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Inclusive Monitoring in Dementia: Progress Towards a Wrist Wearable Based Solution

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Abstract

INTRODUCTION: The rapidly aging global population presents significant challenges, particularly in managing neurodegenerative diseases such as dementia. Addressing these challenges requires innovative solutions that ensure continuous care and monitoring of elderly individuals. Wearable technology offers a path to more inclusive and efficient care for older adults living with cognitive decline.
OBJECTIVES: This paper presents the design, development, and refinement of an integrated wrist-worn wearable system to support the monitoring and care of elderly people living with dementia, expanding a previous proof of concept into a compact and energy-efficient prototype optimized for real-world usability.
METHODS: The proposed system integrates advanced sensor technologies. It includes optical (MAX30101), inertial (BMI270), and GNSS (CAM-M10Q) sensors for monitor heart rate, blood oxygen levels, motion, and location. Data are transmitted via Bluetooth Low Energy (BLE) for indoor communication and LoRa for outdoor connectivity. A custom 4×4 cm PCB was designed to consolidate all components—microcontroller, sensors, power efficiency, communication modules, and display—into a single compact and robust layout. The design process also emphasized ergonomic comfort and usability through iterative prototyping and 3D modelling.
RESULTS: The refined prototype significantly reduced the physical dimensions compared with the original proof of concept, while improving power efficiency, mechanical stability, and user comfort. The device layout and button interface were optimized to ensure intuitive interaction and safe daily use by elderly individuals.
CONCLUSION: The developed prototype establishes the foundation for a fully functional, energy-efficient wearable system tailored to dementia monitoring. Future work will include firmware optimization, extended functional validation, and the integration of intelligent analytics for behaviour recognition and anomaly detection, aiming to provide caregivers with timely and actionable health insights.

Keywords: Wearable Devices, Dementia, Health Technology, Digitalization, Industry 4.0.

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1. Introduction

The global increase in the elderly population has become a significant demographic phenomenon. According to projections by the World Health Organization, by 2030, one in six individuals will be aged sixty or older, and this figure is expected to double by 2050 [1]. This demographic transition is primarily attributed to improvements in living conditions and longer life expectancy. However, aging remains the major risk factor for neurodegenerative diseases, whose prevalence has increased in recent decades. Among these, dementia, caused by the progressive degeneration of cognitive functions, poses a serious risk to individuals in advanced age [2]. As described in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), dementia, or "Major Neurocognitive Disorder" is a clinical syndrome characterized by a gradual decline in cognitive abilities, affecting multiple domains such as memory, executive functioning, language, learning capacity, perceptual-motor skills, and social cognition [3]. The progressive loss of autonomy typically leads individuals to rely on both formal and informal caregivers at early stages of the disease, which impairs their capacity to perform basic daily tasks [4][5]. Recent advances in digital health technologies have opened new possibilities for disease diagnosis and continuous monitoring, promoting safer and more efficient care[6]. In the context of dementia, continuous monitoring systems have shown great potential for tracking daily activities and supporting timely interventions by caregivers [7][6]. This study is part of a broader initiative aimed at developing and validating a new system for location and activity monitoring, promoting active and inclusive aging. The project employs a human-centered design approach to address the specific needs of individuals with dementia and their caregivers.

The proposed solution includes two wearable data acquisition devices: an in-ear device [8] and a wristband, represented in Fig. 1. These devices are designed to measure physiological parameters such as body temperature, heart rate, blood oxygen saturation, as well as information on both indoor and outdoor location. Data are transmitted to a central server for processing and visualization through a web portal accessible to healthcare professionals and caregivers, facilitating personalized care decisions.

This article extends a published paper [9], where an initial proof of concept was introduced and validated. The current version significantly expands that work by presenting hardware refinements and a custom PCB prototype that enhance both usability and energy efficiency.

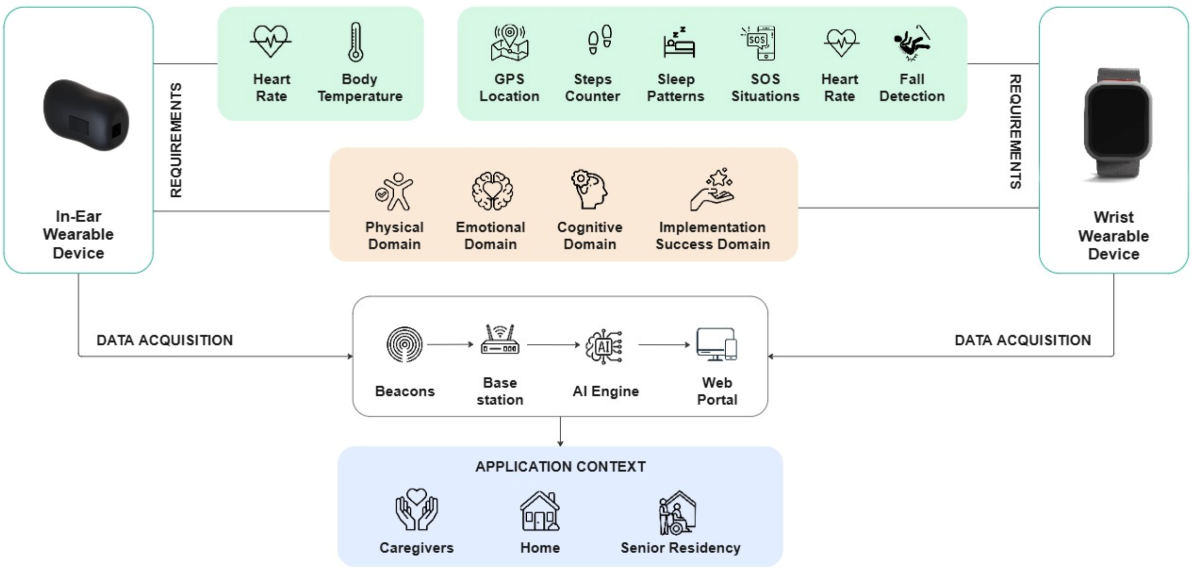

Figure 1. Platform for routine measurement and monitoring overview

This paper is organized in 5 sections. The Section 2, "Methodology", describes the approaches and techniques adopted to guide the design of the system, including the identification of functional requirements, hardware integration, data acquisition, and communication protocols. Section 3, "Development of the Initial Proof of Concept", summarizes the first prototype described in a previous paper and outlines its validation. Section 4, "System Refinement and Current Implementation Progress", presents the most recent developments, including the selection of new components, the design of a custom PCB and improvements in energy efficiency and usability. Finally, Section 5, "Final Remarks", discusses the next steps toward functional testing, firmware optimization, and real-world validation of the proposed solution.

2. Methodology

This study adopted an iterative, user-centered design approach focused on elderly users to develop a wearable monitoring device emphasizing safety, efficiency, and usability. The process involved the integrated development of hardware and software components, along with the ergonomic design of the device's physical structure.

2.1. Product Design

In developing the monitoring system, both functional and non-functional requirements were defined as the foundation for designing a wearable device tailored to the needs of older adults with dementia, as summarized in Table 1.

Functional requirements specify the core capabilities of the system, ensuring the device can effectively monitor physiological and behavioural parameters relevant to dementia care. In contrast, non-functional requirements address the aesthetic, physical, and emotional dimensions of design, fostering user engagement through an empathetic and user-centered approach[7]. The wrist was selected as the most suitable placement for the device, as it provides a minimally intrusive location and a stable site for physiological monitoring due to its proximity to superficial blood vessels and limited range of motion. Each measurable parameter was therefore analyzed to ensure optimal sensor placement and signal reliability. For example, heart rate monitoring requires the sensor to be in direct contact with the skin, and the wrist provides a suitable surface to capture accurate readings. To determine the most appropriate form factor, commercially available wearable designs were systematically reviewed to identify their advantages and limitations. Considering the target users are elderly individuals with dementia, physical design elements play a crucial role in ensuring user acceptance and comfort [10]. In addition, studying the anatomical structure of the wrist was essential to ensure proper sensor placement, enabling reliable data collection without interference. Anatomical variations in wrist size and shape were also accounted for, enabling a design adaptable to a wide range of users.

Following this analysis, three-dimensional models of the device were created using SolidWorks [11]. These designs were then validated through rapid prototyping based on Fused Deposition Modelling (FDM) 3D printing.

Table 1. Functional and non-functional requirements of wearable devices for elderly with dementia.

Requirement Typology	Description	
	Category	Requirement
Functional Requirements	Hardware / Software	Real-time location Steps counting Fall detection Sleep monitoring SOS situation Heart rate measurement Oxygen saturation
Non-Functional Requirements	Physical Domain	Comfort Durability Tangibility Visibility
	Emotional Domain	Aesthetics Equitable use Autonomy Customization Usability
	Implementation Success Domain	Reliability Context Price

2.2. Hardware

The developed wrist-worn device integrates multiple non-invasive sensors to capture biological, positional, and motion-related parameters, including heart rate (HR), blood oxygen saturation (SpO_2), geolocation, acceleration, and angular velocity. These sensors collectively enable continuous monitoring of the user's physiological and behavioural state, providing reliable insights into health status and its evolution over time. The overall system architecture is illustrated in Fig. 2, which outlines the integration of all hardware components described in the subsequent sections.

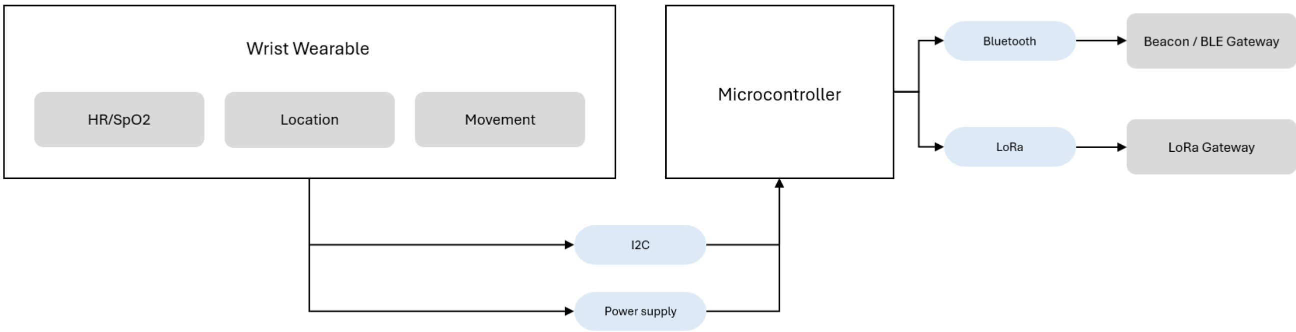

Figure 2. Wrist wearable device architecture

2.3. Data Acquisition

Data acquisition constitutes a crucial phase in which the wearable sensors are evaluated to ensure the accuracy and reliability of the physiological and motion data collected. Reflective pulse oximetry employs light-emitting diodes (LEDs) to project light onto the skin, while a photodiode captures the portion reflected by underlying tissue.
This reflected signal encodes variations in blood volume within the arteries and capillaries, producing a photoplethysmographic (PPG) waveform composed of two components: a direct current (DC) component, corresponding to constant absorption by static tissue, and an alternating current (AC) component, representing the pulsatile nature of arterial flow.
Instantaneous heart rate is subsequently derived from the interval between consecutive systolic peaks extracted from the green-light signal. The overall process is illustrated in Fig. 3.

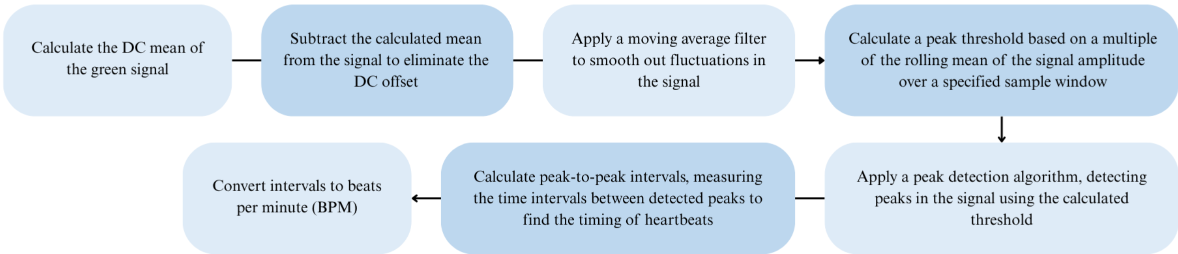

Figure 3. Flowchart of heart rate calculation

The estimation of blood oxygen saturation (SpO_2) is performed using both red (RED) and infrared (IR) photoplethysmographic waveforms, following the algorithm described in [12]. The DC and AC components are first extracted from each signal, after which the normalized ratio (R) between the RED and IR channels is computed.

This ratio, defined in equation (1), reflects the differential absorption of light by oxygenated and deoxygenated hemoglobin, forming the physiological basis for SpO_2 estimation within the PPG sensor.

$$R = \frac{AC_{red}/DC_{red}}{AC_{ir}/DC_{ir}} \quad (1)$$

Here, *ACred* and *DCred* denote the alternating and direct current components of the red signal, respectively, while *ACir* and *DCir* correspond to those of the infrared signal. The ratio *R*, obtained from these components, is subsequently employed to estimate the blood oxygen saturation (SpO_2) through an empirical calibration process, typically implemented via a lookup table or a curvilinear approximation [12]. The complete calibration procedure is expressed in equation (2).

$$SpO2 = 1.5958422 \times R^2 - 34.6596622 \times R + 112.6898759 \quad (2)$$

The implementation of the SpO_2 calculation follows the algorithm integrated in the manufacturer's software library, whose main processing steps are illustrated in Fig. 4.

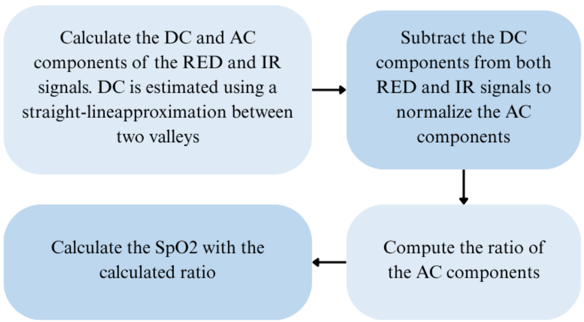

Figure 4. Flowchart of SpO2 calculation

The positioning data, illustrated in Figure 5, are obtained directly from the module's internal memory registers as it processes Global Navigation Satellite System (GNSS) signals. This embedded processing enables the device to deliver high-accuracy location information suitable for real-time monitoring, while requiring only minimal post-processing for standard applications.

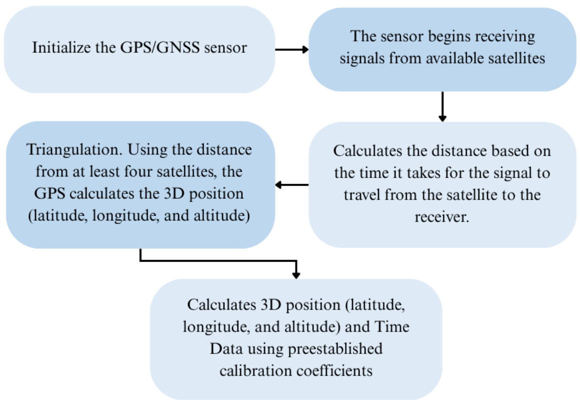

Figure 5. Flowchart of GPS data acquisition

The motion and orientation data, illustrated in Figure 6, are obtained directly from the sensor's internal memory registers, as the device is pre-calibrated to ensure high-accuracy measurements under dynamic conditions. This configuration enables reliable motion tracking and requires only minimal post-processing to transform raw outputs into meaningful activity metrics.

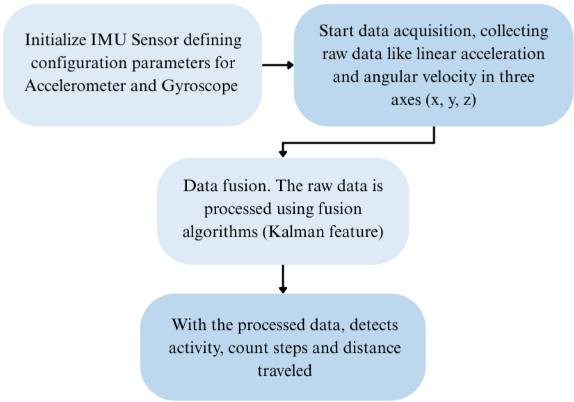

Figure 6. Flowchart of inertial data acquisition

2.4. Communication Protocol

To facilitate wireless communication, two complementary protocols were adopted: Bluetooth Low Energy (BLE) for indoor environments and LoRa (Long Range) for outdoor scenarios. BLE was selected for its low power consumption and efficiency over short distances, enabling seamless data transfer between the wearable device and nearby receivers, such as smartphones or local gateways.

In contrast, LoRa (Long Range) was integrated to support long-distance data transmission while minimal energy demand, providing extensive coverage across both urban and open areas. This dual-protocol configuration ensures continuous and reliable real-time data transmission of physiological and positional information, even in the absence of BLE connectivity, while preserving the device's overall energy efficiency.

3. Development of an initial proof of concept

This section presents the development of the initial proof of concept for a wearable device aimed at monitoring individuals with dementia. The primary goal of this phase was to design and validate a functional prototype that demonstrated the technical feasibility of the proposed system. The work focused on three main aspects: the creation of an ergonomic design suitable for continuous use, the integration of essential sensors for physiological and motion data collection, and the preliminary implementation of wireless communication protocols to enable reliable data transmission. Furthermore, initial strategies for power management and data acquisition were examined to improve efficiency and operational safety, establishing the groundwork for subsequent optimization in later development stages.

Specifically, the following section outlines the key results and technical basis reported in the previous study [9], which provided the foundation for the refinements described in Section 4.

3.1. Hardware

The initial proof of concept was developed using a selection of compact, low-power components specifically optimized for wearable applications. The selection of sensors was guided by two main criteria: minimal power consumption to extend battery life and suitability for continuous operation in small, body-worn devices. The primary goal at this stage was to integrate these essential sensing and communication capabilities into a functional prototype capable of demonstrating the feasibility of continuous physiological and positional monitoring in elderly individuals with dementia. The key hardware components used in this initial prototype are described below:

The MAX30101 and MAX32664 sensors [13] [14] employs photoplethysmography (PPG) to measure heart rate and peripheral oxygen saturation (SpO_2). It integrates red and infrared LEDs, photodetectors, optical components, and ambient light cancellation within a compact package (5.6 × 3.3 × 1.55 mm). Designed for ultra-low power consumption, this sensor is optimized for continuous operation in wearable health monitoring applications.
The SAM-M10Q Global Navigation Satellite System (GNSS) module [15] provides precise positioning data through an integrated antenna and low-power architecture. Its compact size (15.5 × 15.5 × 6.3 mm) and high reliability under obstructed signal conditions make it suitable for portable systems requiring accurate geolocation.

The Inertial Measurement Unit (IMU) selected for the prototype, the BMI270 [16], is a high-performance, ultra-low-power sensor that combines a 3-axis accelerometer and a 3-axis gyroscope. Supporting both I²C and SPI communication protocols, it enables flexible system integration. Its small footprint (2.5 × 3.0 × 0.8 mm) and efficiency make it particularly well-suited for wearable and consumer electronic devices.
Data processing and wireless communication —via Bluetooth and LoRa— are managed by the Heltec Wi-Fi LoRa 32 development board [17] , incorporating the ESP32-S3FN8 microcontroller [18]. This board (44 × 30.5 × 6.8 mm) integrates multiple connectivity options and offers an energy-efficient platform for mobile and wearable health applications.

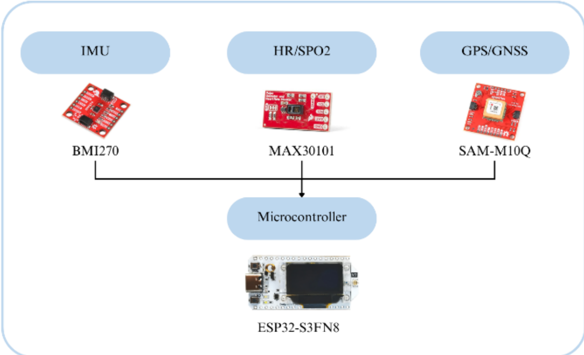

Figure 7. Main components of the proof of concept developed.

Following the selection and evaluation of the hardware components, a functional prototype was assembled using development boards of the chosen sensors, organized into three modules separated by a central structural cover, as illustrated in Figure 8. Once assembled and electrically validated, each sensor was programmed and tested individually to assess data acquisition and calibration procedures. The inertial sensor (BMI270) was configured to record acceleration, angular velocity, step count, distance, and activity parameters. The GNSS module (SAM-M10Q) provided geospatial data including latitude, longitude, altitude, and timestamp. For heart rate monitoring, the MAX30101 sensor operated using red and infrared LEDs, as light at these wavelengths penetrates the superficial skin layers and is absorbed by hemoglobin, facilitating pulse detection while minimizing motion artefacts. This approach, combined with filtering algorithms, enhanced signal stability and measurement precision. Peripheral oxygen saturation (SpO_2) was computed from the red and infrared LED signals using predefined calibration coefficients based on the manufacturer's reference algorithm. Overall, these configurations validated the functionality of the main sensing units, establishing the foundation for the subsequent hardware refinement and system integration stages.

During this development phase, sequential data acquisition from each sensor was evaluated under a Real-Time Operating System (RTOS) environment. The RTOS enabled concurrent task management and precise scheduling, ensuring accurate timing and efficient resource allocation within the system. In parallel, Bluetooth Low Energy (BLE) communication was implemented and validated through data advertising, allowing real-time transmission of sensor data from the wearable device to external receivers such as smartphones.

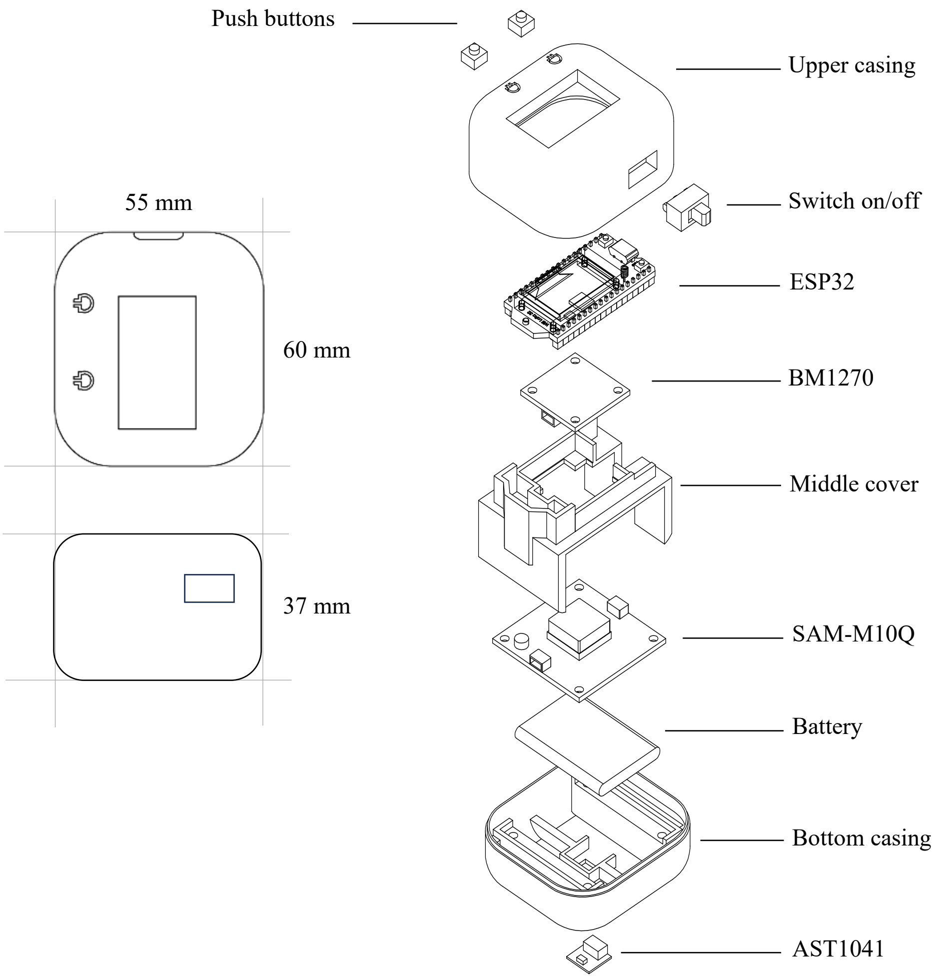

Figure 8. System device overview and dimensions.

3.2. Usability and Ergonomic Design

The studies on sensor layout and device sizing resulted in the creation of several virtual 3D models and physical prototypes. Through iterative testing, design constraints were identified, and optimal methods for securing each component were established to maximize spatial efficiency. Particular consideration was given to inter-component tolerances—critical for accurate data acquisition without signal interference—and to the overall dimensions of the device, accounting for the space required by internal connectors. This iterative process, involving a total of thirty prototype versions, progressively refined the mechanical design and culminated in the functional model illustrated in Figure 8.

In parallel, the display's shape and size were evaluated to confirm their suitability for the target users and usage context. Tables 2 and 3 present the main advantages and limitations identified in this assessment, providing a structured overview of the design considerations. At this stage of development, only the device's shape was finalized based on the conducted analysis. To achieve a more comprehensive evaluation, future stages will include user testing of both the display characteristics and overall form factor, with collected feedback informing subsequent design iterations toward a more accurate and user-centered solution.

Shape

Table 2 indicates that the square or rectangular form offers greater advantages in terms of user adaptation, largely due to its conventional and familiar geometry. Moreover, its compact structure facilitates a more practical internal layout, allowing intuitive placement of action buttons and improved design coherence. However, the presence of sharp vertices in this configuration may cause discomfort during prolonged wear, despite potential design adjustments to mitigate this effect.

Therefore, defining a well-researched and ergonomically validated form factor is essential to ensure comfort and usability in everyday use.

Table 2. Advantages and disadvantages of existing shapes of wrist devices.

Form	Description	
	Advantages	Disadvantages
Square/Rectangular	Compact form Conventional shape Versatility of button placement Unisex design	Uncomfortable extremities
Circular	Compact form Conventional shape Unisex design	Button location Button design curvature
Oval/Cylindrical	Compact form Unisex design	Futuristic design Difficult adaption Button location Button design curvature Short display size

Display size

Table 3 presents two commercially available rectangular display sizes suitable for adult wrist anthropometry. Since the device is intended solely for visual output and not for touch interaction, this consideration informed the selection of a smaller display size, while maintaining adequate readability of the displayed information.

In addition, the smaller display size provided a more balanced proportion between the wrist and the device, allowing the casing to remain compact and ergonomically comfortable during wear.

Table 3. Advantages and disadvantages of existing display sizes for wearable devices.

Display size	Description	
	Advantages	Disadvantages
35mmx41mm	Proportional size to the wrist Appropriate size for reading information	
38mmx45mm	Appropriate size for reading information	Disproportional size to the wrist for female users

4. System refinement and Current Implementation Progress

Following the development and validation of the initial proof of concept, which successfully demonstrated functional data acquisition, it became evident that further refinement was required. Although operational, the prototype exhibited limitations in physical size, structural robustness, and power efficiency—critical aspects for continuous wearable use, particularly among elderly individuals with dementia. Accordingly, the current phase of development focuses on optimizing the hardware architecture through the selection of more compact components, an improved internal layout, and the implementation of advanced power-management strategies to extend battery life. The goal of these enhancements is to deliver a smaller, more durable, and energy-efficient device while preserving full functional capability.

The proof of concept was implemented using individual development boards for each selected sensor. Although this approach enabled rapid integration and testing, it considerably increased the device's physical footprint. Consequently, the prototype dimensions surpassed those of comparable commercial wearable solutions. In addition to the size constraints, the reliance on development boards also resulted in higher power consumption, reducing the system's suitability for continuous, long-term operation. These limitations underscored the need for a custom hardware redesign integrating miniaturized components into a dedicated printed circuit board (PCB). This transition aimed not only to minimize the overall form factor but also to enhance power efficiency and extend battery life.

To overcome the identified limitations, a new set of components was selected with an emphasis on minimizing device size and power consumption while preserving and enhancing core functionalities. A more compact and energy-efficient microcontroller, the Xiao nRF52840 Sense Plus [19], replaced the ESP32-S3FN8, providing integrated BLE connectivity, ultra-low-power operation, and embedded motion and environmental sensors. For long-range communication, the large LoRa module was substituted with the Wio-E5 (SX1262) chip [20], which combines a smaller footprint with improved power management. The GNSS unit was updated to the CAM-M8Q module [21], offering a reduced form factor and higher energy efficiency without compromising positional accuracy. Additionally, a 1.5-inch OLED display (SSD1352) [22] was integrated to provide improved visual output in a smaller format, better aligned with wearable design constraints. Collectively, these component updates contribute to a more compact, efficient, and user-oriented hardware architecture.
For physiological signal monitoring, the MAX30101 sensor [13] was retained in the new design due to its proven accuracy and compact form factor. To enhance signal processing and reduce computational load on the primary microcontroller, the MAX32664 biometric sensor hub [14] was integrated. This companion device performs real-time processing of heart rate and SpO_2 data, executing advanced signal-processing algorithms and thereby improving both energy efficiency and system responsiveness.

With the selection of the new components completed, the subsequent stage focused on the design and development of a custom printed circuit board (PCB) integrating all modules into a compact and efficient layout. The resulting PCB unifies the microcontroller, sensors, communication interfaces, and display on a single platform, significantly reducing the overall footprint and enhancing mechanical stability compared to the previous configuration based on development boards. The layout was carefully optimized to ensure signal integrity, ease of assembly, and support for low-power operation. Additionally, the design incorporates a dedicated interface section featuring a user-selection button and an SOS emergency button, enabling rapid alert activation in critical situations. Figure 9 presents a 3D rendering of the finalized PCB, illustrating the integration and spatial organization of all components within the refined prototype.

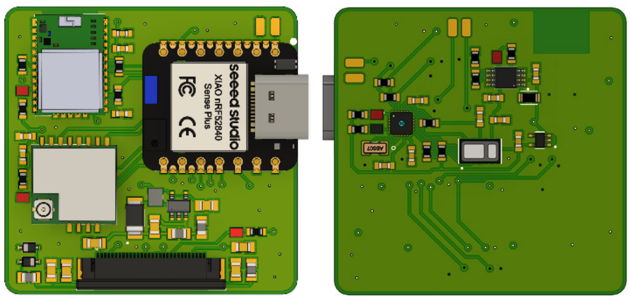

Figure 9. 3D view of the newly developed PCB

The newly developed PCB measures 4 × 4 cm, representing a substantial reduction in size compared with the initial proof of concept. This compact configuration enhances its suitability for wearable applications, improving both comfort and usability for elderly users.
Subsequent stages of development will focus on functional testing of the assembled hardware and the creation of optimized firmware. These efforts include refining sensor interfacing, improving data acquisition routines, and implementing advanced power-management strategies to minimize energy consumption during both active operation and idle periods.

5. Final Remarks

This work describes the progression from an initial proof of concept to a refined, compact, and energy-efficient wearable device developed for the continuous monitoring of elderly individuals with dementia. The latest version incorporates an optimized set of components mounted on a custom-designed 4 × 4 cm PCB, effectively addressing previous constraints related to size, structural robustness, and power efficiency.

Subsequent development stages will focus on comprehensive functional testing of the assembled hardware and the creation of advanced firmware to ensure seamless sensor integration and efficient power management. Particular attention will be devoted to refining data acquisition procedures, implementing low-power operating modes, and validating wireless communication protocols—such as BLE and LoRa—under realistic operating conditions.

From a usability perspective, the device layout will continue to be adapted to the wrist anthropometry of elderly users, with particular focus on improving the design of buttons and straps. Tactile textures and colour coding will be explored to enhance intuitiveness and ensure the SOS emergency button is easily accessible and distinguishable. A secure fastening mechanism will also be introduced to prevent unintentional device removal. In parallel, efforts will focus on developing a dedicated dataset for dementia-related activity monitoring, which will support the training of intelligent algorithms for behaviour detection and anomaly prediction. Data will be transmitted and stored securely using BLE, with potential integration of encryption protocols (AES-CTR) in LoRa communications to ensure data privacy. A future publication will present the results of these experiments and provide a detailed performance analysis of the system under operational conditions.

Overall, this work establishes the groundwork for a fully developed product that is technically robust, user-centered, and suitable for real-world deployment. Ultimately, it aims to enhance the quality of life of individuals with dementia and to support caregivers through timely and reliable health insights.

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[17] LoRa Node Development Kit. 2022.
[18] coprocessor, U., baseband, W.-F., MAC Wi-Fi Baseband Bluetooth Link Controller Bluetooth LE Baseband, W.-F. LE: Product Overview ESP32-S3 is a low-power MCU-based system on a chip (SoC) with integrated 2.4 GHz Wi-Fi and Bluetooth ® Low Energy (Bluetooth LE). It consists of high-performance dual-core microprocessor (Xtensa ® 32-bit LX7), a Wireless Digital Circuits.
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