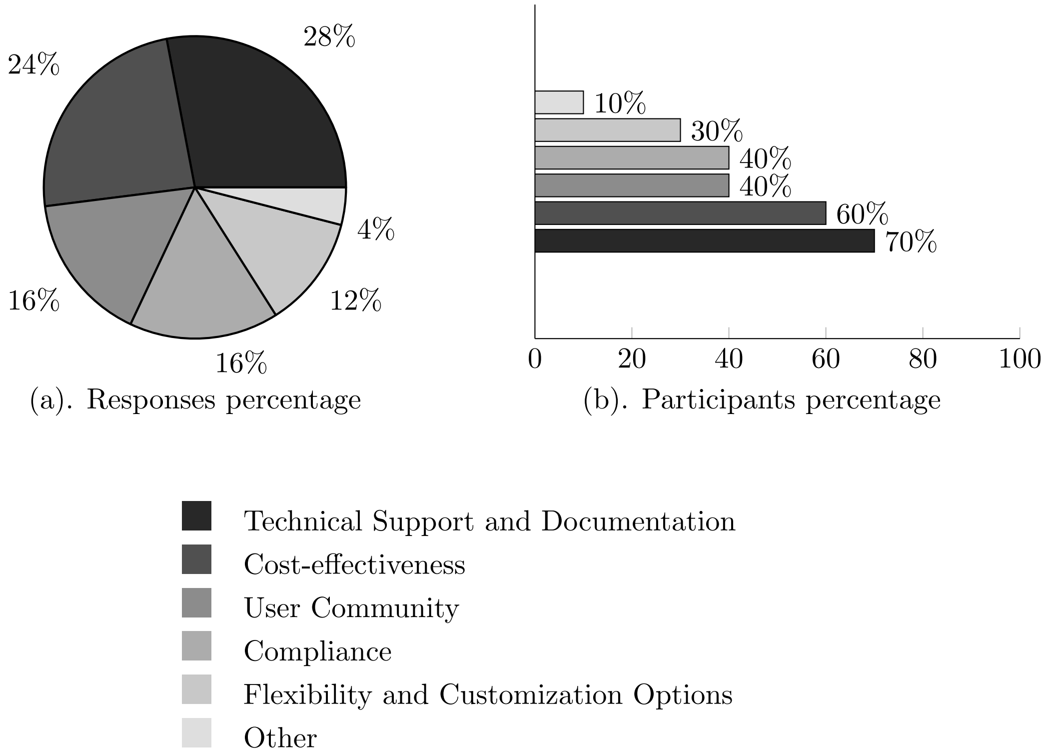
(b). Participants percentage

Figure 3.19: Priority Features for UWDF Development


(a). Responses percentage

(b). Participants percentage

Figure 3.20: Planned Applications for UWDF Platform



(a). Responses percentage

(b). Participants percentage

Figure 3.21: Factors Influencing Platform Adoption

application, selected by six participants (30% of responses, 60% of participants). Data Visualization Tools were planned by 5 participants (25% of responses, 50% of participants). Older Adults Care Solutions was selected by 4 participants (20% of responses, 40% of participants), while Chronic Disease Management Systems were chosen by three participants (15% of responses, 30% of participants). These results indicate health care and monitoring apps were the most popular planned application, followed by data visualization tools and chronic disease management systems.

Question 6: “What factors would influence your decision to adopt a new IoT platform for wearable device development? (Select all that apply)”. This question was constructed to understand the key factors that would drive platform adoption among developers.

As shown in Figure 3.21, Technical Support and Documentation was the most crucial factor, selected by all seven participants (28% of responses, 70% of participants). Cost-effectiveness was chosen by six participants (24% of responses, 60% of participants), while User Community and Compliance with industry standards were each selected by four participants (16% of responses, 40% of participants). Flexibility and Customization Options were important for three participants (12% of responses, 30% of participants). This highlights the importance of comprehen-

ID	Operational Success Rate	Usability Satisfaction Score
1	98%	80
2	95%	90
3	99%	80
4	80%	80
5	90%	90
6	80%	90
7	80%	90
8	50%	50
9	76%	80

Table 3.2: Expected Platform Operation Success Rate and Usability Score

sive developer support and platform flexibility.

Question 7: "Based on your experience and expectations, what operation success rate do you believe a high-quality platform should achieve? Please enter a percentage value (%)". This question aims to establish performance benchmarks.

As shown in Table 3.2, most participants expected very high operational reliability. The responses ranged from 50% to 99%, with a median expectation of 85%. This indicates that technical personnel have high expectations for platform stability and reliability.

Question 8: "As a potential user, what level of satisfaction do you expect regarding the platform's technical usability ? Please enter a percentage value (%)". This question was designed to understand expectations for platform usability and user experience.

As shown in Table 3.2, expectations for technical usability were similarly high, with responses of satisfaction score ranging from 50% to 90% and a median of 81%. This suggests that developers expect a highly intuitive and efficient development experience.

Question 9: "How important is the feature of Data security and encryption when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important)". This question aimed to gauge the relative importance of security features in platform selection.

As shown in Figure 3.22, majority of participants (five participants, 50%) rated security as Very Important (5), while two participants (20%) rated it as Important

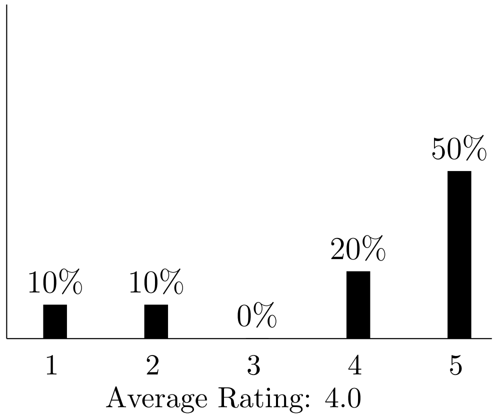


Figure 3.22: Importance of Data Security and Encryption

(4). This underscores the critical nature of robust security measures in the UWDF platform.

3.2.4.2 Discussion and Key Findings

Section 3.2.4.1 outlined the survey results from technical personnel, providing crucial insights into the technical requirements and expectations. From these results, several key findings emerge.

1. Experience with cloud-based platforms like AWS IoT and Microsoft Azure IoT was common, with some also having experience with proprietary, edge computing, and open-source platforms.
2. Key challenges included ensuring data privacy and security, interoperability issues with different devices, limited processing power in wearables, difficulty managing large amounts of data, and integration with healthcare systems.
3. Desired improvements included enhanced device interoperability, better security features, more customizable user interfaces, support for machine learning and AI, and improved data management and analytics tools.
4. Prioritized features for a universal IoT wearable framework like UWDF included modular design for easy customization, enhanced data privacy and user control, cross-platform and device compatibility, real-time monitoring and data analytics, and integration with healthcare services.
5. Potential applications for the UWDF platform included health monitoring apps, health needs management systems, older adults care solutions, remote healthcare platforms, and data visualization tools.
6. Factors influencing the adoption of a new IoT platform included techni-

cal support and documentation, flexibility and customization options, cost-effectiveness, user community and third-party integrations.

7. The technical personnel had high expectations for platform operation success rate and technical usability, with desired percentages generally ranging from 80% to 99%.
8. Data security and encryption were considered very important features when selecting an IoT platform, followed by ease of integration with other systems, cross-device compatibility, and support for real-time data processing.

The feedback from technical personnel sheds light on the critical need for modular design, cross-platform compatibility, and data security. Their desire for better development tools and robust API support aligns with the technical foundation required to attract a broader developer base. Challenges like interoperability and limited device capabilities underscore the necessity for a scalable and flexible platform architecture.

These insights will guide the implementation of modular, developer-friendly architecture with robust API documentation and support. Additional focus will be placed on ensuring interoperability and scalability through the use of standardized protocols and flexible hardware integration. Machine learning capabilities and enhanced analytics tools will also be valuable attempts to expand platform functionalities.

3.3 Discussion of Findings

Building on the user study results presented in Section 3.2, this section discusses the key findings from the cross-group analysis and synthesizes design implications for the UWDF. By comparing these findings with prior studies reviewed in Chapter 2, this section aims to contextualize the study results, highlight areas of alignment and divergence, and strengthen the theoretical foundation of the proposed platform.

3.3.1 Cross-Group Analysis of Key Factors

The cross-group analysis, detailed in Section 3.2, identified four key factors prioritized consistently across older adults, caregivers, healthcare professionals, and technical personnel: simplicity of interfaces, real-time health monitoring, data privacy, and interoperability. These factors were derived from frequency counts of pre-defined response options across the surveys (n=56, covering 18 older adults, 5 caregivers, 23 healthcare professionals, and 10 technical personnel), supplemented by inductive content analysis of free-text responses provided in the "Other" option. No new factors emerged from the free-text inputs, confirming the representativeness of the pre-defined options.

Divergent Priorities in Data Security and Privacy: A striking divergence emerged between stakeholder groups regarding data security. Older adults demonstrated minimal concern, with 76% reporting no apprehension about privacy risks. In contrast, healthcare professionals and technical personnel prioritized security as critical. For instance, 70% of healthcare professionals highlighted ethical concerns in data sharing, while 50% of technical personnel rated security as "very important" in platform selection. This discrepancy underscores the necessity of embedding robust security measures—such as end-to-end encryption and multi-factor authentication—into the UWDF platform without complicating the user experience for less tech-savvy groups.

Transparent data governance frameworks could bridge this gap, ensuring compliance with ethical standards while maintaining simplicity for end-users. Contrary to Olmedo-Aguirre and Singh's findings that older adults typically prioritize privacy in health monitoring systems [32], our study found older adults less concerned, possibly due to lower technical literacy or higher trust in healthcare providers. This divergence highlights the need for user education alongside security measures to align stakeholder expectations, as supported by Sandhu et al.'s emphasis on human-centered design for older adults healthcare IoT [42].

Interface Design versus Technical Complexity: The tension between usability and functionality was evident across stakeholder feedback. Older adults and caregivers emphasized ease of use, with 63% of older adults citing interface complexity as a major barrier. Caregivers similarly advocated for simplified designs to support older adults. Conversely, technical personnel prioritized modular architectures and advanced capabilities like machine learning integration. To reconcile these needs, the UWDF could adopt a layered design: a streamlined front-end for older adults and caregivers, coupled with a customizable back-end for developers. For example, pre-configured modules for fall detection or medication reminders could cater to non-technical users, while open APIs and interoperability standards empower developers to extend functionalities. This finding supports the conclusion drawn by Tun et al. that intuitive interfaces enhance older adults technology adoption [53], and aligns with Petrocchi's human-centered design principle of balancing usability with technical sophistication for older adults care [38]. Our study extends this by proposing a layered approach to meet diverse stakeholder needs.

Data Sharing Preferences and Ethics Challenges: Preferences for data sharing varied significantly. Older adults favored sharing health data with family members (36%) and healthcare professionals (34%), reflecting trust in personal networks. However, healthcare professionals expressed ethical reservations about data transparency and unauthorized access. To address this, the UWDF should incorporate granular privacy controls, allowing users to customize sharing permissions while enforcing compliance with medical ethics. For instance, a tiered access system could enable older adults to selectively share data with family while ensuring healthcare providers receive anonymized, aggregated insights for healthcare decision-making. This supports Olmedo-Aguirre and Singh's recommendation for customizable privacy settings in older adults healthcare systems [32]. However, our study's finding of older adults' openness to data sharing contrasts with Yu et al.'s observation of reluctance among older adults in their SHfE smart home system, possibly due to cultural differences in trust toward family-based caregiving [60].

Functional Priorities for Immediate and Long-Term Needs: The study highlighted distinct functional priorities across groups. Caregivers prioritized practical tools such as fall detection (36%) and real-time alerts, aligning with their day-to-day caregiving responsibilities. Healthcare professionals emphasized continuous vital sign monitoring (87%) and early disease detection, reflecting their healthcare focus. Meanwhile, technical personnel stressed interoperability (70%) and real-time analytics as foundational for scalable solutions. Integrating these priorities requires a platform that combines core functionalities—such as real-time health tracking—with extensible features like advanced data analytics. For example, integrating wearable data with electronic health records could simultaneously support caregivers' immediate needs and healthcare professionals' long-term preventive strategies. This aligns with Perez et al.'s emphasis on IoT systems for enabling older adults independence through comprehensive health monitoring [36] and Sandhu et al.'s advocacy for scalable IoT architectures [42]. Unlike Yu et al.'s finding of limited caregiver demand for real-time alerts [60], our study highlights strong caregiver preference, likely influenced by regional caregiving practices.

3.3.2 Synthesis of Design Implications

The findings reveal inherent tensions in balancing simplicity, security, and technical sophistication. Older adults' preference for autonomy in data management contrasts with healthcare professionals' demand for centralized oversight, while caregivers' emphasis on affordability conflicts with technical personnel's focus on high-performance infrastructure. To resolve these conflicts, the UWDF could adopt a multi-tiered architecture:

- A user-centric interface tailored for older adults, featuring intuitive navigation, adjustable font sizes, and customizable alerts.
- A developer-oriented back-end with modular APIs, cloud integration, and machine learning tools to support advanced applications.
- A secure middleware layer incorporating encryption, ethical data-sharing protocols, and compliance mechanisms to satisfy regulatory and healthcare requirements.

The design of the UWDF relies on integrating the diverse needs of stakeholders, as identified in the user study. User feedback highlights the importance of addressing privacy concerns, despite varying levels of security awareness among older adults, necessitating the inclusion of security measures such as encryption and role-based access control. The framework must accommodate both simplicity for non-technical users and technical functionality for developers, ensuring accessibility and scalability. By incorporating these requirements, the UWDF aims to provide a secure and accessible platform that supports health monitoring for older adults, with implementation details to follow in the Chapter 4.

Chapter 4

Platform Design

This chapter outlines the design of the Unified Wearable Device Framework (UWDF). This platform aims to provide a user-centered approach to utilizing wearable and IoT technology for health applications, particularly for older adults. The UWDF platform is expected to address the challenges identified by older adults, caregivers, healthcare professionals, and technical personnel, such as complex interfaces, lack of interoperability, and privacy concerns (Section 3.2.1, Section 3.2.2, Section 3.2.3, Section 3.2.4), by integrating data from various sensors and providing a unified platform for monitoring, management, and analysis. The platform will be designed based on Human-Centered Computing (HCC) principles, supporting the concept that the needs and preferences of older adults and their caregivers are central to the design process.

4.1 Design Requirements

The design requirements for the UWDF are derived from the findings of the user behavior and needs study (Chapter 3), which identified key themes and priorities across older adults, caregivers, healthcare professionals, and technical personnel. These requirements address the challenges of complex interfaces, limited interoperability, data privacy concerns, and the need for real-time health monitoring, ensuring the platform aligns with HCC principles. The requirements are categorized into functional and non-functional requirements to provide a clear and structured foundation for the platform's design and implementation.

4.1.1 Functional Requirements

This subsection outlines the functional requirements of the UWDF, specifying the core functionalities the platform must deliver to meet user needs. These requirements are derived from stakeholder feedback, emphasizing real-time health monitoring, user control, and data integration.

1. **Real-time Health Monitoring:** The platform is expected to collect and display real-time data from sensors (e.g., heart rate) to support continuous health monitoring, as prioritized by healthcare professionals (87% emphasized continuous vital sign monitoring, Figure 3.13) and caregivers (36% prioritized fall detection alerts, Figure 3.9).
2. **Sensor Status Control:** Users must be able to enable or disable individual sensors (e.g., heart rate, carbon dioxide) via a centralized software interface, addressing older adults' frustration with complex device management (63% cited interface difficulty, Figure 3.3).
3. **Remote Data Access:** The platform must enable authorized users (e.g., caregivers, family members) to access real-time health data remotely, supporting caregivers' need for real-time updates (100% prioritized monitoring daily activities, Figure 3.10).
4. **User Authorization Management:** The platform must provide a mechanism for device owners to grant or revoke data access to specific users via user ID, addressing older adults' preference for controlled data sharing with family (36%) and healthcare professionals (34%, Figure 3.6).
5. **Connection Management:** The platform must allow users to monitor and manage Wi-Fi connection status, ensuring stable data transmission, as highlighted by technical personnel's concerns about connectivity issues (50% cited interoperability challenges, Figure 3.17).
6. **Health Data Integration:** The platform must integrate wearable data with electronic health records to support healthcare professionals' needs for comprehensive data (e.g., blood pressure, glucose levels, 100% and 96% respectively, Figure 3.14).

4.1.2 Non-Functional Requirements

This subsection details the non-functional requirements, focusing on performance, usability, and security attributes that ensure the platform's accessibility, reliability, and scalability. These requirements address stakeholder concerns about ease of use, data privacy, and system interoperability.

1. **Simple User Interface:** The user interface must be intuitive and accessible, with simplified navigation and large, readable fonts, addressing older

adults' challenges with complex interfaces (56% of participants, Figure 3.3) and caregivers' emphasis on ease of use (80%, Figure 3.8).

2. **Data Privacy and Security:** The platform must implement robust encryption (e.g., WPA2 for data transmission) and role-based access control to address healthcare professionals' concerns about ethical data sharing (70%, Figure 3.15) and technical personnel's prioritization of security (50% rated it very important, Figure 3.22).
3. **Interoperability:** The platform must support cross-platform compatibility and integration with multiple sensor types, addressing technical personnel's emphasis on interoperability (70% desired enhanced device interoperability, Figure 3.18).
4. **Scalability:** The platform must be scalable to accommodate additional sensors and users, supporting technical personnel's need for modular design (30% prioritized modular customization, Figure 3.19).
5. **Reliability:** The platform must achieve a high operational success rate (median expectation of 85%, Table 3.2), ensuring stable performance for real-time monitoring, as emphasized by technical personnel.
6. **Cost-Effectiveness:** The platform must utilize affordable hardware (e.g., ESP32S2) and software solutions to align with caregivers' concerns about cost (40%, Figure 3.8).

4.1.3 Integration of Design Requirements

These functional and non-functional requirements (Section 4.1.1, Section 4.1.2) will be grounded in the cross-group analysis (Section 3.3), which highlighted simplicity, real-time monitoring, data privacy, and interoperability as key themes. By addressing these needs, the UWDF is expected to provide accessibility for older adults, practical utility for caregivers and healthcare professionals, and technical robustness for developers, aligning with HCC principles and the literature's emphasis on user-centered IoT systems [38, 42].

4.2 Core Functional Module Design

The UWDF is designed to address the needs of older adults, caregivers, healthcare professionals, and technical personnel through a modular, user-centered platform for health monitoring. This section outlines the core functional modules—sensor management, data management, authorization management, and

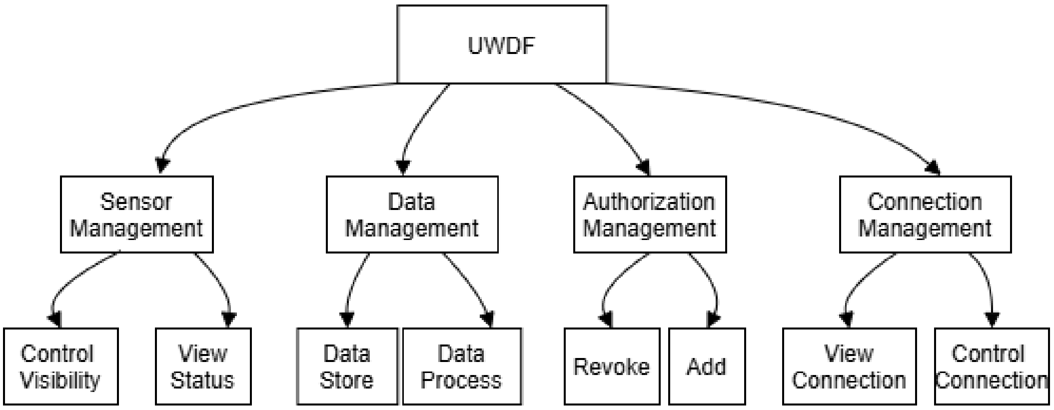


Figure 4.1: UWDF Functional Module

connection management—as depicted in Figure 4.1. These modules collectively enable real-time health monitoring, secure data sharing, and simplified device management, aligning with the functional and non-functional requirements (Sections 4.1.1 and 4.1.2) and HCC principles.

4.2.1 Technical Solution Overview

The UWDF platform adopts a modular architecture to ensure scalability, accessibility, and reliability, addressing the challenges identified in the user study (Chapter 3), such as complex interfaces, interoperability issues, and privacy concerns. The technical solution integrates hardware and software components to deliver a cohesive health monitoring ecosystem, inspired by established IoT architectures like the three-layer model (perception, network, application) discussed in Section 2.4.3.

The platform's core hardware is based on the ESP32S2 development board, selected for its affordability, built-in Wi-Fi module, and support for multiple sensor integrations (Section 4.3). Sensors (e.g., heart rate, carbon dioxide) collect physiological and environmental data, processed by the ESP32S2 and transmitted securely via Wi-Fi to a remote server. The software architecture is layered into user interface, business logic, and communication layers, implemented using HTML/CSS/JavaScript for accessible interfaces and C++ for efficient sensor control and data processing (Section 4.3).

The four core functional modules, shown in Figure 4.1, map to these architectural layers:

- **Sensor Management:** Interfaces with the user interface layer for status display and control, and the business logic layer for sensor operations.
- **Data Management:** Leverages the communication layer for secure data

transmission and the business logic layer for data processing. Authorization Management: Operates through the user interface layer for user input and the business logic layer for access control.

- **Connection Management:** Uses the communication layer to monitor Wi-Fi status and the user interface layer for user feedback.

This modular design ensures flexibility, allowing the platform to accommodate diverse sensors and user needs while maintaining simplicity for older adults and robustness for technical personnel. The technical solution prioritizes HCC principles by embedding user feedback from the study (Section 3.3) into the design, ensuring accessibility, privacy, and real-time functionality.

4.2.2 Sensor Management Module

This module enables real-time data collection and control of health sensors, addressing older adults' need for simplified device management and healthcare professionals' demand for continuous monitoring.

- **Functional Description:** This module will support older adults, caregivers, or family members to view real-time data from all sensors in the device (heart rate sensor, human body sensor, carbon dioxide sensor), and provides on/off management functions for each sensor. Users will be able to centrally control the on/off status of each sensor through the software interface, without having to operate the hardware switches one by one.
- **User Interaction Process:** Through the user interface, users can access a component displaying sensor names, current data (e.g., heart rate in beats per minute), and control options. Selecting a toggle option sends a command to adjust the sensor's status, with immediate feedback on the interface.
- **Design Advantages:** Through centralized management of the software interface, users will not have to rely on physical switches, and they will be able to see the working status of each sensor at a glance, which will be particularly important for users with low technical proficiency.

HCC Implementation: The simplified interface and centralized control mechanism are planned to respond to the frustration expressed by older adults regarding the complexity of managing sensors on existing wearable devices, as identified in the user study (Section 3.2.1). The focus on providing visual clarity and minimizing the need for technical expertise will reflect a strong commitment to accessibility and user-friendliness.

4.2.3 Data Management Module

This module will support the transmission of monitoring data from the device to the remote server, so that authorized users will be able to view the data at any time. The data management module aims to realize remote sharing of real-time data, meet the remote health monitoring needs of caregivers and family members, and ensure the security of data during transmission.

- **Functional Description:** The module encrypts and transmits sensor data via Wi-Fi to a remote server, allowing caregivers and family members to monitor health status remotely. It supports real-time data sharing for timely interventions.
- **Data Processing and Transmission Process:** After the sensor in the device collects the data, the data stream will be expected to flow through a micro-controller for processing and encryption and will be transmitted to the remote server via Wi-Fi. Remote users will be able to call data in real time through authorized interfaces to take intervention measures when necessary.
- **Design Advantages:** The remote transmission of data will enhance the convenience and real-time performance of monitoring, especially when the health status of the older adults changes abnormally, caregivers will be able to obtain data in real time, thereby ensuring the safety of older adults.

HCC Implementation: The data management module will facilitate real-time monitoring and intervention, addressing the needs of caregivers and healthcare professionals to stay informed about the user's health status, as highlighted in the user study (Sections 3.2.2 and 3.2.3). By enabling remote access to data, the platform extends its functionality beyond individual use, promoting communication and collaboration among caregivers and supporting timely interventions to enhance user well-being. The robust security measures implemented within this module will align with user concerns about data privacy and confidentiality.

4.2.4 Authorization Management Module

The authorization management module will provide other family members or caregivers with permission to remotely access device data. This module will manage authorization through user ID, making data access on the platform more secure and personalized.

- **Functional Description:** To ensure the privacy of device data and access security, the authorization management module will allow the device owner to identify and authorize other users to access monitoring data through ID. This feature will provide convenience for remote care and real-time data access by family members.

- **User Interaction Process:** Through the user interface, owners input user IDs to authorize access or view a list of authorized users. Changes are applied instantly, with confirmation displayed on the interface.
- **Design Advantages:** The authorization management module will be expected to enable the controllability and security of data access, making it convenient for older adults to be assisted by family members or caregivers to monitor health data after authorization. This design will comply with the principles of sensor data protection and facilitates potential permission expansion in the future.

HCC Implementation: This module will address healthcare professionals' concerns about data privacy and security (Section 3.2.3) and supports older adults' preferences for controlled data sharing (Section 3.2.1). By allowing users to control who has access to their data and providing a clear process for granting and revoking authorization, the design empowers users and enhances their trust in the platform. The iterative design process, where initial complex authorization procedures were simplified based on user feedback, further reinforces the commitment to a user-centered approach.

4.2.5 Connection Management Module

The connection management module will enable users to easily connect or disconnect from Wi-Fi and will display the current network connection status through the user interface, ensuring that the platform maintains stable data communication in a variety of environments.

- **Functional Description:** This module will provide monitoring and management functions for the device's Wi-Fi connection status, allowing users to view the device's current connection status and perform connection control. When the device connection is interrupted or the network is changed, the user will be able to manually restore or reconfigure the network connection.
- **User Interaction Process:** The user interface shows a connection status indicator (e.g., “Connected” or “Not Connected”) and a reconnect option. Users receive prompts to troubleshoot unstable connections.
- **Design Advantages:** The setting of the connection management module

will enhance the stability of data transmission and will ensure that the platform will work normally in different network environments. Users will grasp the device network situation at any time without frequent inspection of the device's physical connection.

HCC Implementation: By providing a clear and intuitive indicator of the device's connection status and offering a simple way to manage connections, this module is expected to address technical personnel's concerns about connectivity issues and potential data loss, as identified in the user study (Section 3.2.4). The design will prioritize user control and transparency, making it easier for users to understand and manage their device's connection to the platform.

4.3 Platform Architecture Design

The UWDF platform architecture design is divided into two parts: physical architecture and logical architecture. The physical architecture will show the actual layout of the platform hardware and communication network. The logical architecture is divided into the user interface layer, business logic layer, and communication layer, which will handle data display, business processing, and data transmission respectively. This layered design, inspired by widely adopted IoT architectures such as the three-layer model (perception, network, and application layers), aims to ensure the functionality, reliability, and scalability of the platform. As discussed in Section 2.4.3, such architectures are commonly used in both experimental and production-grade IoT systems [18, 20, 27]

4.3.1 Physical Architecture

The physical architecture of the UWDF platform will be composed of a microcontroller, a development board, sensors, and LED indicator lights. The various hardware components are expected to collaborate to facilitate smooth data collection and transmission:

- **ESP32S2 Development Board:** Will be responsible for connecting heart rate sensors, human body sensors, carbon dioxide sensors, etc., for real-time collection of various physiological data. It will integrate a Wi-Fi module for data transmission to remote server after encryption and support user control of sensors.
- **I2C HUB Expansion Board:** Will facilitate the connection of multiple I2C-based sensors to the ESP32S2, expanding the I2C bus capacity. This board provides reliable communication with various sensors, minimizes

wiring complexity, and supports plug-and-play integration for efficient data acquisition.

- **Sensors:** A variety of sensors will be integrated into the platform to monitor physiological and environmental parameters. The sensors will be connected to the ESP32S2 board via digital or analog interfaces and will be configured to support real-time data acquisition with minimal latency.
- **LED Status Indicator:** Will be used to display the device status in real time, such as connection status, data transmission status, etc., so that users will be able to understand the current working status of the device.

4.3.2 Logical Architecture

The logical architecture of the UWDF platform will include the user interface layer, business logic layer, and communication layer. Each layer will be independent and will collaborate with each other to support the efficient implementation of data collection, processing, display, and remote access functions.

- **User Interface Layer:** Will be developed based on HTML/CSS/JavaScript, it will be responsible for displaying the real-time status of sensors, switch control, user authorization, and connection management functions. The interface will be expected to be concise and intuitive, enabling easy use by older adults and caregivers.
- **Business Logic Layer:** Will be written using C++, it is expected to implement core functions such as sensor data collection, processing, transmission, and interface authorization. As an intermediate layer, the business logic layer is planed to provide processed sensor data to the user interface layer and will control the switching operations of the sensor.
- **Communication Layer:** The Wi-Fi module of ESP32S2 will be used for encrypted data transmission, which will be responsible for securely transmitting the processed data to the remote server, and managing two-way communication with users to ensure reliable data transmission and access permission control.

4.4 Data Flow Design

The data flow design of the UWDF platform will cover four main steps: data acquisition, processing, transmission, and display, to promote data integrity and real-time performance. Through these steps, the smooth flow of sensor data in

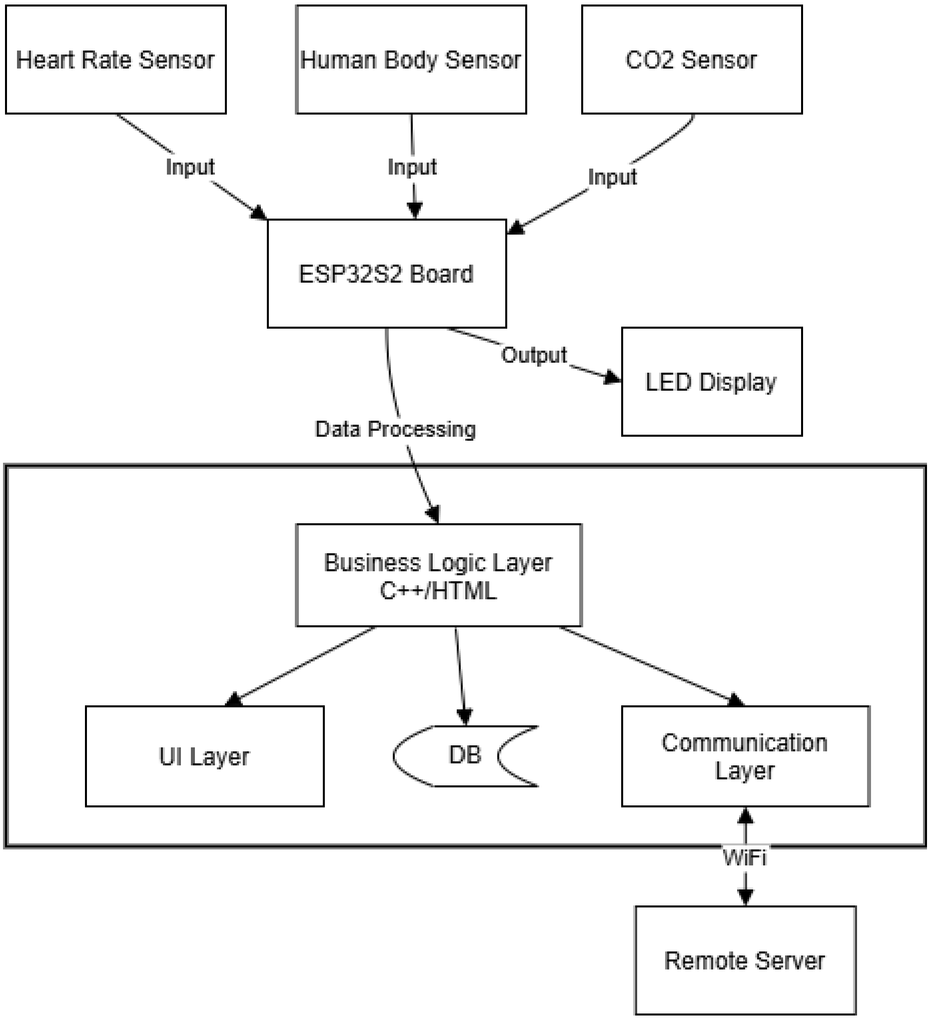


Figure 4.2: UWDF Data Flow

the platform will be realized, and users will be provided with accurate sensor monitoring information, as shown in Figure 4.2. .

- **Sensor Data Acquisition:** Each sensor (such as heart rate sensor, carbon dioxide sensor) is expected to collect data through a micro-controller and send the data to the business logic layer for preprocessing.
- **Data Processing and Transmission:** The business logic layer will control the data flow according to the sensor status set by the user; the encrypted data will be transmitted to the remote server through the Wi-Fi module of ESP32S2.
- **Data Display and Control:** The processed sensor data will be displayed on the platform interface through the user interface layer. Users will be able to view the real-time status, turn on or off the sensor, adjust the device connection status, etc.

- **User Authorized Data Access:** Remote users (such as family members or caregivers) will access real-time data in the server through authorized interfaces, and the platform will perform permission verification based on user ID to ensure the legitimacy and security of data access.

4.5 Technology Selection and Implementation Rationale

The selection of technology stack and implementation for the UWDF platform is driven by the need for cost-effectiveness, scalability, and compatibility with IoT-based health monitoring applications, as discussed in Section 2.4.3.

The ESP32S2 Development Board was chosen as the core processing unit due to its affordability, compact design, and robust feature set, including a built-in Wi-Fi module for secure data transmission and low power consumption. Compared to alternatives like Raspberry Pi, which is resource-intensive, or STM32, which demands more complex programming, the ESP32S2 provides a balanced combination of performance and ease of use, making it ideal for rapid prototyping and integration in home-based monitoring systems [9, 18, 20, 43].

Complementing the ESP32S2, the I2C HUB expansion board was selected to enhance the platform's scalability by enabling seamless connection of multiple I2C-based sensors, such as heart rate and carbon dioxide monitors. This board will provide a standardized interface, reducing integration complexity and ensuring stable data acquisition, which is critical for real-time monitoring. Together, the ESP32S2 and I2C HUB form a cohesive hardware ecosystem that supports the platform's design goals of efficiency, scalability, and user accessibility.

Programming Languages and Frameworks consists of two parts:

- **C++:** Suitable for embedded system development, efficient and easy to manage hardware resources. Used to implement underlying operations such as sensor management, data encryption, and communication control.
- **HTML/CSS/JavaScript:** Used to build the user interface, with high cross-platform compatibility. The interface design will be simple, suitable for the needs of older adults.

C++ is commonly used in ESP32-based systems for its performance and low-level hardware control capabilities [20, 43]. On the application side, HTML, CSS and JavaScript are frequently used to develop web-based GUIs that enable remote interaction with the system [9, 18].

Communication Protocol will be Wi-Fi, which is expected to support stable remote data transmission and enable continuous data monitoring in both home and small-scale care environments. Wi-Fi will be the primary communication protocol in this system, enabling stable remote data transmission and real-time monitoring. This approach will be consistent with other ESP32-based IoT implementations.

HCC Considerations in Technology Choices: The selection of technologies is planned to align with HCC principles by prioritizing user needs and accessibility. The use of HTML/CSS/JavaScript for the user interface supports compatibility across different devices and promotes ease of use, particularly for older adults who may not be familiar with complex software interfaces. The choice of Arduino and ESP32S2 reflects a consideration for affordability and widespread availability, potentially making the platform more accessible to a wider range of users and developers.

4.6 Data Management and Privacy Protection Measures

Data management and privacy protection are critical in platform design, particularly for health monitoring, requiring secure data handling and legal access rights. As discussed in Section 2.4.3, many existing IoT implementations lack robust privacy protection mechanisms. For instance, Cobo et al. [9] describe a system that enables remote control via a web interface but does not implement encryption or authentication. This underscores the importance of integrating user-friendly security features, especially in healthcare applications for older adults [42].

- **Access Permission Control:** Will control the access of device data through the user authorization mechanism. The device owner will be able to authorize designated users through ID to avoid unauthorized access to data.
- **Data Transmission Encryption:** The platform will use the Wi-Fi module of ESP32S2 to encrypt and transmit data using WPA2 protocol to ensure that the data is not tampered with or stolen during transmission.
- **Data Storage and Security Backup:** Important sensor data is planned to be periodically backed up to the server. The server will use an encrypted storage mechanism to further ensure data integrity and security.

HCC and Data Privacy: The robust data management and privacy protection measures will highlight the importance of addressing ethical considerations, a key aspect of HCC. By ensuring data security, user control over access, and responsible data handling practices, the platform will demonstrate a commitment to protecting user privacy and building trust.

The inclusion of user needs, iterative design considerations, accessibility features, and robust testing procedures will demonstrate a strong commitment to user-centered design principles, setting the platform up to be a valuable contribution to the field of wearable technology for healthcare.

4.7 Summary

This chapter describes the design of the UWDF, a platform for health monitoring tailored to older adults, guided by HCC principles. Drawing on user studies (Chapter 3), the UWDF addresses challenges such as complex interfaces, interoperability issues, and privacy concerns through a user-centered design approach.

The platform will be designed to comprise four core functional modules—sensor management, data management, authorization management, and connection management—which will facilitate real-time health monitoring, secure data transmission, and controlled access (Section 4.2). Its physical architecture, based on the ESP32S2 development board, and logical architecture, organized into user interface, business logic, and communication layers, will aim to scalability and compatibility with diverse sensors and healthcare systems (Section 4.3). The data flow design is expected to support efficient acquisition, processing, transmission, and visualization of sensor data, while encryption and role-based access control address privacy requirements (Section 4.4). The use of C++ for embedded systems and HTML/CSS/JavaScript for the interface supports both performance and accessibility. These design elements will provide a structured foundation for the UWDF, with implementation details to be discussed in the subsequent chapter.

Chapter 5

Platform Implementation

This chapter focuses on the implementation of the Unified Wearable Device Framework (UWDF) platform, emphasizing its nature as a prototype for this research. The implementation adopted a streamlined approach to demonstrate the platform's core functionalities.

5.1 Hardware Implementation

5.1.1 ESP32S2 Development Board

As discussed in Section 4.3, the UWDF platform employs the ESP32S2 development board [1] as the central processing unit, leveraging its its key features. This highly integrated, low-power, single-core Wi-Fi SoC offers robust security features, including RSA-3072-based secure boot and AES-XTS-256-based flash encryption. The board's 43 programmable GPIOs can be flexibly configured for various functions, including USB OTG, LCD interface, camera interface, SPI, I2S, UART, ADC, and DAC. Figure 5.1 shows the image of the ESP32S2 development board. The functional block diagram of the ESP32S2 used in this study is shown in Figure 5.2. For more details, refer to the official ESP32S2 documentation [2].

The ESP32S2's integrated Wi-Fi module enables seamless connectivity, facilitating real-time collection and transmission of data. The board's low-power design, coupled with features like ESP-WIFI-MESH support, enhances its efficiency in managing diverse sensors. The UWDF platform incorporates LED status indicators, taking advantage of the ESP32S2's LED PWM capabilities, to provide

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[1] `https://www.espressif.com/en/products/socs/esp32-s2`

[2] `https://www.espressif.com/en/support/documents/technical-documents`

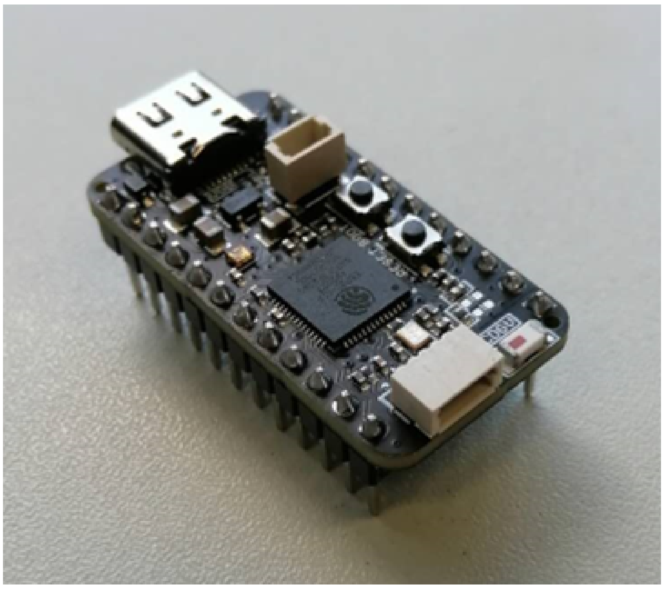

Figure 5.1: ESP32S2 Development Board

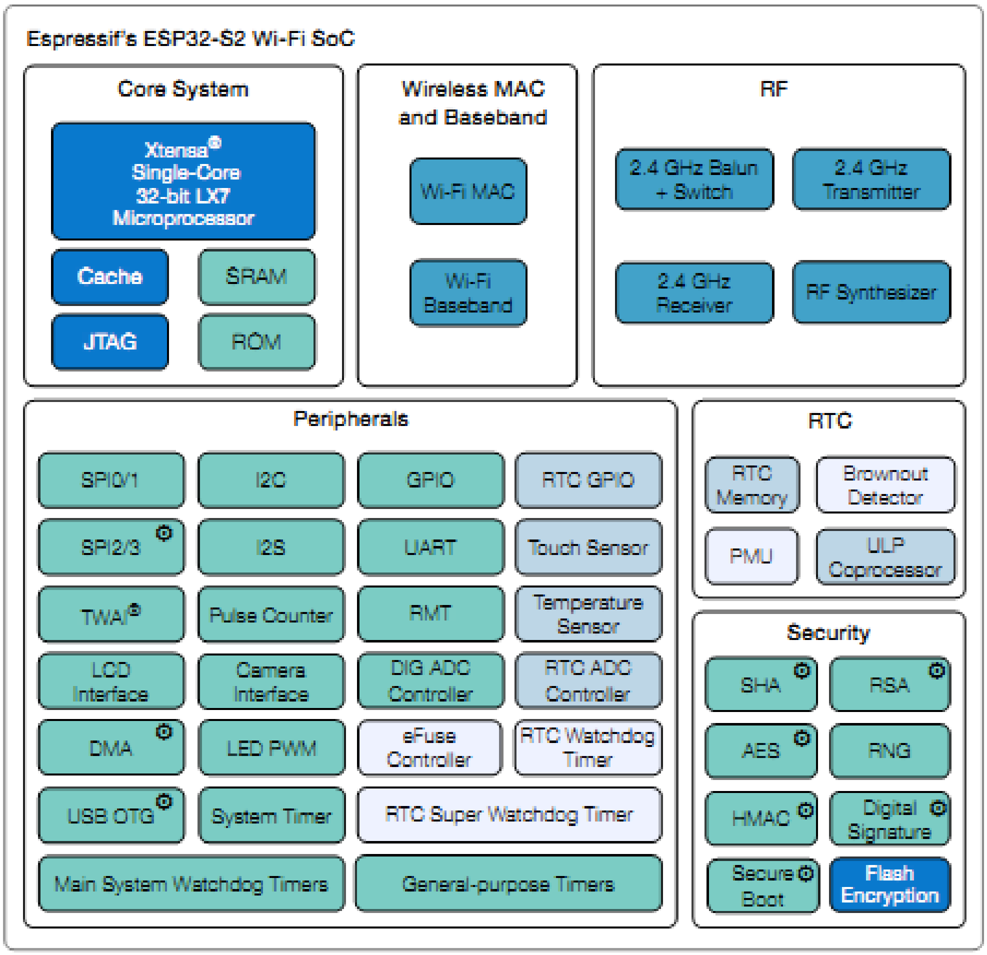

Figure 5.2: Block Diagram of ESP32S2, reproduced from the ESP32S2 datasheet by Espressif Systems [15]

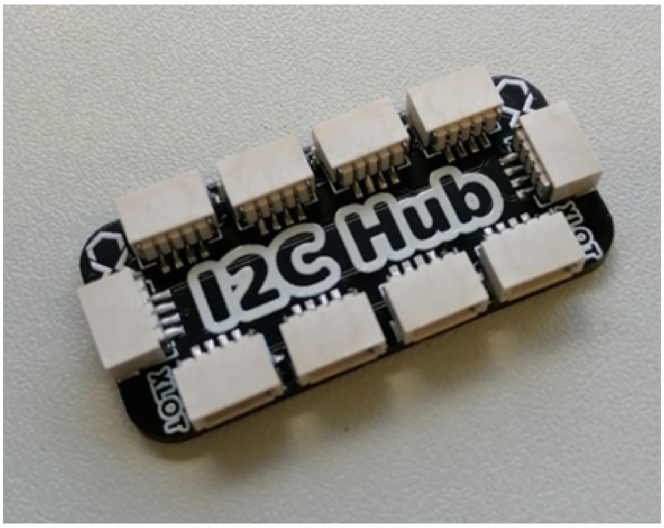

Figure 5.3: I2C HUB Expansion Board

visual feedback on the device's operational state. To gather healthcare related data, various sensors can be integrated: heart rate sensor, human body sensor, temperature sensor, and buzzer.

Furthermore, the ESP32S2's built-in cryptographic accelerators algorithms provide secure data handling, which is crucial for healthcare related applications. The board's ability to support external RAM chips also allows for expanded memory capacity when required for more complex data processing or storage requirements.

5.1.2 Extendable UWDF Hardware Implementation

Considering the platform's scalability, as discussed in Section 4.3, an I2C HUB expansion board [3] was used during the implementation process. The I2C HUB is a high-performance I2C bus expansion module designed specifically for connecting and managing multiple I2C devices. It supports simultaneous operation of multiple I2C associated devices, providing a stable communication interface suitable for various smart devices and embedded system development. Whether it is sensors, displays, or other I2C peripherals, the I2C HUB can be easily integrated, simplifying hardware design and connection processes. Figure 5.3 shows the I2C HUB expansion board, a high-performance I2C bus expansion module designed for connecting and managing multiple I2C devices. This module is utilized in our implementation to enable seamless integration with the ESP32S2 development board, supporting multi-sensor connectivity.

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[3] `https://docs.nanoframework.net/content/getting-started-guides/i2c-explained.html`

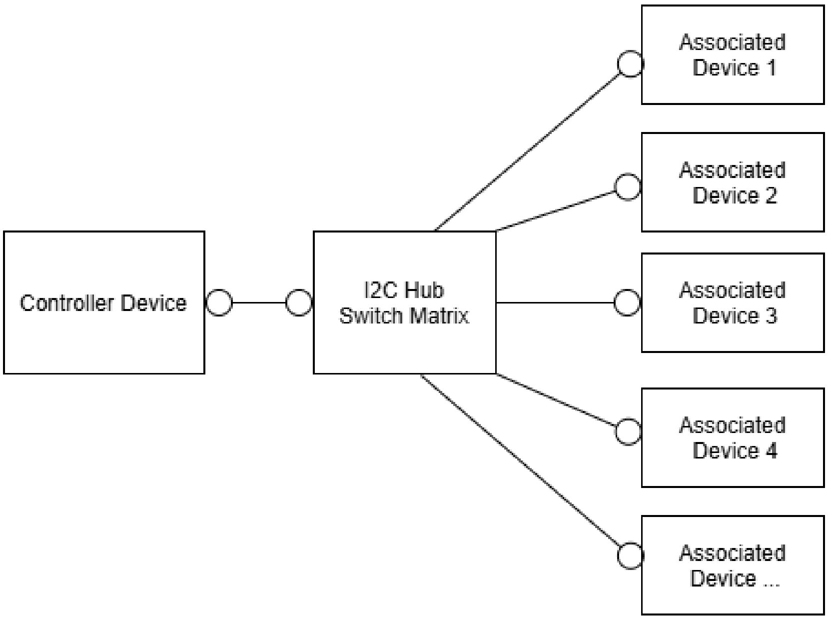


Figure 5.4: I2C HUB Connectivity

Figure 5.4 shows the logic diagram of I2C Hub. With the rich interfaces of I2C HUB, the system architecture in UWDF, which uses ESP32S2 as the main controller, achieves high scalability.

5.1.3 Hardware Configuration

The hardware configuration of the prototype is shown in Figure 5.5, illustrating the ESP32S2 development board connected to multiple sensors via the I2C HUB expansion board, with a laptop serving as the data processing terminal. The I2C HUB facilitates the integration of multiple I2C devices, enabling efficient data acquisition from the sensors. This setup, linked to the laptop via a USB interface, facilitates data processing and transmission within the platform, forming the core architecture for the UWDF system.

Figure 4.2 from Chapter 4, illustrates the prototype's architecture and the data flow process, including sensor data acquisition, preprocessing, transmission, and storage.

In this diagram, the data flow between hardware components is depicted, demonstrating the following.

1. Sensor data collection by the ESP32S2 development board through the I2C HUB.
2. Data preprocessing and encryption on the ESP32S2.
3. Transmission of processed data to a laptop via Wi-Fi.

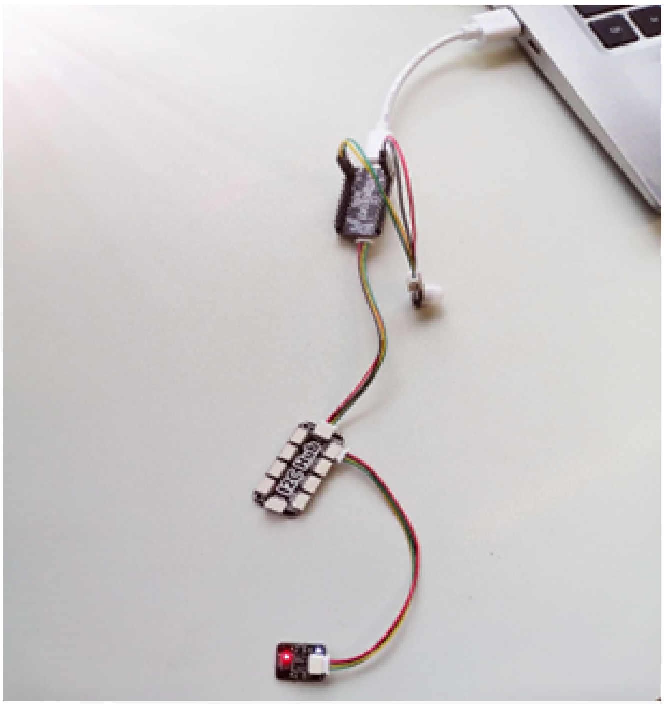


Figure 5.5: UWDF Prototype Implementation

4. Storage and potential visualization of data on the laptop.

5.2 Software Implementation

The UWDF platform's software adopts a three-layered architecture, ensuring efficient data collection, processing, display, and remote access. C++, JavaScript (JS), and HTML/CSS are used comprehensively across these layers, and data transmission utilizes the JSON format.

5.2.1 User Interface Layer

The User Interface Layer is responsible for presenting real-time data and controls to users through a web-based interface. Developed using HTML, CSS, and JavaScript, it provides a clear and functional interface for monitoring and managing the UWDF platform. Figure 5.6 shows the navigation diagram of UWDF prototype UI pages.

5.2.1.1 Sensor Status Display

The Sensor Status Display is the main interface users see after logging into the UWDF platform successfully, as shown in Figure 5.7. To address the needs of end users, the interface includes intuitive controls for activating or deactivating

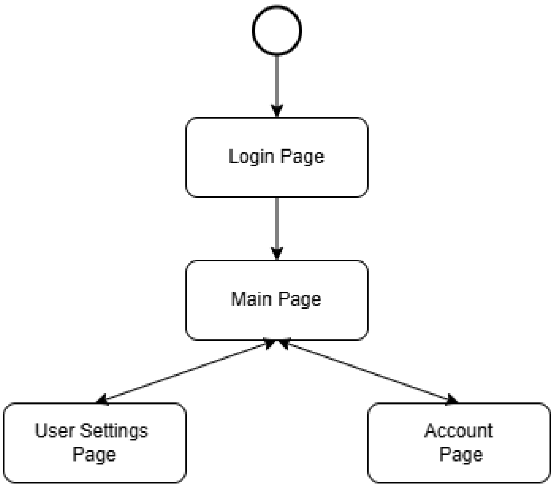
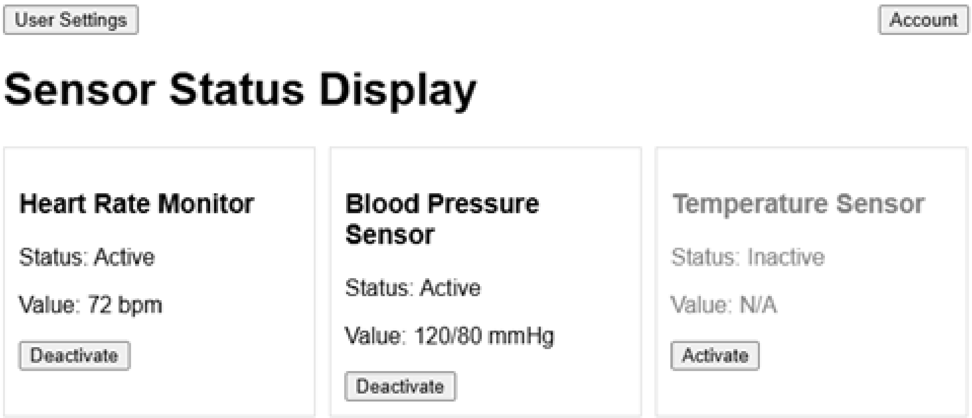


Figure 5.6: UWDF UI Navigation



Sensor Status Display

Heart Rate Monitor

Status: Active

Value: 72 bpm

Blood Pressure Sensor

Status: Active

Value: 120/80 mmHg

Temperature Sensor

Status: Inactive

Value: N/A

Figure 5.7: UWDF Main Interface

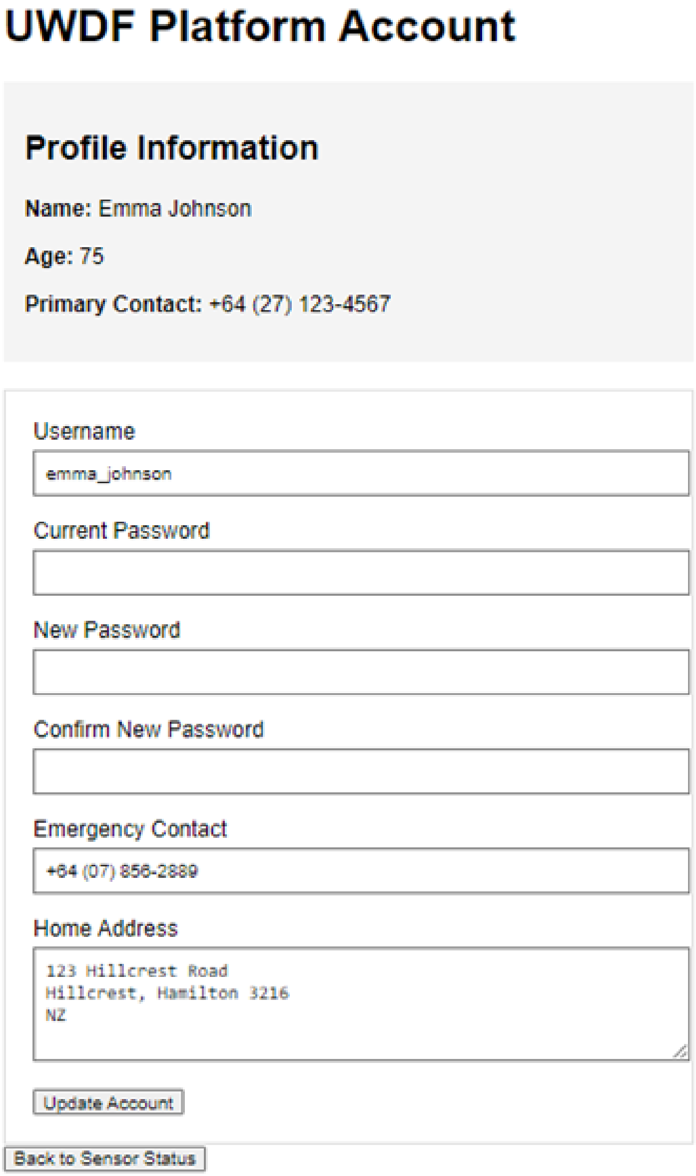
individual sensors and provides visual feedback on real-time data updates. Future iterations will also explore adding simplified preset modes tailored to common use cases (e.g., emergency alert).

Additionally, it includes two key buttons for navigating to other management functions:

1. **Account**: Redirects to the UWDF Account interface, where users can manage platform login account.
2. **User Settings**: Redirects to the User Management interface, where users can manage authorization for remote access to the platform.

5.2.1.2 UWDF Account

This page allows users to modify the account used for logging into the UWDF platform, as shown in Figure 5.8. The data presented in the figure is fictional



UWDF Platform Account

Profile Information

Name: Emma Johnson

Age: 75

Primary Contact: +64 (27) 123-4567

Username: emma_johnson

Current Password:

New Password:

Confirm New Password:

Emergency Contact: +64 (07) 856-2889

Home Address:
123 Hillcrest Road
Hillcrest, Hamilton 3216
NZ

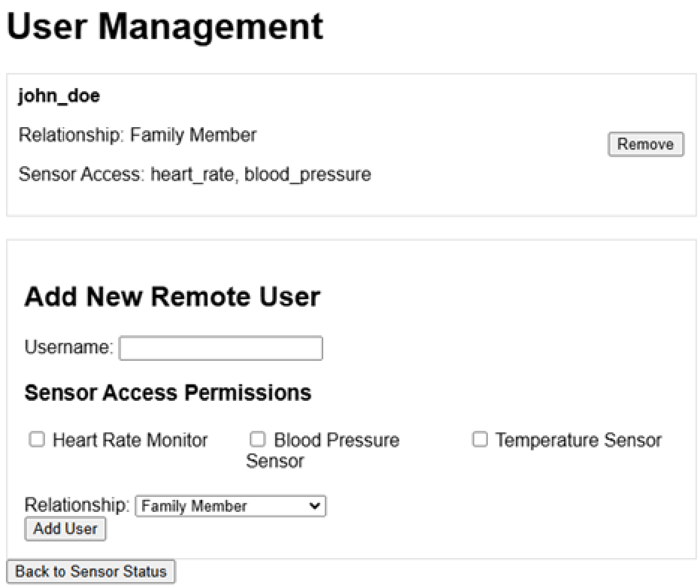
Figure 5.8: UWDF User Account

and used solely for illustrative purposes as part of the prototype design, ensuring compliance with ethical guidelines. This account typically represents the older adults who use the platform directly.

5.2.1.3 User Management Interface

The User Management Interface, accessed via the User Settings button on the Sensor Status Display, provides tools for managing authorized remote users, such as family members, caregivers, or healthcare professionals. Key functions include:

- Adding or removing remote user authorizations.
- Defining access permissions for specific remote users to ensure that they


User Management

john_doe

Relationship: Family Member

Sensor Access: heart_rate, blood_pressure

Add New Remote User

Username:

Sensor Access Permissions

☐ Heart Rate Monitor ☐ Blood Pressure Sensor ☐ Temperature Sensor

Relationship: Family Member

Figure 5.9: UWDF User Management

can only retrieve data from certain sensors.

The User management page is shown in Figure 5.9. This interface ensures that remote stakeholders can securely access platform data without interfering with the local user's operations.

5.2.2 Business Logic Layer

The Business Logic Layer serves as the core processing unit of the software, bridging the user interface and communication layers. It is implemented in C++, leveraging the ESP32S2's computational capabilities and the laptop terminal for advanced processing.

5.2.2.1 User Authorization Mechanisms

User Authorization Mechanisms includes robust user authorization mechanisms to address data security concerns raised by stakeholders. Key findings related to data security concerns include:

- Implementation of access permission control.
- Data transmission encryption.
- Secure data storage with backup mechanisms.

These measures support that user data remains protected and accessible only to authorized individuals. User credentials are validated against a secure database, and access permissions are dynamically updated based on administrative actions.

5.2.2.2 Sensor Data Acquisition and Processing

The process of sensor data acquisition and processing is a critical component of the UWDF platform, providing reliable and accurate data for subsequent analysis. This subsection outlines the methodology employed to collect and preprocess data from sensors connected to the ESP32S2 development board.

The following code snippet in Code Example 5.1 shows the structure and preprocessing mechanism of sensor data. This logic executes the following tasks: (1) Collects raw data from sensors connected to the ESP32S2. (2) Filters and preprocesses the data (e.g. smoothing noisy signals or calculating averages).

Coding Example 5.1: Sensor data preprocessing

```
struct SensorData {
    int sensorId;
    float value;
    String timestamp;
};

SensorData preprocessSensorData(int sensorId, float rawData) {
    static float previousValues[10] = {0};
    static int index = 0;
    previousValues[index] = rawData;
    index = (index + 1) % 10;

    float smoothedValue = 0;
    for (int i = 0; i < 10; i++) {
        smoothedValue += previousValues[i];
    }
    smoothedValue /= 10.0;

    return {
        sensorId,
        smoothedValue,
        String(millis()) // timestamp
    };
}
```

5.2.2.3 User Authorization Management

The User Authorization Management module validates user credentials before granting access to the platform and maintains a secure database of authorized users, updated dynamically based on administrative actions. The following code snippet in Code Example 5.2 demonstrates the access control mechanism based on sensor permissions.

Coding Example 5.2: Data Access Control Mechanism

```
struct ClientPermission {
    int clientId;
    std::vector<String> allowedSensors;
};
bool hasPermission(int clientId, const String& sensorType) {
    for (const auto& permission : clientPermissions) {
        if (permission.clientId == clientId) {
            return std::find(
                permission.allowedSensors.begin(),
                permission.allowedSensors.end(),
                sensorType) != permission.allowedSensors.end();
        }
    }
    return false;
}
```

The Data Encryption: The Data Encryption is designed to secure handling of healthcare data by encrypting it before transmission using cryptographic algorithms supported by the ESP32S2's hardware.

5.2.2.4 Integration with the Interface Layer

The integration employs the ArduinoJson library to convert processed data into a JSON format for seamless integration with the HTML/CSS/JS-based user interface. The code snippet in Code Example 5.3 shows the method of converting sensor data into JSON format data.

Coding Example 5.3: Sensor Data Converting

```
String serializeSensorData(const SensorData& data) {
    StaticJsonDocument<200> doc;
    doc["sensorId"] = data.sensorId;
    doc["value"] = data.value;
    doc["timestamp"] = data.timestamp;
    String jsonString;
    serializeJson(doc, jsonString);
    return jsonString;
}
```

This layer also supports extendibility, allowing future integration of more complex algorithms, such as machine learning models, for predictive analytics or anomaly detection.

5.2.3 Communication Layer

The Communication Layer is responsible for ensuring secure and reliable data exchange between the ESP32S2 and the laptop terminal, as well as between the platform and remote clients. It uses the ESP32S2's Wi-Fi module to manage these interactions. The processing flow as shown in Code Example 5.4 within the loop function is central to this layer.

Coding Example 5.4: Data Transfer

```
if (client.connected() && webSocket.handshake(client)) {
    while (client.connected()) {
        bool dataChanged = false;
        StaticJsonDocument<1024> doc; // Increase JSON document
            size to accommodate more sensors
        for (int i = 0; i < numSensors; i++) {
            SensorData currentData = preProcessSensorData(sensors
                [i].id, sensors[i].readFunction());
            if (currentData.timestamp != lastSentData[i].
                timestamp) {
                JsonObject sensorObj = doc.createNestedObject(
                    sensors[i].name);
                sensorObj["sensorId"] = currentData.sensorId;
                sensorObj["value"] = currentData.value;
                sensorObj["timestamp"] = currentData.timestamp;
                lastSentData[i] = currentData;
                dataChanged = true;
            }
        }

        // Send data only when changes occur
        if (dataChanged) {
            String jsonString;
            serializeJson(doc, jsonString);
            webSocket.sendData(jsonString);
        }
        delay(100); // Short delay, adjust as needed
    }
    Serial.println("Client␣disconnected");
}
```

Key features of the Communication Layer include two-way communication, and data transmission protocols, connection stability and error handling, and support for remote access, as outlined below.

Two-Way Communication

- Supports secure connectivity for authorized clients.

- Enables the ESP32S2 to send real-time sensor data to connected authorized clients.

Data Transmission Protocols

- Utilizes JSON as the standard format for data exchange, ensuring compatibility with diverse client applications.
- Employs additional safeguards, such as checksums, to verify data integrity during transmission.
- WebSocketServer library is used to create a lightweight, asynchronous HTTP server on the ESP32S2, allowing bidirectional communication.

Connection Stability and Error Handling

- Implements reconnection algorithms to ensure minimal disruption during temporary network outages.
- Logs all communication events for diagnostic purposes.

Support for Remote Access

- Allows authenticated external clients to securely access the platform through pre-defined APIs.
- This layer ensures that the UWDF platform can operate seamlessly in real-world scenarios, where network stability and data security are paramount.

5.3 Data Flow

The data flow section elaborates on the movement of sensor data within the UWDF, as shown in Figure 5.10, focusing on data collection, processing, transmission, storage and visualization. A streamlined data flow, aligned with the platform's hardware and software architecture, supports efficient operations.

5.3.1 Sensor Data Collection

Sensor data collection is the first step in the data flow. Multiple sensors integrated into the ESP32S2 development board, including heart rate, body temperature, and motion sensors, collect real-time data. The raw data from these sensors is transmitted to the business logic layer for preprocessing.

The sensors operate on a periodic polling mechanism controlled by the ESP32S2, where each sensor sends its data through the I2C bus. The system provides

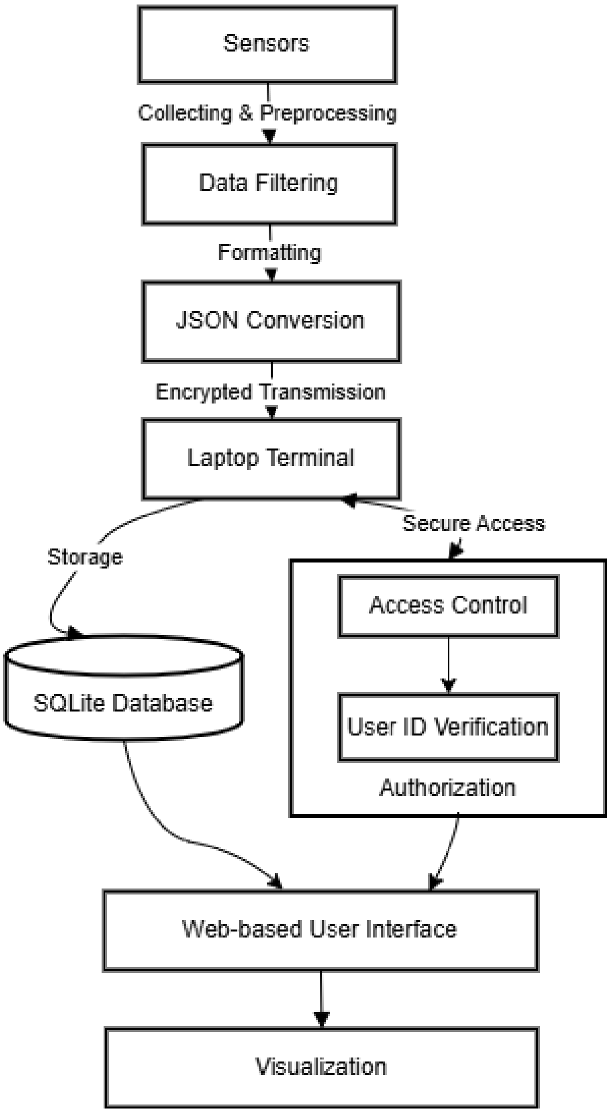


Figure 5.10: Data Flow Chart

synchronization by setting predefined intervals to avoid conflicts and minimize data loss.

5.3.2 Data Preprocessing

At the Business Logic Layer, the ESP32S2 processes the collected raw data. Preprocessing involves:

- Filtering: Removing noise from sensor readings using simple moving average filters to enhance accuracy.
- Formatting: Converting raw data into a structured JSON format to facilitate integration with the web-based user interface.
- Prioritization: Assigning priority levels to data streams, such as high pri-

ority for healthcare-critical data (e.g., heart rate anomalies).

This preprocessing ensures that the transmitted data is concise, accurate, and ready for secure transmission.

5.3.3 Data Transmission

Processed data is transmitted via the ESP32S2's Wi-Fi module to the laptop terminal, which serves as the central data storage and management hub. Data is encrypted using the ESP32S2's hardware accelerator to ensure security during transmission.

5.3.4 Data Storage

The laptop terminal hosts a lightweight open-source database, SQLite, to manage the collected data. SQLite is chosen for its simplicity, low resource requirements, and compatibility with prototype-scale projects. The database schema includes the following tables:

- Sensor_Data: Stores timestamps, sensor types, and values for all collected data.
- User_Access_Log: Tracks access attempts by remote users, including timestamps and outcomes.

Periodic database backups are performed locally on the laptop to ensure data integrity. The prototype's current design does not implement remote storage, aligning with the project's limited scope and emphasizing local storage feasibility.

5.3.5 Data Visualization

Processed data is displayed on the web-based user interface developed using HTML, CSS, and JavaScript, as shown in Figure 5.7. Users can view:

- Real-time sensor readings.
- Historical data trends (limited to session-based storage in the prototype).
- Device connection and sensor status indicators.

The JavaScript implementation for the web interface focuses on historical and real-time data rendering. Processed sensor data is displayed on the user interface, enabling historical data analysis and real-time monitoring.

5.3.6 User Authorization and Data Access

Authorized remote users, such as family or healthcare professionals, can access real-time data via a secure interface based on UWDF public client API after passing user ID verification.

Older adults showed a preference for managing their own data or delegating this responsibility to trusted family members. Based on these findings, the user authorization interface has been designed to allow role assignment and access customization. For instance, caregivers can be authorized to monitor real-time healthcare updates without accessing sensitive historical data, ensuring both usability and privacy.

The UWDF platform's data flow mechanism demonstrates a comprehensive approach to healthcare monitoring data management, integrating robust sensor data processing, secure transmission, and real-time visualization while maintaining high performance and security standards.

5.4 Data Management and Privacy Protection

This section focuses on mechanisms implemented in the UWDF platform to manage data effectively while promoting privacy protection during prototype development.

5.4.1 Data Access Control

Access to platform data is managed through a user authorization mechanism. Only authorized users, such as caregivers or family members, can retrieve data from specific sensors. Authorization is granted using user IDs and maintained in the User_Access_Log table in the SQLite database. The access process includes:

- Verifying the user ID against the database.
- Allowing or denying access based on permissions associated with the ID.

The interface for managing user authorization is simple, ensuring the older adults or caregivers can intuitively add or remove permissions.

5.4.2 Data Storage and Backup Strategy

Data storage is managed locally on the laptop using SQLite. Key design features include:

- Efficient Storage Schema: The database tables are designed to minimize redundancy while ensuring quick query performance.
- Local Backups: Automatic backups are performed at regular intervals (e.g., every 24 hours) to a secondary storage folder on the laptop. Backup files are encrypted using AES-256 to maintain data privacy.

The prototype scope limits storage to a single device. In future iterations, cloud-based storage options or distributed systems could be explored to enhance scalability. This is discussed further in Chapter 7.

5.4.3 Privacy-Oriented User Design

The platform prioritizes transparency and user control in data management, aligning with privacy protection principles:

- Clear Permissions Interface: Users can view and modify access permissions directly through the web-based interface.
- Limited Data Retention: Only essential data is stored during the prototype phase to minimize privacy risks.

5.5 Public APIs to Clients

The UWDF platform provides APIs for secure data access by authenticated clients.

5.5.1 Authentication

The platform includes an authentication endpoint: `POST /auth/login`

- Authenticates the user and returns an access token.
- Requires user credentials in the request body.

This interface authenticates the user and returns an access token.

5.5.2 API Endpoints

The API endpoints are designed to support different levels of data access and interaction. API examples include the following.

GET /sensors/authorized

- Returns the status of sensors the authenticated user has permission to access.

- Response includes sensor IDs, types, and operational status for authorized sensors.

GET /sensors/data/sensorId

- Retrieves real-time data from a specific sensor.
- Requires sensor-specific authorization.

GET /sensors/history/sensorId

- Fetches historical data for a given sensor within a specified time range.
- Supports query parameters for time range and data resolution.

5.5.3 Data Format

All API responses are in JSON format. A typical response structure is shown in Code Example 5.5:

Coding Example 5.5: Sample API Response

```
{
    "sensorId": "HR001",
    "type": "heart_rate",
    "timestamp": "2024-12-12T15:30:00Z",
    "value": 72,
    "unit": "bpm"
}
```

5.5.4 Error Handling

The API implements standard HTTP status codes for error reporting:

- 200: Successful request
- 400: Bad request (e.g., invalid parameters)
- 401: Unauthorized access
- 403: Forbidden (lack of permissions for specific data)
- 404: Resource not found
- 500: Internal server error
- 503: Service Unavailable (e.g., sensor offline)

5.5.5 Security Measures

To ensure data privacy and system integrity, the API implements several security measures:

- HTTPS: All communications are encrypted using TLS.
- Rate Limiting: To prevent abuse, the API enforces request rate limits per user.
- Data Encryption: Sensitive data is encrypted both in transit and at rest. This API design supports that the UWDF platform can securely and efficiently share data with authorized external clients while maintaining user privacy and system security.

5.6 Summary

This chapter detailed the implementation of the UWDF platform, focusing on its hardware and software components as a prototype for healthcare monitoring. The hardware implementation leveraged the ESP32S2 development board and I2C HUB for scalable sensor integration, while the software architecture adopted a three-layered approach—comprising the User Interface Layer, Business Logic Layer, and Communication Layer—to provide efficient data processing, secure transmission, and user-friendly visualization. The data flow mechanism, supported by robust preprocessing, encryption, and storage strategies, addressed the platform's functional and privacy requirements. Additionally, the public API design facilitated secure data access for authorized clients, enhancing the platform's interoperability. The complete codebase is available at `https://github.com/cnmount/uwdf_src/` for further inspection. The prototype demonstrates technical feasibility and lays a foundation for future enhancements. The next chapter Chapter 6 will discuss the evaluation of this implementation, analyzing its performance, limitations, and potential improvements to meet the needs of end-users.

Chapter 6

Platform Evaluation

This chapter evaluates the Unified Wearable Device Framework (UWDF) platform to validate the effectiveness of its functional design and gather user feedback. The evaluation comprises three sections: feature comparison, functional testing, and usability testing. Feature comparison highlights UWDF's distinctions from other platforms; functional testing verifies the reliability and robustness of core functions; and usability testing assesses ease of use based on industry user feedback.

6.1 Feature Comparison

To evaluate the effectiveness of the UWDF in addressing the needs of older adults in healthcare applications, this section compares its features against three prominent platforms: AWS IoT, ThingsBoard, and Teladoc Health. The comparison assesses how UWDF's design aligns with user requirements, focusing on seven key features identified through user research (Section 3.3). By benchmarking against platforms with diverse architectures and market applications, this analysis highlights UWDF's strengths, limitations, and unique contributions to wearable IoT systems for healthcare.

6.1.1 Comparison Platforms Selection Criteria

To ensure a robust evaluation of the UWDF against platforms that reflect diverse IoT and healthcare solutions, the selection of comparison platforms was guided by criteria tailored to older adults' healthcare needs. As outlined in Section 6.1, the comparison focuses on seven key features derived from user research, necessitating platforms that align with the demands of wearable IoT systems for healthcare management and independent living [42]. The literature emphasizes the need for scalable, user-centric IoT platforms that incorporate human-centered design (HCD) principles (Section 2.3 and Section 2.4) [23, 53]. Based on these insights, the following criteria were developed to select platforms for comparison:

- **Market relevance**: Platforms were selected for their significant adoption in IoT or healthcare markets, reflecting their practical impact. Sandhu et al. [42] highlight the growing reliance on IoT for healthcare, while Ali [3] notes that market-leading platforms often provide robust architectures suitable for real-world deployment.
- **Functional diversity**: Platforms were chosen to represent varied architectural approaches, including cloud-based, edge computing, open-source, and healthcare-specific systems. Akasiadis [2] underscores the need for flexible IoT architectures to support diverse use cases, enabling a comprehensive assessment of UWDF's design.
- **Potential applicability**: Platforms were evaluated for their ability to address older adults' healthcare needs, either directly or through customization. Alsadoon [1] emphasizes telemonitoring's role in supporting independent living, while ISO 9241-210 [23] advocates for adaptable, user-centric designs to meet diverse user requirements.
- **Technological maturity**: Platforms were required to demonstrate proven reliability and performance, critical for healthcare applications. Perez and Zeadally [37] stress the importance of standardized, reliable frameworks, supported by mature technologies like ESP32 microcontrollers [18].

The selected platforms—AWS IoT, ThingsBoard, and Teladoc Health—meet these criteria and represent a spectrum of IoT solutions:

- **AWS IoT**: Amazon's cloud-based IoT platform, targeting developers and enterprises for large-scale device management and real-time data processing.[1]
- **ThingsBoard**: An open-source IoT platform offering device management, data visualization, and rule engines, emphasizing flexibility and customization. [2]
- **Teladoc Health**: Established in 2002, is a leading telemedicine provider in the United States. It is a telehealth service that integrates wearable device data, providing health monitoring and virtual care. [3]

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[1] `https://aws.amazon.com/iot/`

[2] `https://thingsboard.io/`

[3] `https://en.wikipedia.org/wiki/Teladoc_Health/`

These criteria, grounded in the literature's focus on interoperability, scalability, and HCD [23, 37, 42], ensure a comprehensive comparison that positions UWDF within the IoT healthcare ecosystem. The rationale for selecting these platforms is further detailed in Section 6.1.2.

6.1.2 Comparison Platforms Overview

As discussed in Section 2.4.2, three IoT platforms, AWS IoT [3], ThingsBoard [53], and Teladoc Health [31], were introduced for their roles in supporting older adults' healthcare through wearable sensors and remote monitoring. AWS IoT was highlighted for its scalable cloud-based integration, ThingsBoard for its open-source flexibility in data visualization, and Teladoc Health for its specialized telehealth services. This section compares these platforms based on their features, usability, and suitability for healthcare applications, drawing on recent data to evaluate their strengths and limitations in addressing the needs of older adults and their caregivers.

6.1.2.1 AWS IoT

According to the 2024 IoT & Embedded Developer Survey Report by the Eclipse Foundation, AWS IoT [14] continues to lead in IoT Cloud Platforms. Its market share has increased to 45.00%, rising from 41% in 2023. The platform provides a robust suite of services including device connectivity, device management, data processing, security, and analytics integration.

AWS IoT targets technical users and requires significant development expertise to implement solutions. While powerful, its user interfaces are designed for technical operators rather than end-users like older adults or non-technical caregivers.

6.1.2.2 ThingsBoard

ThingsBoard is an open-source IoT platform emphasizing flexibility and customization. Known as an open-source IoT platform which can be used for data collection, processing, visualization, and device management, ThingsBoard offers end-to-end enterprise solutions along with device management, data visualization, rule engine capabilities, multi-tenancy support, and extensive support options.

ThingsBoard provides customised IoT solutions for specific use cases and industries, demonstrating its adaptability. It supports flexible deployment on both local computers and cloud environments.

ThingsBoard supports applications in Smart Energy, SCADA, Environment Monitoring, Smart Office, Water Metering, Smart Retail, Smart Farming, Fleet Tracking, Air Quality Monitoring, Health Care and so on. In addition, this platform can support HTTP, OPC-UA, MQTT and even other protocols such as LoRaWAN and SNMP[52]. As an open-source platform, ThingsBoard provides extensive customization options but requires development resources to adapt to specific use cases.

6.1.2.3 Teladoc Health

Teladoc Health is a specialized telehealth platform integrating wearable device data with clinical services. As of 2024, Teladoc was serving 90 million people across its virtual care products in the United States[51]. The platform offers virtual consultations, health monitoring integration, electronic health records, medication management, and specialty care access.

Unlike the other compared systems, Teladoc Health is specifically designed for healthcare applications but focuses primarily on clinical communication rather than comprehensive device management.

6.1.3 Feature Definition and Selection Rationale

The features selected for comparison—Interoperability, Data Storage, Sensor Status Management, Remote Data Transmission, Real-time Health Monitoring, User Authorization Management, and Simple User Interface—are directly derived from the design requirements defined in Section 4.1 and informed by user study with older adults, caregivers, and healthcare professionals (Section 3.2). These seven features, mapped to the four-layer IoT architecture (Application Layer, Processing Layer, Network Layer, and Perception Layer) as shown in Figure 6.1, form a dedicated framework for wearable IoT systems in older adults' healthcare. The selection rationale is based on their alignment with stakeholder priorities and their applicability to platforms like AWS IoT, ThingsBoard, and Teladoc Health, as introduced in Section 2.4.2.

Each feature's definition and inclusion rationale are detailed below. These features were selected based on the statistical significance found in the UWDF user study (Section 3.2), representing priorities for at least 30% of one or more stakeholder groups.

- **Interoperability**: Integrate and exchange data seamlessly with diverse devices and systems.

  Definition: Functions allowing the platform to connect with various hardware (e.g., sensors, wearables) and software (e.g., healthcare systems) using standard protocols.

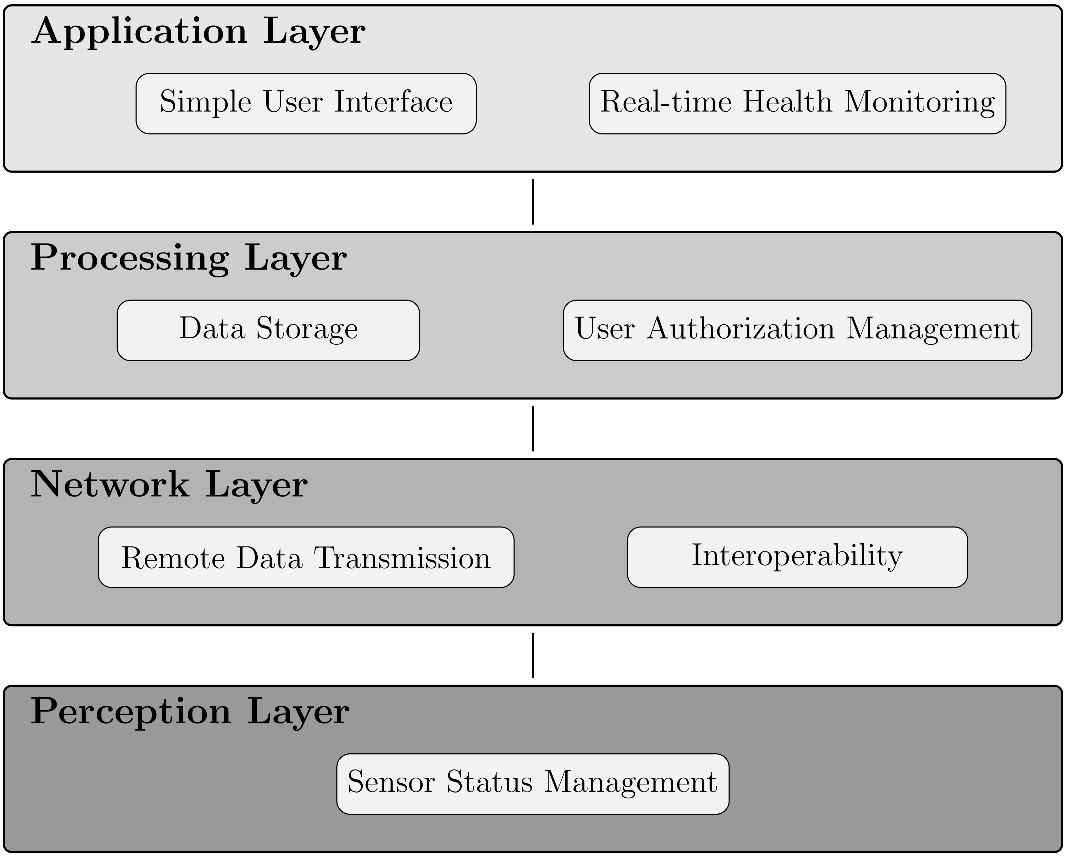


Figure 6.1: Comparative Features in IoT Architecture Layers

Rationale: 50% of technical personnel identified interoperability issues as a key challenge in wearable device development (Figure 3.18), with 70% desiring improved device interoperability (Figure 3.19) and 50% prioritizing cross-platform compatibility (Figure 3.20).

- **Data Storage**: Secure storage and management of health-related data for monitoring and analysis.

  Definition: Specifies the storage mechanism, capacity, and access features, based on the prototype implementation.

  Rationale: 100% of healthcare professionals reported the need for blood pressure data storage (Figure 3.14), indicating a critical need for reliable records.

- **Sensor Status Management**: The ability to monitor, configure, and troubleshoot connected sensors.

  Definition: Functions enabling users to view device battery levels, connectivity status, and perform basic troubleshooting.

  Rationale: Our survey shows 58% of older adults reported uncertainty about whether their devices were functioning correctly (Figure 3.17).

- **Remote Data Transmission**: Capabilities for sending health data to authorized recipients.

  Definition: Secure protocols for transmitting health data to caregivers and healthcare providers.

  Rationale: 72% of healthcare providers cited remote access to patient data as essential (Figure 3.12).

- **Real-time Health Monitoring**: Continuous tracking and alerting for health parameters.

  Definition: Near real-time data collection, processing, and notification for critical health metrics.

  Rationale: 87% of healthcare professionals emphasized the need for continuous monitoring (Figure 3.13).

- **User Authorization Management**: Controls allowing users to grant and revoke data access permissions.

  Definition: Features enabling granular permission settings for caregivers and healthcare providers.

  Rationale: 41% of older adults expressed desire to self-manage their data sharing (Figure 3.5), highlighting privacy concerns.

- **Simple User Interface**: An interface designed specifically for users with limited technical expertise.

  Definition: UI/UX elements adhering to general accessibility standards with simplified navigation, large text, high contrast, and minimal complexity.

  Rationale: 63% of older adults reported difficulty with complex interfaces (Figure 3.3), indicating a critical need for simplification.

6.1.4 Feature Comparison Results

This section compares the functionalities of the UWDF platform with AWS IoT, ThingsBoard, and Teladoc Health, focusing on human-centered design. Table 6.1 summarizes the comparison across seven key features. Below, the table is fully described, analyzing each feature and explaining how and why each system meets or fails to meet it, in comparison to UWDF.

Table 6.1: Feature Comparison of UWDF with Other Platforms

Feature	**UWDF**	**AWS IoT**	**Things Board**	**Teladoc Health**
Interoperability	Planned	Yes	Yes	Limited
Data Storage	Yes	Yes	Yes	Limited
Sensor Status Management	Yes	No	Yes	No
Remote Data Transmission	Yes	Yes	Yes	Yes
Real-time Health Monitoring	Yes	Yes	Yes	Yes
User Authorization Management	Yes	Yes	Yes	Yes
Simple User Interface	Yes	No	Planned	Yes

6.1.4.1 Interoperability

UWDF: Marked as “Planned.”, UWDF uses an I2C HUB expansion board for multi-sensor connectivity, indicating a modular design with potential for broader integration. UWDF’s public APIs (e.g., GET /sensors/data) lay the groundwork for future system interoperability. However, the current prototype is limited to local hardware expansion and lacks full integration with diverse systems, making it a planned rather than implemented feature.

AWS IoT: Marked as “Yes.” AWS IoT supports MQTT, HTTP, and WebSockets protocols, integrating with AWS services (e.g., S3, Lambda) and third-party systems via SDKs and APIs. Its extensive device and service support ensures strong interoperability, surpassing UWDF’s current prototype.

ThingsBoard: Marked as “Yes.” As an open-source platform, ThingsBoard supports MQTT, CoAP, HTTP, and integration with external systems (e.g., Kafka) via its rule engine. Its flexibility matches AWS IoT, exceeding UWDF’s planned stage.

Teladoc Health: Marked as “Limited.” Teladoc Health focuses on integrating medical devices (e.g., wearables) with health systems, but its scope is narrower, lacking broad IoT ecosystem support. Compared to UWDF’s future potential, its current interoperability is more restricted.

Comparison with UWDF: AWS IoT and ThingsBoard lead in interoperability with mature integration capabilities, while UWDF is still in the planning phase. Teladoc Health’s interoperability is limited by its medical focus, currently less versatile than UWDF’s potential.

6.1.4.2 Data Storage

UWDF: Marked as “Yes.” UWDF supports local storage using SQLite on a laptop, managing sensor data and user access logs, with AES-256 encrypted backups every 24 hours. Though limited to local storage, it meets basic secure storage needs, albeit with less capacity and scalability than cloud solutions.

AWS IoT: Marked as “Yes.” AWS IoT leverages Amazon S3 and DynamoDB for cloud storage, supporting large-scale data management and HIPAA compliance. Its storage capability far exceeds UWDF’s local implementation.

ThingsBoard: Marked as “Yes.” ThingsBoard offers flexible storage options (e.g., PostgreSQL, TimescaleDB), configurable for local or cloud deployment, supporting time-series data. Its configurability surpasses UWDF’s fixed local storage.

Teladoc Health: Marked as “Yes (Limited).” Teladoc Health uses cloud storage for patient data, compliant with HIPAA, but focuses on medical data, lacking the general scalability of AWS IoT or ThingsBoard, thus marked “Limited.”

Comparison with UWDF: AWS IoT and ThingsBoard’s cloud storage solutions outperform UWDF’s local SQLite in capacity and scalability, though UWDF meets basic needs. Teladoc Health’s storage is similar to UWDF but narrower due to its medical focus.

6.1.4.3 Sensor Status Management

UWDF: Marked as “Yes.” UWDF implements the “Sensor Status Display” interface, allowing users to toggle sensors and view real-time status (e.g., battery levels), enhanced by ESP32S2 LED indicators.

AWS IoT: Marked as “No.” AWS IoT monitors device connectivity via Device Management but lacks direct end-user tools for sensor configuration or troubleshooting, requiring additional development, thus not meeting the need for ordinary users.

ThingsBoard: Marked as “Yes.” ThingsBoard offers device management dashboards to monitor sensor status and configure via rule engines, similar to UWDF but more flexible.

Teladoc Health: Marked as “No.” Teladoc Health focuses on data collection rather than sensor management, with no evidence of end-user sensor control features.

Comparison with UWDF: UWDF and ThingsBoard support sensor status management with user-friendly features; AWS IoT and Teladoc Health do not meet this due to lack of direct support.

6.1.4.4 Remote Data Transmission

UWDF: Marked as “Yes.” UWDF confirms encrypted (AES) data transmission via Wi-Fi to a laptop, with APIs supporting remote access.

AWS IoT: Marked as “Yes.” AWS IoT uses MQTT and HTTPS for secure transmission, with TLS encryption ensuring reliability.

ThingsBoard: Marked as “Yes.” Supports MQTT, HTTP, and WebSockets with encryption and checksums for data integrity.

Teladoc Health: Marked as “Yes.” Transmits patient data via secure cloud connections, likely HTTPS.

Comparison with UWDF: All platforms support remote data transmission, with UWDF’s local Wi-Fi solution comparable to the cloud-based capabilities of AWS IoT, ThingsBoard, and Teladoc Health, showing no significant differences.

6.1.4.5 Real-time Health Monitoring

UWDF: Marked as “Yes.” UWDF supports real-time data collection (e.g., heart rate), transmission, and web interface display.

AWS IoT: Marked as “Yes.” Supports real-time data streaming via AWS IoT Core and Kinesis, integrable with dashboards.

ThingsBoard: Marked as “Yes.” Provides real-time telemetry and dashboard visualization.

Teladoc Health: Marked as “Yes.” Designed for real-time patient monitoring (e.g., vital signs) displayed to providers.

Comparison with UWDF: All platforms meet real-time health monitoring needs, with UWDF’s implementation on par with AWS IoT, ThingsBoard, and Teladoc Health, differing only in implementation focus.

6.1.4.6 User Authorization Management

UWDF: Marked as “Yes.” UWDF designed a user management interface and authorization system, with API authentication.

AWS IoT: Marked as “Yes.” Uses IAM and device certificates for fine-grained access control.

ThingsBoard: Marked as "Yes." Supports role-based access control and user management.

Teladoc Health: Marked as "Yes." Provides secure access management for providers and patients, HIPAA-compliant.

Comparison with UWDF: All platforms support user authorization management, with UWDF's implementation matching the security and functionality of AWS IoT, ThingsBoard, and Teladoc Health.

6.1.4.7 Simple User Interface

UWDF: Marked as "Yes." UWDF's human-centered design includes a web interface designed for older adults, with high usability scores from testing.

AWS IoT: Marked as "No." Its interface (e.g., AWS Management Console) targets developers, not older adults.

ThingsBoard: Marked as "Planned." Offers customizable dashboards, but the default interface requires simplification for non-technical users.

Teladoc Health: Marked as "Yes." Provides an easy-to-use interface for patients and providers.

Comparison with UWDF: UWDF and Teladoc Health offer simple interfaces for non-technical users; AWS IoT does not meet this need; ThingsBoard lags behind UWDF due to customization requirements.

6.1.5 Overall Analysis

Compared to UWDF, AWS IoT and ThingsBoard excel in technical features like interoperability and data storage but lack a simple user interface for older adults. Teladoc Health aligns closely with UWDF in health monitoring and interface simplicity but falls short in interoperability and sensor management. UWDF's strength lies in its user-oriented design tailored to older adults healthcare, addressing stakeholder needs such as simplified interfaces. However, its interoperability and sensor status management remain underdeveloped due to limited support for universal standards and automated diagnostics. These limitations will be addressed in future research to enhance device integration and sensor functionality, building on the requirements outlined in Section 4.1.

6.2 Functional Testing

Following the feature comparison presented in the previous section, this section details the functional testing of the UWDF prototype. The testing focuses on four critical aspects—reliability, performance, robustness, and communication—to evaluate the prototype's operational capabilities. Given that the outputs from the platform design (Chapter 4) and implementation (Chapter 5) stages are prototypes aimed at validating foundational theories rather than delivering production-ready systems, the testing plan balances scientific rigor with the practical constraints of the current setup, such as limited sensor availability and manual data handling. This section outlines the testing process, objectives, expected outcomes, and test environment, all tailored to the prototype's scope and its role in advancing the thesis objectives.

6.2.1 Objectives and Expected Outcomes

Each test's objectives align with the critical aspects identified earlier—reliability, performance, robustness, and communication—providing a framework to assess the prototype's performance against its design goals. Expected outcomes offer measurable criteria for success, detailed in Table 6.2. These metrics build on the feature comparison by quantifying the prototype's operational effectiveness.

These outcomes are deliberately conservative yet realistic, reflecting the prototype's purpose of validating foundational theories rather than achieving production-level performance. For example, a $>90\%$ reliability target accounts for potential data drops due to manual logging, while a $<$ 2-second response time threshold aligns with the simplicity of the local web interface. Together, these metrics provide a quantitative basis to evaluate the prototype's strengths and limitations, complementing the qualitative insights from the feature comparison.

6.2.2 Testing Process

The functional testing plan is structured to rigorously evaluate the UWDF prototype across four critical aspects: reliability, performance, robustness, and communication. Each test type is designed to assess specific operational capabilities of the prototype, ensuring alignment with the design goals outlined in Chapter 4 and implementation details in Chapter 5. The testing process is systematic, repeatable, and tailored to validate the prototype's core functionalities, providing quantitative and qualitative insights into its effectiveness. Below, each test type is described, with detailed steps provided in the respective subsections to ensure clarity and reproducibility.

Table 6.2: Objectives and Expected Outcomes

Testing Type	Objective	Expected Outcomes
Reliability	Assess the frequency and consistency of sensor data collection and logging.	> 90% data capture at 1 Hz over 1 hour (e.g., at least 3240 out of 3600 samples per sensor). Example: 3590 samples = 99.7% reliability.
Performance	Evaluate efficiency in processing and displaying sensor data.	Average response time from collection to display < 2 seconds across 10 runs. Example: 1.8-second average, no UI freezes.
Robustness	Test ability to maintain functionality under adverse conditions.	System resumes normal operation within 5 seconds after interruptions. Example: Data logging restarts within 4 seconds post-Wi-Fi reconnect.
Communication	Verify reliability and security of data transmission between ESP32S2 and laptop.	100% data transmission success under normal conditions (e.g., all 3600 samples received). Access control enforced (e.g., unauthorized API call returns "Access Denied").

6.2.2.1 Reliability Testing

Reliability testing assesses the consistency and frequency of sensor data collection and logging, a critical requirement for the prototype's ability to capture health-related data over time. The objective, as detailed in Table 6.2, is to achieve a data capture rate exceeding 90% over a 1-hour period at a 1 Hz polling rate. The testing process is designed to verify the prototype's ability to maintain reliable data collection under typical operating conditions. The steps are as follows:

1. Connect 2-3 sensors (e.g., heart rate, temperature) to the ESP32S2 via an I2C HUB to enable data acquisition.
2. Poll sensor data at 1 Hz (1-second intervals) for a duration of 1 hour to simulate continuous operation.
3. Log the collected data to an SQLite database via Wi-Fi using a pre-written script to ensure automated storage.
4. Count the recorded entries and compare them against the expected 3600

samples using automated analysis scripts.

5. Calculate the reliability percentage programmatically to quantify the data capture success rate.

This process ensures reliable data capture through low-frequency polling and automated logging, validating the prototype's ability to consistently collect and store sensor data with minimal manual intervention. The results provide a quantitative measure of reliability, as exemplified by achieving 3590 samples (99.7% reliability) in a test run.

6.2.2.2 Performance Testing

Performance testing evaluates the efficiency of the prototype in processing and displaying sensor data, focusing on response times and system resource usage. As shown in Table 6.2, the goal is to achieve an average response time below 2 seconds across 10 runs. The testing process is as follows:

1. Configure 2-3 sensors to operate at a 1 Hz polling rate.
2. Measure the time from data collection to display on the local web interface using a timing script.
3. Log operation timestamps via Arduino IDE Serial Output and system resource usage via laptop logs.
4. Calculate the average response time over 10 runs using automated scripts.
5. Qualitatively note any delays or UI freezes during the test.

This approach ensures accurate measurement of processing efficiency, focusing on the core functionality of the prototype's data pipeline.

6.2.2.3 Robustness Testing

Robustness testing verifies the prototype's ability to maintain functionality under adverse conditions, such as sensor or network interruptions. The objective is to ensure system recovery within 5 seconds, as specified in Table 6.2. The testing steps are:

1. Disconnect one sensor during a 30-minute test to simulate hardware failure.
2. Disable Wi-Fi for 1 minute, three times within a 1-hour period, to mimic network disruptions.
3. Check logs and the user interface for data gaps or error messages.
4. Input one invalid value to test error handling capabilities.

5. Record the recovery time and system status after each interruption.

These steps assess the prototype’s resilience and error recovery mechanisms under controlled adverse conditions.

6.2.2.4 Communication Testing

Communication testing ensures reliable and secure data transmission between the ESP32S2 and the laptop. The objective is to achieve 100% data transmission success under normal conditions, as outlined in Table 6.2. The testing process includes:

1. Send sensor data at 1 Hz for 1 hour via Wi-Fi to the laptop.
2. Compare sent versus received data using a verification script to confirm transmission accuracy.
3. Verify encryption implementation (AES-XTS-256) through code review.
4. Manually reduce Wi-Fi signal strength and note any transmission interruptions.

This process validates the reliability and security of the prototype’s communication framework.

6.2.2.5 API Functionality Testing

API functionality testing ensures that public APIs operate correctly, securely, and responsively. The goal is to achieve response times under 500 milliseconds and effective authentication, as specified in Table 6.2. The testing steps are:

1. Send GET requests to ‘/sensors/authorized‘ and ‘/sensors/data/sensorId‘ at 1 Hz for 1 hour using a test script (e.g., Python ‘requests‘).
2. Measure API response times using a timing script, targeting responses under 500 milliseconds.
3. Test error handling by sending one malformed GET request (e.g., invalid ‘sensorId‘).
4. Validate authentication by sending ‘POST /auth/login‘ requests with valid and invalid credentials, and test authorized versus unauthorized access to ‘/sensors/data/sensorId‘.
5. Log API responses and errors automatically for analysis.

This process confirms the functionality, security, and responsiveness of the prototype’s API under typical usage scenarios.

6.2.3 Test Environment

The testing occurred in a controlled lab setting to ensure consistency and minimize external variables, leveraging the prototype's existing configuration as follows:

Hardware

- ESP32S2 microcontroller as the core processing unit.
- I2C HUB for connecting 2-3 sensors (e.g., heart rate, temperature).
- Laptop serving as a data processing and central server, equiped with an Intel Core i5-10210U processor (Dual cores, 2.11 GHz base frequency), 8 GB RAM, and 512 GB SSD.

Software

- SQLite database for logging sensor data on the laptop.
- Web interface (HTML/CSS/JavaScript) for real-time display.
- C++ firmware on the ESP32S2 for sensor polling and Wi-Fi transmission.
- Scripts for automated data logging, timing, and analysis.

Conditions

- Indoor environment with stable 2.4 GHz Wi-Fi connectivity.
- No external interference beyond manual test interruptions (e.g., Wi-Fi signal reduction).
- Ambient temperature of 22-25°C, typical of indoor use.

This environment ensures replicability and supports the evaluation of the prototype's performance under controlled conditions, building on the design and implementation insights from earlier sections.

6.2.4 Testing Results

This section reports the performance of the UWDF prototype during functional testing.

To ensure reproducibility and provide an average success rate, each test type was repeated a minimum of five times, with results averaged across these runs. Tests were performed between 20 March 2025 and 3 April 2025, under stable conditions with an environmental temperature of 22°C to 25°C and consistent Wi-Fi signal

Table 6.3: Test Results for Reliability

Test level	Expected	Actual	Success Rate (%)
Heart Rate/Oxygen Sensor			
Test 1	3,600	3,574	99.28
Test 2	3,600	3,575	99.33
Test 3	3,600	3,563	99.31
Test 4	3,600	3,583	99.53
Test 5	3,600	3,580	99.44
Average	3,600	3,575	99.31
Temperature Sensor			
Test 1	3,600	3,554	98.72
Test 2	3,600	3,568	99.11
Test 3	3,600	3,569	99.14
Test 4	3,600	3,565	99.03
Test 5	3,600	3,574	99.28
Average	3,600	3,566	99.06
Heart Rate/Oxygen Sensor and Temperature Sensor			
Average	3,600	3,572	99.22

strength. Results are presented by test type, including a description of each test, tabulated results, and analysis.

6.2.4.1 Reliability Testing

This test was repeated five times to assess the consistency of sensor data collection. Each run used two sensors (heart rate/oxygen sensor HR001 and temperature sensor TEMP001), polled at 1 Hz for 1 hour, with data logged into SQLite via a script. The target was a data capture rate greater than 95%. As shown in Table 6.3, a total of 3,600 samples were expected. The average actual recorded samples were 3,576 for heart rate and oxygen saturation and 3,568 for temperature, achieving a capture rate exceeding 99%, surpassing the target.

Analysis: The missing samples were primarily due to the nature of the prototype's press-type sensors, which require the test subject to actively press their finger against the sensor surface for signal detection. Over the course of the one-hour test, it was difficult for the subject to maintain consistent finger pressure, leading to occasional signal interruptions and subsequent data loss. These interruptions were momentary and did not significantly impact the overall recording rate. The reliability percentages were automatically calculated by a script, which compared the number of successfully recorded data points against the total

Table 6.4: Test Results for Performance

Test Run	Data Processing Time (ms)	Memory Usage (MB)	CPU Usage (%)
Test 1	423	42.50	14.98
Test 2	398	42.48	15.03
Test 3	417	42.52	15.05
Test 4	413	42.50	15.02
Test 5	388	42.54	15.03
Average	408	42.51	15.02

expected samples. Specifically, the script counted the actual number of sensor readings received within the test duration and divided it by the expected 3,600 samples per sensor. Since the capture rate remained above 99%, this suggests that, despite minor interruptions, the system maintains stable performance when operating at a low polling frequency (1 Hz). In other words, at this sampling rate, the brief loss of contact does not significantly degrade the overall reliability of data collection.

6.2.4.2 Performance Testing

Performance testing was conducted five times to evaluate the prototype's efficiency in data processing and display, using two sensors (heart rate sensor HR001 and temperature sensor TEMP001) operating at 1 Hz. The performance goals included an average response time below 0.5 seconds, memory usage under 50 MB, and CPU usage under 30%. The evaluation involved timestamp recording and log analysis to measure the time interval from data collection to display, while continuously monitoring CPU and memory usage. As shown in Table 6.4, The results demonstrated an average response time of 408 milliseconds, memory usage of 42.51 MB, and CPU usage of 15.02%. Correspondingly, the performance goals included an average response time below 0.5 seconds, memory usage under 50 MB, and CPU usage under 30%. The test results met the target requirements.

Analysis: The results demonstrate that the UWDF exhibits strong performance in a small-scale sensor environment (two sensors), with data processing delays well below 500 ms. However, as high-load testing was not conducted, future evaluations should include simulations of concurrent requests to assess system scalability.

Table 6.5: Test Results for Sensor Disconnection

Test Run	Interruption Time (min)	Average Recovery Time (s)	Log/UI Feedback
Test 1	13th	4	Data Gap
Test 2	12th	5	Data Gap
Test 3	10th	4	Data Gap
Test 4	15th	6	Data Gap
Test 5	15th	5	Data Gap
Average	10-15th	4.8	-

Table 6.6: Test Results for Wi-Fi Interruption 1

Test Run	Interruption Time (min)	Average Recovery Time (s)	Log/UI Feedback
Test 1	35th	38	Error Prompt
Test 2	38th	40	Error Prompt
Test 3	40th	39	Error Prompt
Test 4	33th	37	Error Prompt
Test 5	40th	38	Error Prompt
Average	30th–45th	38.4	-

6.2.4.3 Robustness Testing

This test assessed the UWDF's ability to recover from abnormal conditions such as network interruptions and sensor disconnections. To ensure reproducibility and provide an average success rate, robustness testing was performed five times, each run lasting 1 hour. Each test included one of four specific scenarios: sensor disconnection, two Wi-Fi interruptions, and invalid temperature input. As shown in Table 6.5 - Table 6.8, the scenarios were executed within the following time ranges, logs showed clear data gaps following each interruption, with the user interface displaying error messages and updating upon reconnection (Code 6.1 and Figure 6.2). In the tests, the duration of sensor shutdown and WiFi interruption was less than 60 seconds, and invalid temperature inputs exceeded 50°C that were successfully filtered, without adverse impact on the system.

```
14:30:01.616 -> 32 Bpm
14:30:01.616 -> SpO2 70%
14:30:01.635 -> error: wifi connection lost
14:31:41.264 -> WiFi reconnected
14:31:41.598 -> 20 Bpm
14:31:41.598 -> SpO2 48%
```

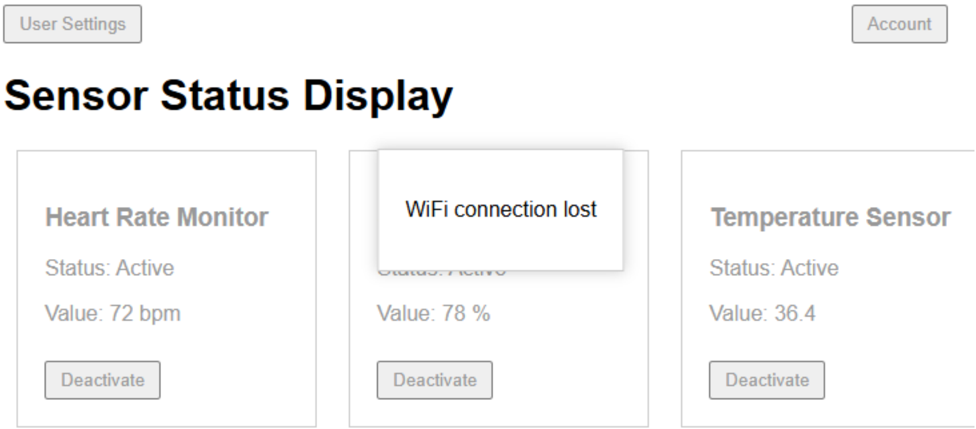
Code Snippet 6.1: WiFi Interruption Log

Table 6.7: Test Results for Wi-Fi Interruption 2

Test Run	Interruption Time (min)	Average Recovery Time (s)	Log/UI Feedback
Test 1	39th	40	Error Prompt
Test 2	44th	41	Error Prompt
Test 3	45th	39	Error Prompt
Test 4	39th	42	Error Prompt
Test 5	45th	40	Error Prompt
Average	30th–45th	40.4	-

Table 6.8: Test Results for Invalid Input

Test Run	Interruption Time (min)	Log/UI Feedback
Test 1	52th	Successfully Filtered
Test 2	50th	Successfully Filtered
Test 3	54th	Successfully Filtered
Test 4	51th	Successfully Filtered
Test 5	53th	Successfully Filtered
Average	50th–55th	Successfully Filtered



WiFi connection lost

Figure 6.2: UI of Wifi connection lost

Analysis: The system demonstrated the ability to automatically recover connections and sensor data collection within 1 minute and effectively filter invalid data, meeting initial robustness expectations and satisfying preliminary assessment criteria.

Table 6.9: Test Results for Signal Degradation Interruption

Test Run	Expected	Actual	Transmission Distance (m)	Success Rate (%)
Test 1	3,600	3,556	5	98.78
Test 2	3,600	3,486	8	96.83
Test 3	3,600	3,391	10	94.19
Test 4	3,600	3,280	12	91.11
Test 5	3,600	3,008	15	83.56

6.2.4.4 Communication Testing

The communication testing was conducted five times to assess the reliability and security of data transmission between the ESP32S2 and the laptop. Each test involved transmitting data at a frequency of 1 Hz for 1 hour under normal conditions, with a target success rate of 95% data transmission assumed under the premise that the transmission distance does not exceed 10 meters, as shown in Table 6.9. Using the heart rate sensor HR001, 3,600 samples were expected in each run. Across all tests, an average of 3,344 samples were successfully received, yielding an overall success rate of 92.89%.

The tests also evaluated the impact of transmission distance on performance. For distances up to 10 meters, the average number of samples successfully received was 3,477 (across Tests 1 to 3 at 5, 8, and 10 meters), corresponding to an average success rate of 96.60%. For distances from 10 to 15 meters, the average number of samples successfully received dropped to 3,144 (across Tests 4 and 5 at 12 and 15 meters), resulting in an average success rate of 87.33%. Starting at a baseline distance, the distance between the ESP32S2 and the laptop was incrementally increased up to 15 meters. As the distance increased, the number of lost samples rose progressively: from 44 samples lost at 5 meters to 592 samples lost at 15 meters.

As the transmission distance between the ESP32S2 and laptop was gradually increased to 15 meters, the number of lost samples progressively rose. Normal data transmission resumed once the distance was reduced to 1 meter without obstruction. Code review confirmed correct implementation of AES-XTS-256 encryption, with no decryption errors detected.

Analysis: The results indicate that the communication system achieves high reliability when the transmission distance is kept at or below 10 meters, with an average success rate of 96.60%, consistently meeting or exceeding the target of 95% and no physical obstructions present, thereby satisfying the target suc-

Table 6.10: Test Results for API Functionality (Normal Access)

Test Item	Target Response Time (ms)	Average Response Time (ms)	Conclusion
/sensors/data/{sensorId}	<500	408	Meets Target
/sensors/authorized	<500	436	Meets Target
/auth/login	<500	400	Meets Target

cess rate under these conditions. The AES-XTS-256 encryption was effectively implemented, as no decryption errors were detected, meeting the basic security validation requirements. However, as the distance increased from 10 to 15 meters, the average success rate dropped significantly to 87.33%, with the lowest success rate of 83.56% observed at 15 meters. This suggests that transmission distance is a critical factor influencing reliability, with performance degrading progressively as distance increases beyond 10 meters.

6.2.4.5 API Functionality Testing

API functionality testing ensured the correctness, security, and responsiveness of public APIs. Unlike other tests, this testing focus on functional validation rather than long-term reliability, targeting response times under 500 milliseconds and effective authentication and authorization. Testing used Python requests scripts to test /auth/login, /sensors/authorized, and /sensors/data/HR001. Each endpoint was tested with 500 GET requests for normal access scenarios, and an additional 500 requests were sent for abnormal access scenarios (e.g., invalid sensorId, unauthorized access), totaling 1500 normal and 1500 abnormal requests across the three endpoints.

Testing used Python requests scripts to test /auth/login, /sensors/authorized, and /sensors/data/HR001. As shown in Table 6.10 and Table 6.11, a total of 3,000 GET requests were sent, with average response times below 450 milliseconds, meeting the target.

Malformed requests (invalid sensorId) returned a 404 status code, with normal error handling. POST /auth/login testing showed valid credentials receiving a 200 status code and invalid credentials a 401, while unauthorized access returned a 403, as expected. All responses were logged, with no anomalies observed. Across the 500 requests tested in this single run, each request type consistently produced the expected results.

Table 6.11: Test Results for API Functionality (Abnormal Access)

Abnormal Scenario	Target Return Value	Actual Return Value	Conclusion
Invalid Sensor ID	404	404	Meets Target
Authentication Failure	403	403	Meets Target
Credential Failure	401	401	Meets Target

Analysis: Response times were consistently below target values, indicating stable API performance. Effective error handling and authentication mechanisms ensured data access security. Results suggest robust API performance within the prototype scope, though testing was limited to single-user, low-frequency requests, with high-concurrency scenarios yet to be simulated.

6.2.4.6 Summary of Results

The functional testing of the UWDF prototype demonstrated strong performance across key areas, validating its foundational capabilities for healthcare applications. Reliability testing achieved an average data capture rate of 99.22%, exceeding the 90% target, confirming consistent sensor data collection. Performance testing yielded an average response time of 408 milliseconds, well below the 2-second goal, with low CPU and memory usage (15.02% and 42.51 MB, respectively). Robustness testing showed effective recovery within 5 seconds after sensor disconnections and Wi-Fi interruptions, with invalid inputs successfully filtered. Communication testing achieved a 96.60% success rate at distances up to 10 meters, and API functionality testing confirmed response times under 450 milliseconds with robust error handling and authentication. These results highlight the prototype's stability and efficiency within its current scope.

Although the results met all performance conditions, the following optimization suggestions are proposed to further enhance the UWDF platform's capabilities.

- Enhance system scalability by conducting high-load testing with concurrent sensor inputs and network requests to identify potential bottlenecks and improve resource management under peak conditions.
- Improve communication robustness by implementing adaptive transmission protocols that can dynamically adjust to varying distances and environmental obstructions, reducing data loss as observed during the 15-meter distance test.
- Strengthen API performance under high-concurrency scenarios by optimiz-

ing server-side resource allocation and implementing load balancing to ensure consistent response times and security when handling multiple simultaneous user requests.

Overall, the UWDF prototype performed well across reliability, performance, robustness, communication, and API functionality, meeting all test goals. While optimization opportunities remain under high-load conditions, the system demonstrates stable operation and fulfills the basic requirements for health monitoring applications. These test results provide critical data for future improvements and clear guidance for optimization directions.

6.3 Usability Testing

This section introduces the usability testing conducted to evaluate the UWDF during its platform evaluation phase. The testing aimed to assess the platform's usability, functionality, and technical performance from the perspective of technical users, providing insights to refine its design for supporting IoT wearable device development in older adults healthcare. Due to resource constraints, the testing was limited to technical personnel (n=11) and excluded older adults, the primary target group. This limitation is acknowledged as a gap in directly evaluating the platform's accessibility for its intended users, and future iterations should include older adult participants to validate real-world applicability.

The literature review (Chapter 2) emphasizes human-centered design (HCD) principles, particularly ISO 9241-210's framework for human-centered evaluation and addressing the whole user experience, as critical for ensuring platform accessibility and usability (Sections 2.3.2 and 2.3.3). This framework guides the assessment of the whole user experience, though the current testing focuses on technical users due to the prototype's developmental stage. Additionally, the review highlights biomedical monitoring devices, such as heart rate, blood pressure, and temperature sensors, as key to meeting older adults' health needs (Section 2.2), informing the focus on user interactions with these sensor modules. Guided by these principles and user requirements identified in Chapter 3, the usability testing evaluates the UWDF's interface intuitiveness and stakeholder satisfaction, aligning with the human-centered design objectives established in Chapter 4. However, the findings are constrained by the lack of older adult input, necessitating further evaluation to ensure alignment with their specific needs.

6.3.1 Methodology

6.3.1.1 Participants

The usability testing survey targeted technical personnel involved in IoT wearable device development, including software engineers, hardware engineers, technical consultants, and students. A total of 11 participants were recruited, reflecting a diverse mix of expertise relevant to the UWDF's technical implementation. Data collection occurred between January 31, 2025, and February 28, 2025, ensuring recent feedback aligned with the platform's current state.

6.3.1.2 Protocol

The study employed a questionnaire-based approach, conducted online to accommodate participants across different locations. Participants were provided with access to the UWDF platform prototype, including its ESP32S2 hardware and web-based interface, and asked to perform tasks such as sensor configuration, data monitoring, and user management. The survey was distributed via an electronic form (e.g., Microsoft Forms), with responses automatically recorded and exported to Excel for analysis. The process ensured accessibility and efficiency, with data privacy maintained through anonymization and secure storage.

6.3.1.3 Survey Questions

The survey included fifteen questions, among which five were multi-select questions allowing multiple answers. Some multi-select questions contained an optional 'Other' option with an open-text field for additional details. Participants could select 'Other' without providing explanations, balancing usability and response burden to reduce participant fatigue while capturing potential unlisted responses. The questions were tailored to technical users' needs, focusing on functionality and optimization, as listed below:

1. What improvements would you suggest enhancing the platform's usability?
2. Which tools or features would be most helpful for usability testing?
3. Which metrics would you consider most important for evaluating the UWDF platform?
4. Which areas need the most improvement during your work with UWDF?
5. What additional tools or resources would help improve your efficiency?
6. How would you rate the usability of the Ease of Hardware Setup? (1=Poor, 5=Excellent)

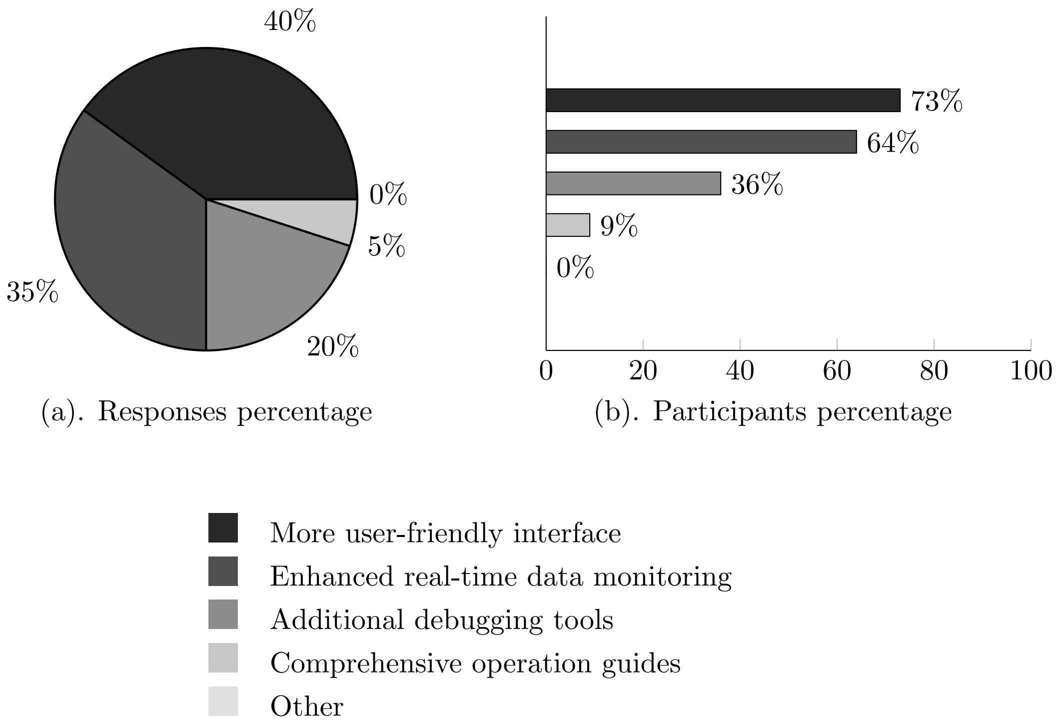
7. How would you rate the usability of the Flexibility in Integrating New Sensors? (1=Poor, 5=Excellent)
8. How would you rate the usability of the Efficiency of Data Processing and Transmission? (1=Poor, 5=Excellent)
9. How would you rate the usability of the Intuitiveness of the User Interface? (1=Poor, 5=Excellent)
10. How would you rate the usability of the Functionality of Access Control and Data Security? (1=Poor, 5=Excellent)
11. To what extent does the platform's user interface meet the needs of technicians? (1=Not Effective, 5=Highly Effective)
12. How effective is the UWDF platform in providing feedback during usability testing? (1=Not Effective, 5=Highly Effective)
13. How intuitive was it to use the web-based interface to manage sensor activation, user accounts, and remote user authorization? (1=Not Intuitive, 5=Very Intuitive)
14. How confident are you in the security measures implemented for data transmission and storage? (1=Not Confident, 5=Very Confident)
15. How would you rate the interoperability of the UWDF platform with different devices or systems you tested? (1=Very Poor, 5=Excellent)

6.3.2 Results

The survey for technical personnel in the evaluation phase offered a comprehensive assessment of the UWDF prototype's usability from a technical perspective. As key users interacting with the prototype's hardware and software, the 11 participants provided valuable insights into usability challenges, essential tools, and performance strengths, bridging the gap between implementation and practical application. Their feedback directly informs both immediate enhancements and long-term optimization of the platform. Results for each question are presented below, focusing on the data collected and key observations, with findings visualized in corresponding figures.

Question 1: "What improvements would you suggest enhancing the platform's usability? (Select all that apply)".

As shown in Figure 6.3, the results indicate a strong preference for a "More user-friendly interface" selected by 8 participants (40% of responses, 73% of participants), underscoring the need for an intuitive design to reduce complexity



(a). Responses percentage

(b). Participants percentage

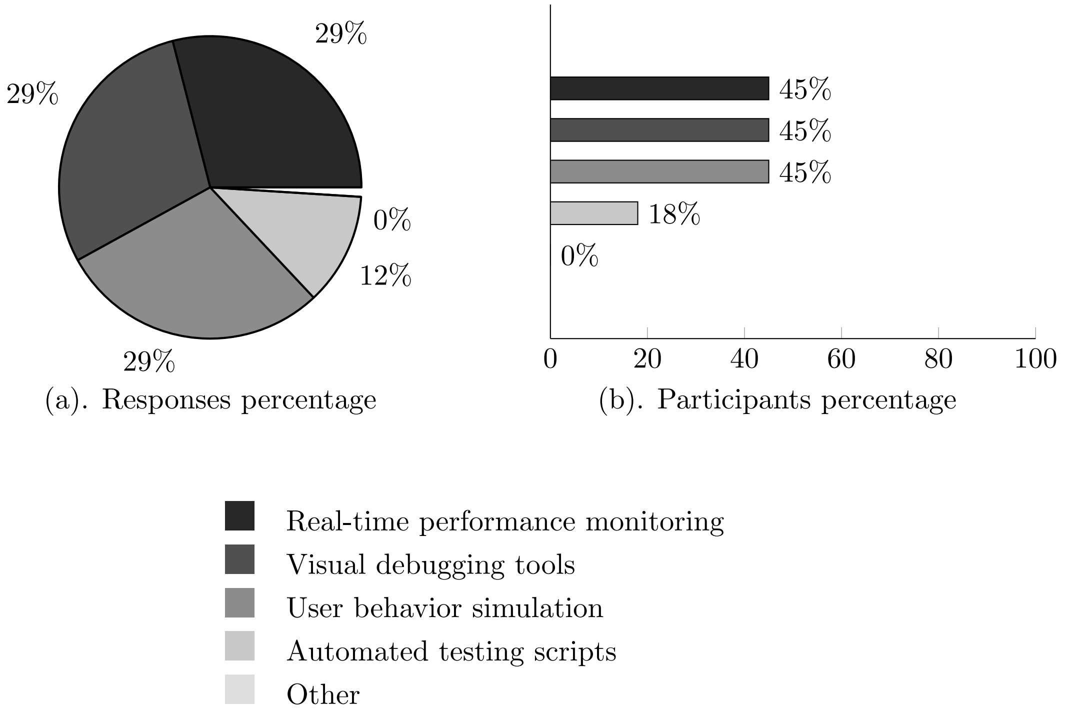
Figure 6.3: Usability Improvement Suggestions

during platform use. “Enhanced real-time data monitoring tools” was the second most popular choice, chosen by 7 participants (35% of responses, 64% of participants), reflecting the importance of timely data insights in wearable device development. “Additional debugging and testing utilities” were noted by 4 participants (20% of responses, 36% of participants), suggesting a demand for robust diagnostic tools. The emphasis on interface simplicity and real-time monitoring aligns with the need for efficient workflows, while debugging support highlights technical users’ focus on reliability.

Question 2: “Which tools or features would be most helpful for usability testing? (Select all that apply)”.

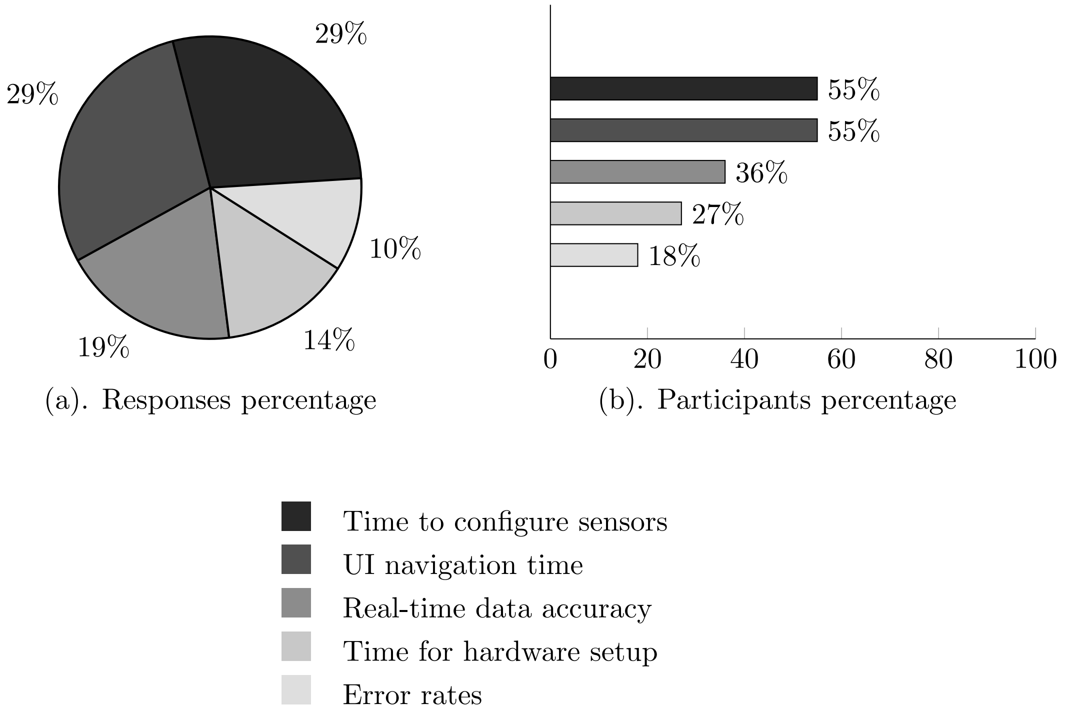
As shown in Figure 6.4, “Real-time performance monitoring tools”, “Visual debugging tools for data handling” and “User behavior simulation systems” each garnered 5 participants (29% of responses, 45% of participants), highlighting the value of performance monitoring, visual diagnostics and simulated user interactions. “Automated testing script support” was chosen by 2 participants (12% of responses, 18% of participants), suggesting moderate interest in automation. The preference for real-time and visual tools reflects technical users’ focus on precision and efficiency in usability testing.

Question 3: “Which of the following metrics would you consider most important



(a). Responses percentage (b). Participants percentage

Figure 6.4: Helpful Tools for Usability Testing

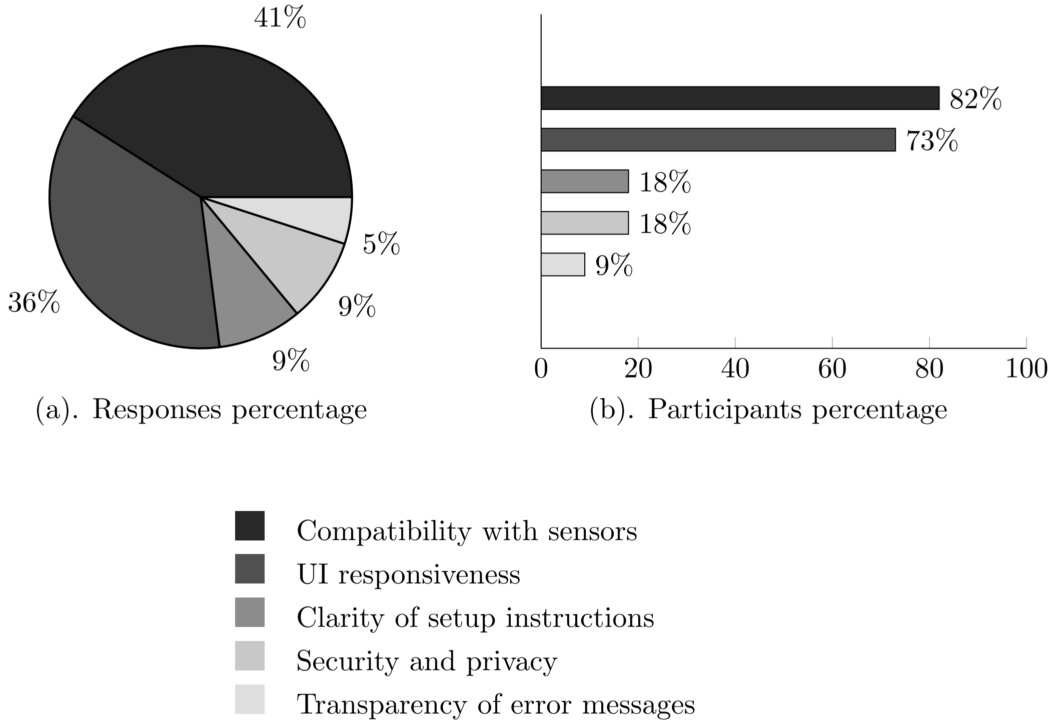


(a). Responses percentage (b). Participants percentage

Figure 6.5: Important Metrics for Evaluation

for evaluating the UWDF platform? (Select all that apply)".

As shown in Figure 6.5, "Time required to configure new sensors" and "User interface (UI) navigation time and success rate" were both the most valued met-



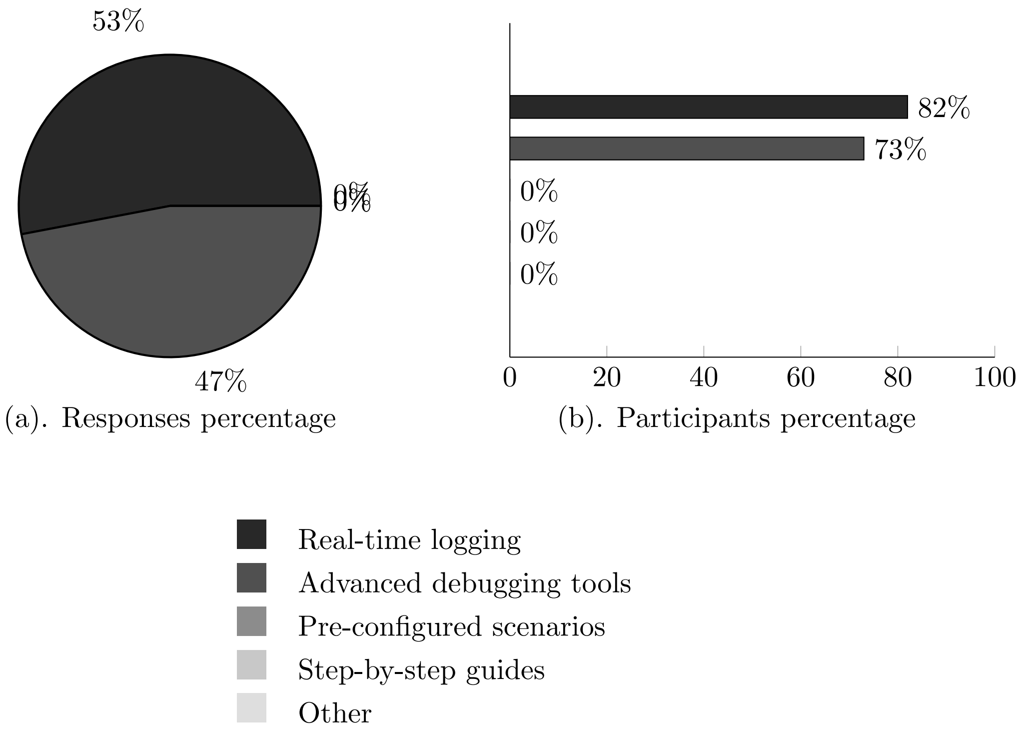
(a). Responses percentage (b). Participants percentage

Figure 6.6: Areas Needing Improvement

ric, selected by 6 participants (29% of responses, 55% of participants), reflecting the importance of a navigable interface and sensor integration. “Real-time data accuracy and consistency” was selected by 4 participants (19% of responses, 36% of participants), indicating concerns about reliability and data quality. “Time required for hardware setup” was chosen by 3 participants (14% of responses, 27% of participants), and “Error rates during sensor integration or data handling” was chosen by 2 participants (10% of responses, 18% of participants), suggesting they're lesser priorities. The focus on configuration time and UI navigation underscores usability as a key evaluation criterion.

Question 4: “Which of the following areas need the most improvement during your work with UWDF? (Select all that apply)”.

As shown in Figure 6.6, “Compatibility with additional sensors” was the most cited area, selected by 9 participants (41% of responses, 82% of participants), highlighting a significant interoperability challenge. “Responsiveness and reliability of the user interface” followed with 8 participants (36% of responses, 73% of participants), indicating usability concerns. “Clarity of setup instructions” and “Security and privacy handling” each had 2 participants (9% and 6% of responses, 18% of participants), suggesting documentation, security and privacy gaps. “Transparency of error messages and debugging tools” was noted by 3 participants (18% of responses, 27% of participants), showing these is less pressing



(a). Responses percentage

(b). Participants percentage

Figure 6.7: Tools for Efficiency Improvement

but still relevant. The dominance of sensor compatibility reflects a core technical limitation needing urgent attention.

Question 5: “What additional tools or resources would help improve your efficiency? (Select all that apply)”.

As shown in Figure 6.7, “Real-time logging and visualization of platform performance” was overwhelmingly favored, selected by 9 participants (43% of responses, 82% of participants), indicating a strong need for performance transparency. “Advanced debugging tools for sensor data issues” followed with 8 participants (38% of responses, 73% of participants), reinforcing the demand for diagnostic support. “Pre-configured testing scenarios or presets”, “Step- by-step guides or tutorials” and “Other” were not selected by any participants.

Question 6: “How would you rate the usability of the Ease of Hardware Setup in the UWDF platform?”.

As shown in Figure 6.8, the majority (10 participants, 91%) rated the ease of hardware setup as 4 (Excellent), with 1 participant (9%) selecting 3 (Moderate). No ratings fell below 3, indicating generally positive feedback. The high concentration at 4 suggests the ESP32S2-based setup, supported by the I2C HUB, is user-friendly and efficient, though the single moderate rating hints at minor inconsistencies or challenges for some users, possibly related to setup clarity.

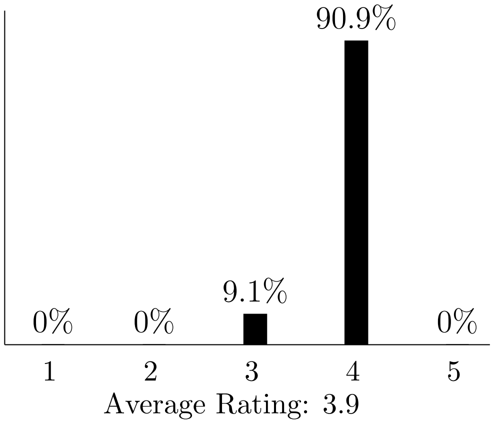


Figure 6.8: Ease of Hardware Setup Rate

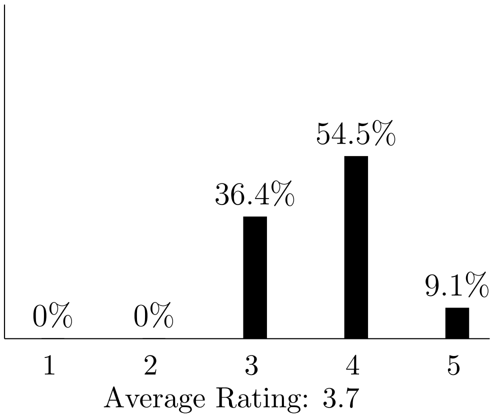


Figure 6.9: Flexibility in Sensors Integration Rate

Question 7: "How would you rate the usability of the Flexibility in Integrating New Sensors in the UWDF platform?".

As shown in Figure 6.9, ratings were distributed with 6 participants (55%) selecting 4 (Excellent), 4 (36%) choosing 3 (Moderate), and 1 (9%) rating 5 (Outstanding). The majority view it positively, but the spread suggests variability in experience. The high ratings reflect the I2C HUB's scalability, yet the moderate scores align with the frequent call for improved sensor compatibility, indicating potential integration challenges.

Question 8: "How would you rate the usability of the Efficiency of Data Processing and Transmission in the UWDF platform?".

As shown in Figure 6.10, eight participants (73%) rated it 4 (Excellent), and 3 (27%) gave it 5 (Outstanding). The consistently high ratings indicate strong performance of the ESP32S2's Wi-Fi and preprocessing capabilities. The absence of lower scores suggests reliable data handling, aligning with the demand for real-time monitoring tools.

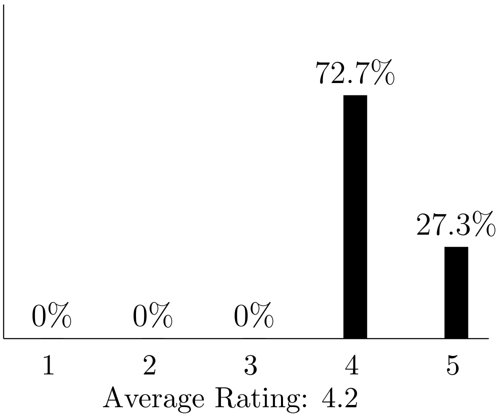


Figure 6.10: Efficiency of Data Processing Rate

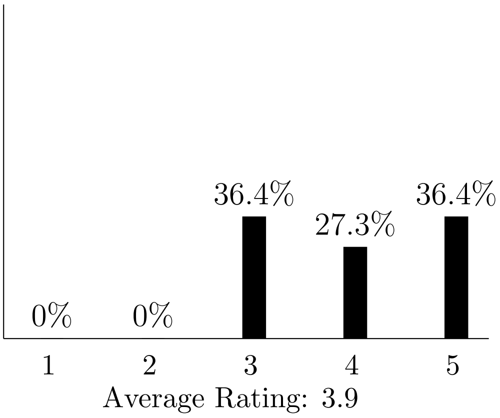


Figure 6.11: UI Intuitiveness Rate

Question 9: "How would you rate the usability of the Intuitiveness of the User Interface (UI) in the UWDF platform?".

As shown in Figure 6.11, four participants (36%) rated it 4 (Excellent), 3 (27%) chose 3 (Moderate), and 4 (36%) selected 5 (Outstanding). The positive skew indicates a generally intuitive UI, supported by the web-based design, but moderate ratings suggest room for refinement, consistent with calls for a more user-friendly interface.

Question 10: "How would you rate the usability of the Functionality of Access Control and Data Security in the UWDF platform?".

As shown in Figure 6.12, eight participants (73%) rated it 4 (Excellent), with 2 each (18%) selecting 5 (Outstanding). The high ratings reflect confidence in the AES encryption and permission controls, though moderate scores suggest minor concerns, possibly linked to transparency or usability of security features.

Question 11: "To what extent does the platform's user interface meet the needs of technicians?".

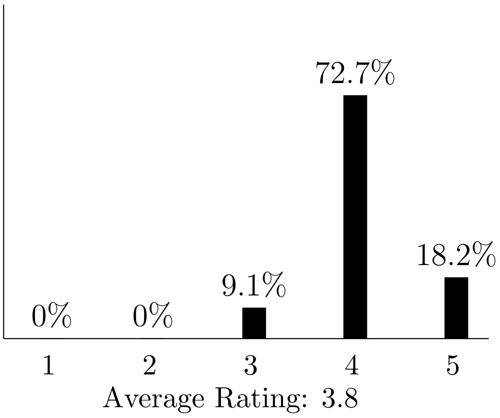


Figure 6.12: Access Control and Security Rate

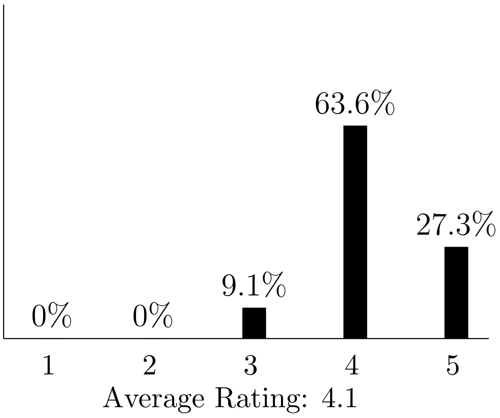


Figure 6.13: UI Effectiveness for Technicians

As shown in Figure 6.13, seven participants (64%) rated the UI as 4 (Effective), while 3 (27%) selected 3 (Moderately Effective) and 1 (9%) selected 5 (Highly Effective). The absence of ratings below 3 indicates a generally positive perception, with the majority finding the UI effective for their needs. The high concentration at 4 suggests the web-based interface, with features like sensor status display and user management, aligns well with technicians' tasks, though the moderate ratings hint at potential gaps in fully addressing all technical requirements, possibly related to responsiveness or customization.

Question 12: "How effective is the UWDF platform in providing feedback during usability testing?".

As shown in Figure 6.14, eight participants (73%) rated feedback effectiveness as 4 (Effective), and 3 (27%) gave it 5 (Highly Effective). The consistently high ratings, with no scores below 4, suggest the platform excels at providing clear and useful feedback, likely due to real-time data displays and logging features. This aligns with the strong demand for real-time monitoring tools, indicating that the

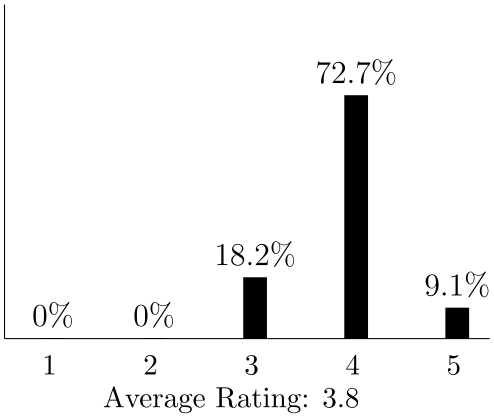


Figure 6.14: Feedback Effectiveness During Testing

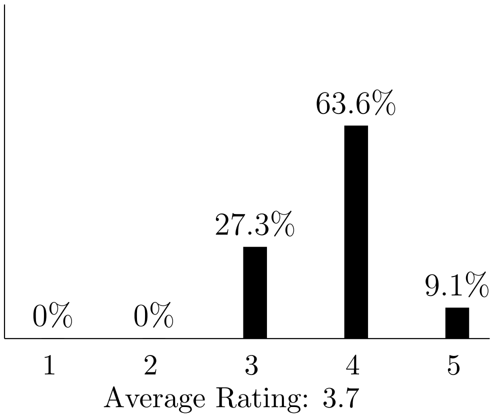


Figure 6.15: Intuitiveness of Web-Based Interface for Sensor Management Rate

UWDF supports technicians in identifying issues promptly during testing.

Question 13: “How intuitive was it to use the web-based interface to manage sensor activation, user accounts, and remote user authorization?”.

As shown in Figure 6.15, seven participants (64%) rated it 4 (Intuitive), with 3 (27%) selecting 3 (Moderately Intuitive) and 1 (9%) selecting 5 (Very Intuitive). The positive skew, with no ratings below 3, indicates the interface is generally easy to navigate for managing sensors and users. The majority at 4 reflects the effectiveness of features like the sensor status display and user management pages, though moderate ratings suggest minor complexities, possibly in remote authorization workflows, warranting refinement.

Question 14: “How confident are you in the security measures implemented for data transmission and storage?”.

As shown in Figure 6.16, seven participants (64%) rated their confidence as 4 (Confident), with 1 (9%) selecting 3 (Moderately Confident) and 3 selecting 5 (Very Confident). The lack of low ratings suggests broad trust in the AES encryp-

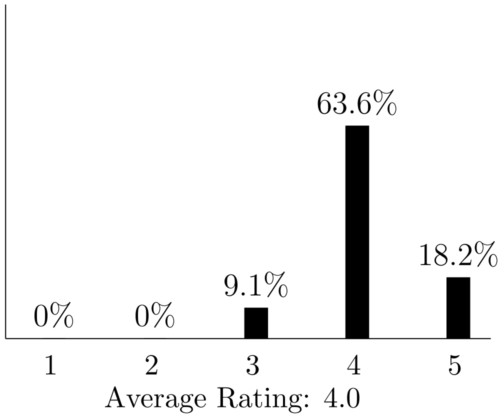


Figure 6.16: Confidence in Security Measures

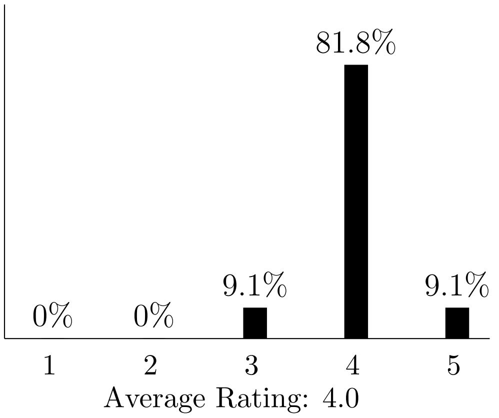


Figure 6.17: Interoperability with Different Devices or Systems Rate

tion and access control mechanisms. The majority at 4 indicates solid security implementation, though the moderate scores may reflect concerns about transparency or perceived vulnerabilities, consistent with earlier calls for improved error messaging and security handling.

Question 15: "How would you rate the interoperability of the UWDF platform with different devices or systems you tested?".

As shown in Figure 6.17, nine participants (82%) rated interoperability as 4 (Good), 1 (9%) gave 5 (Excellent), and 1 (9%) selected 3 (Moderate). The high ratings, with most at 4 or above, suggest the ESP32S2 and I2C HUB facilitate effective device integration. However, the single moderate rating and the frequent mention of sensor compatibility issues (82% in Question 4) indicate lingering challenges, likely with specific sensors or external systems, necessitating further standardization efforts.

6.3.3 Discussion and Key Findings

The usability testing of the UWDF prototype, conducted with 11 technical personnel, provided critical insights into its performance and areas for improvement, particularly in supporting IoT wearable device development for older adults' healthcare. The survey was designed to assess usability, functionality, and technical performance, with fifteen questions tailored to technical users' needs. Five multi-select questions explored improvement areas, tools, metrics, and resources, while ten rating-based questions evaluated specific usability aspects. Below, the key findings are discussed in relation to the survey design and results, highlighting the platform's strengths and opportunities for refinement.

The survey included questions to identify enhancements for platform usability, such as Question 1, which asked participants to suggest improvements. The intent was to uncover preferences for interface design, monitoring capabilities, and debugging tools. Results showed a strong preference for a more user-friendly interface (73% of participants) and enhanced real-time data monitoring (64%), indicating that technical users prioritized intuitive design and timely data insights. This aligns with the high ratings for UI intuitiveness (average 3.9, 73% at 4 or 5) and feedback effectiveness (average 3.8, 100% at 4 or 5), suggesting that the web-based interface, with features like sensor status display, was effective but could be streamlined to reduce complexity. Future iterations should focus on simplifying navigation and enhancing real-time visualization to support efficient workflows.

Questions 2 and 3 targeted tools and metrics for usability testing and platform evaluation, aiming to pinpoint priorities for testing capabilities and performance indicators. Participants valued real-time performance monitoring, visual debugging tools, and user behavior simulation equally (45% each), alongside time to configure sensors and UI navigation time (55% each). These findings reflect the importance of precision and efficiency in testing, with real-time data accuracy (36%) also a key concern. The emphasis on these metrics suggests that the platform's current real-time logging and data processing capabilities (average rating 4.2, 100% at 4 or 5) were well-received, but additional diagnostic tools and simulation features could further enhance testing efficiency. Integrating automated testing scripts and visual debugging interfaces would address these needs.

Question 4 sought to identify areas needing improvement, revealing compatibility with additional sensors as the top concern (82% of participants), followed by UI responsiveness (73%). This question was designed to highlight technical pain points, and the results underscored interoperability challenges, consistent with the moderate ratings for sensor integration flexibility (average 3.7, 36% at 3). Despite good interoperability ratings (average 4.0, 91% at 4 or 5), the frequent mention of sensor compatibility indicates uneven performance with certain devices. The I2C HUB facilitated integration, but standardization efforts are needed to support a broader range of sensors, enhancing the platform's scalability.

Efficiency and debugging were explored through Questions 5 to 9, with Question 5 identifying real-time logging (82%) and advanced debugging tools (73%) as critical for improving efficiency. Questions 6 to 9 rated hardware setup (average 3.9), sensor integration (3.7), data processing (4.2), and UI intuitiveness (3.9). These questions aimed to assess core usability aspects, and the high ratings for data processing and hardware setup confirmed the ESP32S2's reliability and the I2C HUB's user-friendliness. However, the demand for debugging tools and moderate UI scores suggest that adding diagnostic utilities and refining interface responsiveness would further streamline technical workflows.

Security and trust were evaluated through Questions 10 and 14, which assessed access control functionality (average 3.8) and confidence in security measures (average 4.0). These questions aimed to gauge trust in protecting sensitive health data, a critical concern for healthcare applications. The majority (82% at 4 or 5 for access control, 91% for security confidence) expressed trust in the AES encryption and permission controls, but minor concerns about transparency (18% for security handling) suggest a need for clearer error messaging and security documentation. Questions 11 to 13 further confirmed the UI's effectiveness for technicians (average 4.1) and intuitiveness for managing sensors and users (average 3.7), though moderate ratings (27% at 3) indicated areas for refinement in remote authorization workflows.

Question 15 directly addressed interoperability, rated highly (average 4.0, 91% at 4 or 5), but the single moderate rating (9%) and strong call for sensor compatibility (82%) highlighted lingering integration challenges. This question aimed to evaluate a foundational requirement for a universal wearable framework, and the results suggest that while the platform supports effective device integration, specific sensors or external systems pose difficulties. Future development should prioritize standardized protocols to enhance cross-device compatibility.

Overall, the survey results validated the UWDF prototype as a robust platform with strong usability for technical users, particularly in hardware setup, data processing, and feedback provision. However, challenges in sensor compatibility, UI responsiveness, and debugging support require targeted improvements. Enhancing interoperability through standardized protocols, optimizing UI navigation for responsiveness, and integrating advanced diagnostic tools will address these gaps, aligning the platform more closely with technical users' needs and advancing its applicability in older adults' healthcare.

6.4 Summary

This chapter outlined the evaluation of the UWDF to assess its effectiveness, reliability, and usability for older adults healthcare applications through feature comparison, functional testing, and usability testing. The evaluation employed a three-pronged approach: (1) a Feature Comparison, which involved comparing UWDF with leading IoT and healthcare platforms (AWS IoT, ThingsBoard, Teladoc Health); (2) Functional Testing, which involved testing the prototype's reliability, performance, robustness, communication, and API functionality; and (3) Usability Testing, which involved conducting usability testing with 11 technical personnel. These efforts validated UWDF's design while identifying key areas for improvement.

The feature comparison highlighted UWDF's strengths in providing a user-friendly interface and sensor status management, surpassing AWS IoT's developer-centric design. However, its interoperability remains in the planning stage, lagging behind the mature integration capabilities of AWS IoT and ThingsBoard. Functional testing confirmed robust performance, with 99.22% average data capture reliability, 408 ms response time, and effective recovery from interruptions, though communication reliability dropped to 87.33% at 15 meters. Usability testing revealed that 91% of participants rated hardware setup as excellent and 82% rated interface intuitiveness as 4 or 5, but 91% emphasized sensor compatibility as a critical improvement area, alongside UI responsiveness (73%) and debugging tools (36%).

These findings suggest that UWDF may serve as a human-centered platform, meeting users' needs for simplicity and privacy, caregivers' demands for real-time monitoring, and technical personnel's focus on interoperability. Suggested improvements include enhancing sensor compatibility, optimizing communication protocols for reliable data transmission beyond 10 meters, and improving UI responsiveness. As a prototype, UWDF's performance provides a strong foundation, though limitations such as local storage, limited sensor variety, and small-scale testing require further refinement. These results guide iterative development and will be analyzed further in the Discussion chapter to contextualize UWDF's contributions, with future directions proposed in the Conclusion.

Chapter 7

Discussion

This chapter revisits the research questions outlined in Chapter 1 to analyze the significance of the Unified Wearable Device Framework (UWDF) within the context of older adult healthcare IoT and human-centered design. It evaluates how the UWDF meets stakeholder needs, compares its positioning to existing solutions, and explores its limitations and future directions.

7.1 Addressing the Research Questions

This section addresses the research questions outlined in Chapter 1 to evaluate the UWDF in the context of older adult healthcare IoT and human-centered design. The answers integrate findings from the literature review (Chapter 2), user research (Chapter 3), usability testing (Section 6.3), and functional testing (Section 6.2).

7.1.1 Research Question 1: Types of IoT-Based Wearable Devices in Older Adult Healthcare

RQ1: "What types of IoT-based wearable devices are currently being used by older adults in health-related contexts?"

The literature review (Chapter 2) identifies smartwatches, fall detection pendants, and heart rate monitors as prevalent IoT-based wearable devices for older adults, used for activity tracking, fall detection, and vital sign monitoring. Perez et al. [36] note these devices often rely on platforms like AWS IoT or ThingsBoard for data integration. User research (Chapter 3) corroborated these findings, with stakeholders (older adults, caregivers, healthcare professionals) reporting widespread use of such devices. However, 63% of older adults cited difficulties with complex interfaces (Figure 3.3), and 41% raised privacy concerns (Figure 3.5), indicating gaps in usability and security in existing solutions.

7.1.2 Research Question 2: Applying Human-Centered Computing Principles in Wearable IoT Design

RQ2: "How could Human-Centered Computing (HCC) principles be applied in the design of wearable IoT devices for older adults and their caregivers?"

HCC principles prioritize accessibility, usability, and stakeholder needs [53]. User research (Chapter 3) highlighted older adults' preference for simple interfaces (63% reported difficulties, Figure 3.3), caregivers' need for real-time monitoring (87% prioritized continuous monitoring, Figure 3.13), and technical personnel's emphasis on interoperability (50% cited challenges, Figure 3.18). The UWDF incorporated these through an intuitive web interface, real-time visualization, and a modular ESP32S2 architecture. Usability testing (Section 6.3) showed 72.8% of technical personnel rated the interface as intuitive (4 or 5, Figure 6.11), with 91% approving the hardware setup (Figure 6.8). Functional testing (Section 6.2) confirmed 99.22% data capture reliability (Table 6.3) and a 408 ms response time (Table 6.4), meeting real-time needs.

7.1.3 Research Question 3: Platform-Level Strategies for Sensor Data Integration and Interoperability

RQ3: "What platform-level strategies best support sensor data integration, visualization, and secure interoperability among heterogeneous devices?"

Effective IoT platforms require modular architectures and secure protocols [47]. The UWDF uses an ESP32S2-based modular design with an I2C HUB for sensor integration (e.g., heart rate, temperature), achieving 99.22% data capture reliability (Table 6.3). Its web-based dashboard delivers real-time visualization with a 408 ms response time (Table 6.4), and AES-256 encryption ensures secure data transmission (Table 6.9). These address caregivers' monitoring demands (87% priority, Figure 3.13) and technical personnel's interoperability needs (50%, Figure 3.18). However, sensor compatibility limitations were noted by 82% of technical personnel (Figure 6.6), suggesting areas for improvement.

7.2 Relationship to Previous Work

This section positions the UWDF relative to existing IoT solutions in older adult healthcare, highlighting its contributions to human-centered design and technical performance.

7.2.1 Comparison with Existing Platforms

The UWDF builds on IoT wearable devices like smartwatches and fall detection pendants, which often use platforms such as AWS IoT and ThingsBoard [36]. AWS IoT prioritizes scalability but is critiqued for complex interfaces unsuitable for non-technical users [42], whereas UWDF's interface was rated intuitive by 72.8% of technical personnel (Figure 6.11). ThingsBoard supports interoperability via MQTT and CoAP but requires customization for non-technical users [42]; in contrast, UWDF's streamlined design and AES-encrypted controls address older adults' simplicity (63% reported interface difficulties, Figure 3.3) and privacy needs (41%, Figure 3.5). Unlike Teladoc Health, which focuses on telehealth with limited device interoperability, UWDF's modular design supports diverse wearables.

7.2.2 Contributions to the Field

The UWDF contributes to older adult healthcare IoT by integrating HCC principles with robust functionality. Its stakeholder-driven approach, informed by user research (Chapter 3), addresses accessibility and privacy gaps noted in prior work [36, 42]. The framework's modular architecture and secure APIs enhance interoperability, though sensor compatibility remains a challenge (82% of technical personnel, Figure 6.6), aligning with hardware limitations discussed by Sicari et al. [47]. These contributions, supported by usability and functional testing (Sections 6.2 and 6.3), position UWDF for further refinement.

7.3 Human-Centered Approach

This section details how the UWDF applies Human-Centered Computing (HCC) principles to meet stakeholder needs in older adult healthcare, as explored in RQ2 (Section 7.1.2). The UWDF's design process, described in Chapter 4, involved prototyping based on stakeholder feedback, though iterative design was limited (Section 7.5). The ESP32S2-based modular architecture supports accessible hardware setup, with 91% of technical personnel rating it highly (4, Figure 6.8). The web-based interface, refined through design-phase questionnaires, addresses older adults' need for simplicity, with 72.8% of technical personnel rating it intuitive (4 or 5, Figure 6.11). Functional testing (Section 6.2) demonstrated 99.22% data capture reliability (Table 6.3) and a 408 ms response time (Table 6.4), enabling real-time monitoring for caregivers, such as fall detection scenarios.

This approach aligns with HCC principles [53], emphasizing user-driven design. Unlike AWS IoT, critiqued for complex interfaces [36], UWDF prioritizes accessibility. However, evaluation feedback (Figure 6.6) noted sensor compatibility issues (82%) and UI responsiveness concerns (73%), consistent with Petrocchi's recommendations for continuous iteration [38].

7.4 Comparative Value

This section examines the UWDF's platform-level strategies for sensor data integration, visualization, and secure interoperability, as explored in RQ3 (Section 7.1.3). The UWDF's ESP32S2 architecture with an I2C HUB enables seamless sensor integration (e.g., heart rate, temperature), achieving 99.22% data capture reliability (Table 6.3). Its web-based dashboard provides real-time visualization with a 408 ms response time (Table 6.4), rated intuitive by 82% of technical personnel (Figure 6.11). Secure interoperability is ensured through AES-256 encrypted transmission (Table 6.9) and public APIs (e.g., GET /sensors/data, Table 6.10).

Compared to existing platforms (Table 6.1), UWDF's simple interface surpasses AWS IoT's developer-centric design [48]. ThingsBoard's complexity for non-technical users [42] contrasts with UWDF's streamlined approach, while Teladoc Health's focus on telehealth limits broader wearable support. However, sensor compatibility gaps (82% of technical personnel, Figure 6.6) highlight scalability needs, consistent with Sicari et al. [47].

7.5 Limitations

The UWDF, despite achieving 99.22% data capture reliability (Table 6.3), faces several limitations impacting its applicability in older adult healthcare. First, its reliance on Arduino and ESP32S2 boards restricts sensor compatibility, with 82% of technical personnel citing the need for broader device support (Figure 6.6). This is compounded by the limited number of sensors (2–3) used in functional testing (Section 6.2), which constrained the assessment of diverse sensor integration. Second, Wi-Fi-based data transmission degrades at extended distances, dropping to 87.33% success rate at 15 meters (Table 6.9), limiting use in large or remote settings. Third, UWDF supports only basic monitoring, lacking AI-driven analytics for predictive health insights. In addition, functional testing was conducted at a low polling rate (1 Hz) over a short duration (1 hour), limiting the evaluation of long-term reliability and scalability. Fourth, while early-stage needs assessment was conducted through interviews as part of the human-centered design (HCD) approach, iterative design based on user feedback was not performed due to time and resource constraints. Moreover, functional testing relied on manual logging and lacked advanced profiling tools, restricting the depth of performance and robustness analysis. Additionally, post-implementation usability testing (Section 6.3) was limited to technical personnel (n=11) and excluded older adults, restricting direct feedback on user experience for the primary target group. Furthermore, the literature review (Chapter 2) lacked detailed context about the application and testing of cited technologies, such as Chi et al.'s [11] textile-based ECG monitoring system, where specifics on testing scale and real-world adoption were not fully explored. This limited the ability to robustly support the motivation for designing IoT-based wearable devices tailored to older adult ecosystems, as highlighted by the need for user-centric and interoperable solutions.

These limitations align with challenges in the literature. Sicari et al. [47] note hardware dependence as a barrier to IoT scalability, mirroring UWDF's sensor compatibility issues and testing constraints. Chen et al. [7] emphasize AI's role in advanced healthcare IoT, highlighting UWDF's functional gap. The absence of iterative design and older adult testing, combined with simplified functional testing protocols, contrasts with Petrocchi's [38] advocacy for continuous user involvement to ensure adoption. These findings, informed by HCC's iterative approach and evaluation-phase feedback, guide future development priorities.

7.6 Future Work

To enhance the UWDF and address limitations outlined in Section 7.5, future work will integrate technical advancements with Human-Centered Computing (HCC)-driven research to ensure scalability and user inclusivity.

7.6.1 Technical Enhancements

Integrating platforms like Raspberry Pi will expand sensor compatibility, addressing concerns from 82% of technical personnel (Figure 6.6). This includes supporting a broader range of sensors beyond the 2–3 used in functional testing (Section 6.2), enabling comprehensive validation of diverse sensor integration. Adaptive communication protocols, such as LoRa or Zigbee, will improve transmission reliability beyond 10 meters, where success dropped to 87.33% at 15 meters (Table 6.9). To address the underdeveloped interoperability highlighted in Section 6.1.5, future work will incorporate universal standards like IEEE 11073 to enable seamless integration with diverse wearable sensors and healthcare systems, responding to technical personnel's concerns about interoperability challenges (50%, Figure 3.17). Additionally, increasing the polling rate beyond 1 Hz and extending test durations beyond 1 hour will enhance the evaluation of long-term reliability and scalability, addressing limitations in functional testing (Section 6.2). The introduction of automated profiling tools will replace manual logging, enabling deeper performance and robustness analysis. Additionally, sensor status management will be enhanced through automated diagnostic tools to monitor device battery levels and connectivity status, reducing older adults' uncertainty about device functionality (58%, Figure 3.17). Integrating machine learning for predictive analytics, as suggested by Chen et al. [7], will enable proactive health monitoring, addressing the current limitation of basic monitoring functions. A cloud-based architecture will enhance data management scalability for hospital settings, responding to needs identified in Section 6.1.

7.6.2 Human-Centered Computing-Driven Research

To fully realize the human-centered design (HCD) approach, iterative design cycles based on user feedback will be implemented, addressing the absence of this step due to resource constraints in the current study. Comprehensive usability testing with older adults and caregivers will validate accessibility and effectiveness, overcoming the limited testing scope with technical personnel (Section 6.3). This includes extending functional testing to involve older adults and caregivers, ensuring the prototype's reliability (99.22%, Table 6.3) and responsiveness (408 ms, Table 6.4) meet their real-world needs. A 6–12-month longitudinal study, as recommended by Petrocchi [38], will assess long-term usability and adoption, ensuring cultural inclusivity per Tun et al. [53]. Interface responsiveness, cited as a concern by 73% of technical personnel (Figure 6.6), will be refined through diverse user studies. Additionally, future work will address the literature review's limitations by conducting a more comprehensive analysis of cited studies, such as Chi et al. [11], to include detailed testing contexts (e.g., participant numbers, prototype vs. real-world deployment) and outcomes. This will strengthen the evidence supporting the need for user-centric IoT ecosystems tailored to older adults, ensuring alignment with HCC principles and stakeholder needs.

Chapter 8

Conclusion

This chapter summarizes the key findings, contributions, and implications of the study, focusing on the Unified Wearable Device Framework (UWDF) and its potential impact in the field of older adult healthcare.

8.1 Summary of Findings

The UWDF, developed with a human-centered approach, addresses the requirements of various stakeholders, including older adult users, caregivers, healthcare professionals, and developers, through its intuitive interface, modular architecture, and real-time monitoring capabilities. Early-stage needs assessment through interviews (Chapter 3) informed the design, ensuring alignment with stakeholder needs, such as simplicity for older adults (Figure 3.3) and real-time monitoring for caregivers (Figure 3.13). Functional testing (Section 6.2) demonstrated 99.22% data reliability and a 408 ms response time (Table 6.4).

However, due to resource constraints, iterative design based on user feedback was not conducted, and usability testing (Section 6.3) was limited to technical personnel (n=11), excluding older adults and caregivers. These limitations indicate that, despite positive technical performance (Section 6.2), further validation with primary users is needed. The platform's reliance on ESP32S2 boards also limits sensor compatibility, and network reliability challenges in remote settings remain, as noted in Section 7.5, indicating areas for future improvement.

8.2 Contributions

The UWDF platform contributes to IoT solutions for older adult healthcare through its human-centered design and continuous data monitoring. This design facilitates accessibility and usability for older adult users, addressing key barriers such as interface complexity and privacy concerns, as validated by stakeholder feedback. Additionally, the modular architecture allows for greater flexibility and scalability, enabling the system to adapt to a wide range of use cases and hardware configurations.

The platform also provides real-time health monitoring capabilities, which provide caregivers and healthcare professionals with timely data on the health status of older adult users. These contributions are rooted in the feedback gathered from a diverse group of stakeholders, which guided the design and development of the platform.

8.3 Final Thoughts

In conclusion, the UWDF platform establishes a foundation for supporting IoT healthcare solutions for older adults. By addressing the diverse needs of its stakeholders through its human-centered design and real-time monitoring, it provides a solid foundation for further research and development. While limitations persist, the platform's design and the insights gained from the user study and evaluation phase provide clear guidance for future research, such as enhanced sensor compatibility and AI integration, enabling the system to evolve to meet the growing demands of older adult care.

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Appendix A

Ethics Approval

This appendix contains the ethics approval letters for two studies: the qualitative study for user requirements gathering, described in Section 3.1, and the usability testing study for platform evaluation, described in Section 6.3.

The University of Waikato
Private Bag 3105
Hamilton, New Zealand, 3240
0800 WAIKATO (924 528)

HECS Human Ethics Committee
Brett Langley
Telephone +64 77 838 4060
Hecs-ethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

31 October 2024

Yigang Shi

Jemma König

**Re: HECS Ethics Approval of Application HREC(HECS)2024#56 "Unified Wearable Device Framework (UWDF) User Study
"**

Dear Yigang:

Thank you for submitting your amended application HREC(HECS)2024#56 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of up to 50 participants for an online or paper-based survey. Participants will be from New Zealand and China, who will be information and technology or computer science technicians, students, and/or users of IoT wearable platforms.
- Conduct survey, which will will focus on the participants' understanding, concerns and experiences with wearable devices that they have used, including the functions, user interface, usage habits, pros and cons of different IoT wearable platforms, as well as their evaluation and expectations for a universal IoT wearable framework. Questions will also ask about the participants' technical background and work experience.
- The survey will take less than one hour to complete.

Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Kind regards,

BLangley

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato

The University of Waikato
Private Bag 3105
Hamilton, New Zealand, 3240
0800 WAIKATO (924 528)

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

24 January 2025

Yigang Shi

Jemma König

Re: HECS Ethics Approval of Application HREC(HECS)2025#02 “Unified Wearable Device Framework (UWDF) User Study-Usability Evaluation”

Dear Yigang:

Thank you for submitting your application HREC(HECS)2025#02 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of up to 10 participants from China and New Zealand for a study that evaluates the usability of UWDF platform, with a particular emphasis on its prototype implementation, user interface, and system performance.
- Have participants evaluate the platform's interface, setting up hardware, integrating sensors, and complete a survey. The survey will assess their experiences with the platform.

Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato

Appendix B

Survey Questionnaire

This appendix contains the fully formatted survey questionnaire used in the user behavior and needs study, described in Section 3.1, and the usability testing study for platform evaluation, described in Section 6.3.

UWDF User Study Survey (for Older Adults) UWDF用户研究调查（针对老年人）

* Required

We value your privacy. 我们重视您的隐私。

Your personal information will be securely stored and used solely for the purpose of this survey. It will not be disclosed to any external party. 您的个人信息将被安全存储，仅用于本次调查目的。不会向任何外部方披露。

1. Participant Information Sheet and Research Consent Form 参与者信息表和研究同意书 *

○ Please check this box to indicate that you have read and agree to the content of the Participant Information Sheet and Research Consent Form 请阅读参与者信息表和研究同意书，然后勾选此框，表示您已阅读并同意其中的内容 (https://waikatouniversitynz-my.sharepoint.com/:w:/g/personal/jemma_konig_waikato_ac_nz/EcGje1YsjpRNiFDrpvTqublBtFYebeBSmFa_1kvhZBSaQw?e=gVq1Bg).

2. Name 姓名 *

3. Age 年龄（65岁以上) *

Please enter a number greater than 65

4. Job title 职业 *

5. Contact Information 联系方式

Questionnaire 调查问卷

6. Which of the following electronic products and wearable devices are you currently using? (Select all that apply) 您目前正在使用以下哪些电子产品和可穿戴设备？（可多选）

☐ Smartphones 智能手机

☐ Smartwatches 智能手表

☐ Fitness trackers 健身追踪器

☐ Blood pressure monitors 血压监测仪

☐ Other

7. What conveniences have you experienced while using these devices?(Select all that apply) 您在使用这些设备时体验到哪些便利？（可多选）

☐ Easier health monitoring 更便捷的健康监测

☐ Improved safety/security 提高了安全性

☐ Better communication 更好的沟通

☐ Other

8. What inconveniences have you experienced while using these devices? (Select all that apply) 您在使用这些设备时遇到过哪些不便？（可多选）

☐ Difficulty understanding the interface 难以理解界面

☐ Frequent technical issues 经常出现技术问题

☐ Concerns about data security 对数据安全的担忧

☐ Other

9. What health difficulties do you think wearable devices could help with in daily life? (Select all that apply) 您认为可穿戴设备可以帮助解决日常生活中的哪些健康困难？（可多选）

☐ Mobility issues 行动问题

☐ Memory problems 记忆问题

☐ Managing medications 药物管理

☐ Other

10. Have you used or been aware of wearable devices that address the following issues? (Select all that apply) 您是否使用过或了解过解决以下问题的可穿戴设备？（可多选）

☐ Health monitoring 健康监测

☐ Medication reminders 服药提醒

☐ Fall detection 跌倒检测

☐ Other

11. How would you prefer to manage and control your personal health data? (Select all that apply) 您更倾向于如何管理和控制您的个人健康数据？（可多选）

☐ I would like to manage it myself 我想自己管理

☐ I prefer a family member to manage it 我更喜欢由家庭成员管理

☐ I prefer my healthcare provider to manage it 我更喜欢由医疗服务提供者管理

☐ Other

12. Who would you like to share your health data with? (Select all that apply) 您愿意与谁共享您的健康数据？（可多选）

☐ Family members 家庭成员

☐ Healthcare professionals 医疗专业人员

☐ Caregivers 照护人员

☐ No one 不想共享

☐ Other

13. How concerned are you about data security and privacy when using wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Concerned, 5 = Very Concerned) 在使用可穿戴设备时，您对数据安全和隐私的担忧程度如何？（1-5分，1=不担心，5=非常担心）

☆ ☆ ☆ ☆ ☆

UWDF User Study Survey (for Caregiver) UWDF户研究调查（针对照护者）

* Required

We value your privacy. 我们重视您的隐私。

Your personal information will be securely stored and used solely for the purpose of this survey. It will not be disclosed to any external party. 您的个人信息将被安全存储，仅用于本次调查目的。不会向任何外部方披露。

1. Participant Information Sheet and Research Consent Form 参与者信息表和研究同意书 *

○ Please check this box to indicate that you have read and agree to the content of the Participant Information Sheet and Research Consent Form 请阅读参与者信息表和研究同意书，然后勾选此框，表示您已阅读并同意其中的内容 (https://waikatouniversitynz-my.sharepoint.com/:w:/g/personal/jemma_konig_waikato_ac_nz/EcGje1YsjpRNiFDrpvTqubIBtFYebeBSmFa_1kvhZBSaQw?e=gVq1Bg).

2. Name 姓名 *

3. Age 年龄（10~80岁之间) *

Number must be between 10 ~ 80

4. Job title 职务 *

5. Contact information 联系方式

6. What factors do you think influence older adults' willingness to use IoT-based wearable devices? (Select all that apply) 您认为哪些因素会影响老年人使用可穿戴设备的意愿？（可多选）

☐ Ease of use 易用性

☐ Trust in technology 对技术的信任

☐ Cost 成本

☐ Recommendation from healthcare professionals 医疗专业人员的推荐

☐ Other

7. What information would you like to obtain about the older adults' health through wearable devices? (Select all that apply) 您希望通过可穿戴设备获取老年人哪些健康信息？（可多选）

☐ Heart rate 心率

☐ Daily activity level 日常活动水平

☐ Sleep patterns 睡眠模式

☐ Fall alerts 跌倒警报

☐ Other

8. How do you think wearable devices can help you care for older adults? (Select all that apply) 您认为可穿戴设备如何能帮助您照顾老年人？（可多选）

☐ Providing real-time health updates 提供实时健康更新

☐ Monitoring daily activities 监测日常活动

☐ Sending alerts in case of emergencies 发送紧急情况警报

☐ Other

9. What features would you like wearable devices to have? (Select all that apply) 您希望可穿戴设备具有哪些功能？（可多选）

☐ Remote health monitoring 远程健康监测

☐ Simple interface for older adults use 适合老年人使用的简单界面

☐ Automatic emergency alerts 自动紧急警报

☐ Other

10. What problems have you encountered with existing older adults physiological monitoring devices orplatforms? (Select all that apply) 您在使用现有的老年人生理监测设备或平台时遇到过哪些问题？（可多选）

☐ Inaccurate data 数据不准确

☐ Difficulty setting up the device 设备设置困难

☐ Limited features 功能有限

☐ Other

UWDF User Study Survey for Healthcare Professional UWDF用户研究调查-针对医疗专业人员

* Required

We value your privacy. 我们重视您的隐私。

Your personal information will be securely stored and used solely for the purpose of this survey. It will not be disclosed to any external party. 您的个人信息将被安全存储，仅用于本次调查目的。不会向任何外部方披露。

1. Participant Information Sheet and Research Consent Form 参与者信息表和研究同意书 *

○ Please check this box to indicate that you have read and agree to the content of the Participant Information Sheet and Research Consent Form 请阅读参与者信息表和研究同意书，然后勾选此框，表示您已阅读并同意其中的内容 (https://waikatouniversitynz-my.sharepoint.com/:w:/g/personal/jemma_konig_waikato_ac_nz/EcGje1YsjpRNiFDrpvTqubIBtFYebeBSmFa_1kvhZBSaQw?e=gVq1Bg).

2. Name 姓名 *

3. Age 年龄（10~80岁之间) *

Number must be between 10 ~ 80

4. Job title 职务 *

5. Contact information 联系方式

Questionnaire 调查问卷

6. How do you think wearable devices can be applied to older adults health management and chronic disease prevention? (Select all that apply) 您认为可穿戴设备如何应用于老年人健康管理和慢性病预防?

☐ Continuous monitoring of vital signs 持续监测生命体征

☐ Early detection of health issues 早期发现健康问题

☐ Assistance with medication management 协助药物管理

☐ Other

7. What data would you like to obtain from wearable devices to assist in diagnosis and treatment? (Select all that apply) 您希望从可穿戴设备中获取哪些数据来辅助诊断和治疗?（可多选）

☐ Blood pressure 血压

☐ Blood glucose levels 血糖水平

☐ Heart rate variability 心率变异性

☐ Sleep quality 睡眠质量

☐ Other

8. What inconveniences have you experienced while using these devices? (Select all that apply) 您在使用这些设备时遇到过哪些不便? （可多选）

☐ Unauthorized access to patient data 未经授权访问患者数据

☐ Lack of transparency in data usage 数据使用缺乏透明度

☐ Ethical concerns in data sharing 数据共享的伦理问题

☐ Other

UWDF User Study Survey (for Technicians) UWDF用户研究调查（针对技术人员）

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2. Name 姓名 *

3. Age 年龄（10~80岁之间) *

Number must be between 10 ~ 80

4. Job title 职务 *

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Questionnaire

6. How many years of work experience do you have in developing IoT-based wearable devices? 您在开发基于物联网的可穿戴设备方面有多少年工作经验?

○ Less than 1 year 不到1年

○ 1-3 years 1-3年

○ 3-5 years 3-5年

○ 5-10 years 5-10年

○ More than 10 years 超过10年

7. What is your primary role in IoT wearable device projects? (Select all that apply) 您在物联网可穿戴设备项目中的主要角色是什么？（可多选）

☐ Software engineer 软件工程师

☐ Hardware engineer 硬件工程师

☐ Data scientist 数据科学家

☐ Project manager 项目经理

☐ System architect 系统架构师

☐ Other

8. Which stage(s) of IoT wearable device development have you been involved in? (Select all that apply) 您参与过物联网可穿戴设备开发的哪些阶段？（可多选）

☐ Concept development 概念开发

☐ System architecture design 系统架构设计

☐ Software development 软件开发

☐ Hardware development 硬件开发

☐ Data analysis and integration 数据分析和集成

☐ Testing and validation 测试和验证

☐ Other

9. What types of IoT platforms do you have experience working with? (Select all that apply) 您有使用过哪些类型的物联网平台？（可多选）

☐ Cloud-based platforms (e.g., AWS IoT, Microsoft Azure IoT) 基于云的平台

☐ Edge computing platforms 边缘计算平台

☐ Proprietary IoT platforms 专有物联网平台

☐ Open-source IoT frameworks 开源物联网框架

☐ Other

10. What challenges have you encountered while developing IoT wearable devices? (Select all that apply) 您在开发物联网可穿戴设备时遇到过哪些挑战？（可多选）

☐ Interoperability issues with different devices 不同设备的互操作性问题

☐ Limited processing power in wearables 可穿戴设备处理能力有限

☐ Ensuring data privacy and security 确保数据隐私和安全

☐ Difficulty in managing large amounts of data 管理大量数据的困难

☐ Integration with healthcare systems 与医疗系统的集成

☐ Other

11. What improvements would you like to see in existing IoT wearable device platforms? (Select all that apply) 您希望在现有物联网可穿戴设备平台中看到哪些改进？（可多选）

☐ Improved data management and analytics tools 改进的数据管理和分析工具

☐ Enhanced device interoperability 增强的设备互操作性

☐ Better security features 更好的安全功能

☐ More customizable user interfaces 更多可定制的用户界面

☐ Support for machine learning and AI 支持机器学习和人工智能

☐ Other

12. What features would you prioritize in the development of a universal IoT wearable framework like UWDF? (Select all that apply) 在开发像UWDF这样的通用物联网可穿戴框架时，您会优先考虑哪些功能？（可多选）

☐ Modular design for easy customization 便于定制的模块化设计

☐ Enhanced data privacy and user control 增强的数据隐私和用户控制

☐ Cross-platform and device compatibility 跨平台和设备兼容性

☐ Real-time monitoring and data analytics 实时监测和数据分析

☐ Integration with healthcare services 与医疗服务的集成

☐ Other

13. What applications would you develop on the UWDF platform? (Select all that apply) 您会在UWDF平台上开发什么应用？（可多选）

☐ Health monitoring apps 健康监测应用

☐ Chronic disease management systems 慢性病管理系统

☐ Older adults care solutions 老年人护理解决方案

☐ Remote healthcare platforms 远程医疗平台

☐ Data visualization tools 数据可视化工具

☐ Other

14. What factors would influence your decision to adopt a new IoT platform for wearable device development? (Select all that apply) 哪些因素会影响您采用新的物联网平台进行可穿戴设备开发的决定？（可多选）

☐ Technical support and documentation 技术支持和文档

☐ Flexibility and customization options 灵活性和定制选项

☐ Cost-effectiveness 成本效益

☐ User community and third-party integrations 用户社区和第三方集成

☐ Compliance with industry standards (e.g., HIPAA, GDPR) 符合行业标准

☐ Other

15. Question: Based on your experience and expectations, what operation success rate do you believe a high-quality platform should achieve? Please enter a percentage value(%). Operation success rate refers to the proportion of users successfully completing intended operations on the platform. 根据您的经验和期望，您认为一个高质量的平台应该达到怎样的操作成功率？请填写一个百分比数值（%）。操作成功率指的是用户在平台上成功完成预期操作的比例。

    Number must be between 0 ~ 100

16. As a potential user, what level of satisfaction do you expect regarding the platform's technical usability (e.g., ease of use, response time, stability)? Please enter a percentage value (%). Technical usability satisfaction refers to the user's level of satisfaction with the technical aspects of their experience using the platform. 作为潜在用户，您对平台的技术可用性（如易用性、响应速度、稳定性等）的满意度期望是多少？请填写一个百分比数值（%）。技术可用性满意度指的是用户对平台技术层面使用体验的满意程度。

    Number must be between 0 ~ 100

17. How important is the feature of Data security and encryption when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important) 在选择物联网平台用于可穿戴设备时，数据安全和加密功能的重要性如何？（1-5分，1=不重要，5=非常重要）

    ☆ ☆ ☆ ☆ ☆

18. How important is the feature of Scalability when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important) 在选择物联网平台用于可穿戴设备时，可扩展性功能的重要性如何？（1-5分，1=不重要，5=非常重要）

    ☆ ☆ ☆ ☆ ☆

19. How important is the feature of Ease of integration with other systems when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important) 在选择物联网平台用于可穿戴设备时，与其他系统易于集成的功能重要性如何？（1-5分，1=不重要，5=非常重要）

    ☆ ☆ ☆ ☆ ☆

20. How important is the feature of User-friendly interface when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important) 在选择物联网平台用于可穿戴设备时，用户友好界面的重要性如何？（1-5分，1=不重要，5=非常重要）

    ☆ ☆ ☆ ☆ ☆

21. How important is the feature of Support for real-time data processing when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important) 在选择物联网平台用于可穿戴设备时，支持实时数据处理的功能重要性如何？（1-5分，1=不重要，5=非常重要）

    ☆ ☆ ☆ ☆ ☆

22. How important is the feature of Cross-device compatibility when selecting an IoT platform for wearable devices? (Rate on a scale of 1 to 5, where 1 = Not Important, 5 = Very Important) 在选择物联网平台用于可穿戴设备时，跨设备兼容性的重要性如何？（1-5分，1=不重要，5=非常重要）

☆ ☆ ☆ ☆ ☆

UWDF User Study-Usability Evaluation

* Required

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2. Name *

3. Age (between 18~80) *

Number must be between 18 ~ 80

4. Job title *

5. Contact information

Questionnaire

6. What improvements would you suggest enhancing the platform’s usability? (Select all that apply)

☐ More user-friendly interface design

☐ Enhanced real-time data monitoring tools

☐ Additional debugging and testing utilities

☐ Comprehensive operation guides

☐ Other

7. Which tools or features would be most helpful for usability testing? (Select all that apply)

☐ Real-time performance monitoring tools

☐ Visual debugging tools for data handling

☐ User behavior simulation systems

☐ Automated testing script support

☐ Other

8. which of the following metrics would you consider most important for evaluating the UWDF platform? (Select all that apply)

☐ Time required for hardware setup

☐ Time required to configure new sensors

☐ Error rates during sensor integration or data handling

☐ User interface (UI) navigation time and success rate

☐ Real-time data accuracy and consistency

☐ Other

9. Which of the following areas need the most improvement during your work with UWDF? (Select all that apply)

   ☐ Clarity of setup instructions

   ☐ Compatibility with additional sensors

   ☐ Responsiveness and reliability of the user interface

   ☐ Transparency of error messages and debugging tools

   ☐ Security and privacy handling during test scenarios

   ☐ Other

10. What additional tools or resources would help improve your efficiency? (Select all that apply)

    ☐ Pre-configured testing scenarios or presets

    ☐ Advanced debugging tools for sensor data issues

    ☐ Real-time logging and visualization of platform performance

    ☐ Step-by-step guides or tutorials tailored to testing procedures

    ☐ Other

11. How would you rate the usability of the Ease of Hardware Setup in the UWDF platform? (1 = Poor, 5 = Excellent)

    ☆ ☆ ☆ ☆ ☆

12. How would you rate the usability of the Flexibility in Integrating New Sensors in the UWDF platform? (1 = Poor, 5 = Excellent)

    ☆ ☆ ☆ ☆ ☆

13. How would you rate the usability of the Efficiency of Data Processing and Transmission in the UWDF platform? (1 = Poor, 5 = Excellent)

    ☆ ☆ ☆ ☆ ☆

14. How would you rate the usability of the Intuitiveness of the User Interface (UI) in the UWDF platform? (1 = Poor, 5 = Excellent)

    ☆ ☆ ☆ ☆ ☆

15. How would you rate the usability of the Functionality of Access Control and Data Security in the UWDF platform? (1 = Poor, 5 = Excellent)

    ☆ ☆ ☆ ☆ ☆

16. To what extent does the platform's user interface meet the needs of technicians? (Rate on a scale of 1 to 5, where 1 = Not Effective and 5 = Highly Effective)

☆ ☆ ☆ ☆ ☆

17. How effective is the UWDF platform in providing feedback during usability testing? (Rate on a scale of 1 to 5, where 1 = Not Effective and 5 = Highly Effective)

☆ ☆ ☆ ☆ ☆

18. How intuitive was it to use the web-based interface to manage sensor activation, user accounts and remote user authorization? (1=Not Intuitive, 5=Very Intuitive)

☆ ☆ ☆ ☆ ☆

19. How confident are you in the security measures implemented for data transmission and storage? (1=Not Confident, 5=Very Confident)

☆ ☆ ☆ ☆ ☆

20. How would you rate the interoperability of the UWDF platform with different devices or systems you tested (e.g. sensors, laptops, external client apps)? (1 = Very Poor Interoperability, 5 = Excellent Interoperability).

☆ ☆ ☆ ☆ ☆