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A New Hardware/Software Assistive Wi-Fi Device for Elderly Bed-Exit Event at Night

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Abstract

This article describes a new hardware/software alert system designed to assist elderly people and prevent falls due to bed-exit events at night. To assist the elderly during the night, it is important to implement automatic lighting activation in the bedroom. This helps reduce the risk of falls when they need to, for example, go to the bathroom. The caregiver can be alerted immediately via Wi-Fi, during the night, providing immediate assistance to the elderly person. The developed HW/SW system combines a passive infrared motion sensing device, a light sensor, and dedicated hardware based on the ESP32-C6 RISC-V microcontroller that communicates via Wi-Fi with a developed Android dedicated App, which the caregiver can access using a tablet or smartphone. Nighttime falls remain one of the most serious health problems for older people. The main innovative contribution of this work is the development of a low-cost preventive battery-free assistive system that does not require an internet access contract, preserves the elderly person's privacy, and promptly alerts the caregiver whenever the elderly person gets out of bed during the night. The system is directly integrated with automated lighting, preventing the elderly person from walking in the dark and without appropriate aid. The system also supports the caregiver by generating alerts through an open-source mobile App.

Keywords: healthcare electronics; active assisted living; Wi-Fi assistive device; RISC-V 32-bit microcontroller; Society 5.0

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1. Introduction

1.1. Motivation

The World Health Organization estimates that falls are one of the leading causes of injuries in older adults and represent annual costs of tens to hundreds of billions of dollars worldwide [1]. The primary motivation for this work is based on the need to find an effective way to prevent falls in older adults who receive 24 h care at home, given that the consequences of such falls can be extremely serious. Currently, there are many permanent elderly care companies that draw attention to this problem, which highlights the need for a simple, low-cost, and innovative solution, since, according to [2], at home, 28% of falls occur in the bedroom, 15% in the kitchen, and 15% on the stairs. In addition, 8 out of 10 people who suffer falls are women.

For older adults who resist using wearable assistive devices, "environmental" systems have drawn interest, especially due to their ability to monitor and act without physical contact. The effectiveness of traditional warning devices is limited by the fact that, in up to 80% of cases of serious falls, the elderly person is unable to, or forgets to, press the panic button. The future will increasingly lie in passive systems that require no user intervention.

The developed work presented in this article falls within the perspective of the emerging Society 5.0 [3–7], which seeks to use advanced, human-centered technologies to address social challenges such as population aging. By proposing a simple, low-cost (in this article, the term 'low-cost' reflects estimated retail acquisition prices for the assistive device components, not manufacturing or commercial lifecycle cost), and innovative solution for detecting nighttime bed-exit events among elderly individuals receiving 24 h home care, this project makes a significant contribution to increasing the safety, autonomy, and quality of life of older people. The developed system can be installed in a bedroom in just a few minutes, and can help prevent night falls and improve the quality of life for the elderly. It uses the local Wi-Fi network, requiring only a router, and works even without the need of an internet service provider.

This work emerged from a need identified in the 24 h senior care company Home24 Almada and presently serves as a case study for a proof of concept, involving the modification of the electrical installation in a private home. In the future, the developed solution may also be adapted for institutions that provide support to the elderly. As proof of concept, functional assessments with the low-cost developed device are presented, to show its performance and advantages. The system is expected to reduce anxiety (the "fear of falling") and prolong the independence of elderly people at home.

1.2. Paper Structure

In Section 2, the current state of the art and recent research on this topic are presented. Section 3 describes the new hardware/software alert system that has been developed. Section 4 presents the preliminary findings and their discussion. Finally, Section 5 presents the conclusions of this work, and highlights directions for future work.

2. State of the Art

In older populations, falls are a frequent cause of injury, hospitalization, and loss of independence. A fall detection system reduces the time between a fall and the arrival of help, which constitutes a primary prognostic indicator of recovery. Fall detection systems (FDSs) are automated solutions developed to identify falls and fall events among older adults [8,9] and other at-risk individuals [10,11]. The major fall detection approaches published in scientific articles can be classified as follows [12]:

- Wearable device-based;
- Vision-based;
- Smartphone-based;
- IoT and Cloud-based;
- Kinematic signal-based;
- Sound analysis-based;
- Biomedical signal-based.

Human fall detection systems [13–18] have evolved from simple handheld panic buttons to proactive intelligent systems that utilize technologically advanced sensors and artificial intelligence (AI) algorithms. In this work, in terms of technologies, we decided to group the fall detection systems into wearable (sensors worn on the body) and non-wearable FDSs (sensors installed in the environment). Table 1 shows different devices and systems, both wearable and non-wearable, for prevention, fall detection, and alarm,

in case of dangerous situations for humans. Typically, fall detection systems also generate alarms. More detailed information can be found in the references provided. The first line presents the developed system in this work. As mentioned before, the main objectives were to develop a low-cost fall prevention system. Wi-Fi connectivity and the availability of a mobile App are key features of the proposed assistive system.

Table 1. Nighttime bed-leaving alert and fall-prevention light (BP), fall detection (FD), and alarm (AL) devices and systems.

##	Device/System	Wearable	Main Type	Main Sensors	Wi-Fi	App	Ref
1	This article	No	BP	PIR, LDR, SOS Button	Yes	Yes	-
2	Apple—Watch (Series 9, 10, 11 and SE 3)	Yes	FD	Acc, Gyro, Magn, Baro, ALS, GPS	Yes	Yes	[19]
3	Samsung—Galaxy Watch (6, 7 and 8)	Yes	FD	Acc, Gyro, Magn, Baro, ALS, GPS	Yes	Yes	[20]
4	Samsung—Galaxy Fit 3	Yes	FD	Acc, Gyro, ALS	No	Yes	[21]
5	Reachfar—Watch V046	Yes	FD	Acc, GPS	No	Yes	[22]
6	Medical Guardin—MGMini Lite	Yes	FD	Acc, GPS	No	Yes	[23]
7	Chatthen—Alarm Seniors Wi-Fi Home	Yes	AL	SOS Button	Yes	Yes	[24]
8	UnaliWear—Kanega Watch	Yes	FD	Acc, GPS	Yes	Yes	[25]
9	Reachfar—SOS Bracelet V048	Yes	FD	Acc, GPS	No	Yes	[26]
10	AnteaMED—Opplà	Yes	AL	SOS Button	Yes	Yes	[27]
11	Bay Alarm Medical—SOS All-In-One2	Yes	FD	Acc, GPS	No	Yes	[28]
12	Zênite.Tec—ZL25	No	FD	LiDAR	No	Yes	[29]
13	Verso Vision—Verso Vision	No	FD	V-Camera	Yes	Yes	[30]
14	Vayyar Home—Vayyar	No	FD	Radar	Yes	Yes	[31]
15	Tuya–Smart Fall Detector Radar	No	FD	Radar	Yes	Yes	[32]
16	Milesight—VS373	No	FD	Radar	Yes	Yes	[33]
17	KamiCare—Kami Fall Detect	No	FD	V-Camera	Yes	Yes	[34]
18	Voxela—VCare	No	FD	V-Camera	Yes	Yes	[35]
19	Scanalytics—Smart Floor	No	FD	P-Sensor	No	Yes	[36]
20	Talius–Bed Sensor	No	AL	P-Sensor	No	Yes	[37]
21	MariCare—Elsi Smart Floor	No	FD	C-Touch	No	Yes	[38]

Notation: Accelerometer (Acc), gyroscope (Gyro), magnetometer (Magn), barometer (Baro), ambient light sensor (ALS), Global Positioning System (GPS), LiDAR, millimeter-wave radar technology (Radar), vision camera (V-Camera), pressure sensor (P-Sensor), capacitive touch-sensing floor (C-Touch).

2.1. Wearable Fall Detection Systems

Wearable devices and FDSs remain the market standard due to their portability, usability and reduced cost. Nowadays, the state of the art is no longer limited to accelerometers and gyroscopes; other sensors such as magnetometers, barometers, ambient light sensors, and the Global Positioning System are also used in modern FDSs. Table 1 shows ten wearable FDSs, using different sensor technologies:

- Accelerometer, gyroscope and magnetometer (Acc, Gyro and Magn);
- Barometer (Baro);
- Ambient light sensor (ALS);
- Global Positioning System (GPS).

The wearable Reachfar—SOS Bracelet V048 for elderly people, presented in Figure 1 (adapted from [26]), allows fall detection; monitoring heart rate, blood pressure and body temperature in real time; pill reminders; advanced GPS tracking; one-key SOS; two-way voice calling; and voice messaging.

In Figure 2 is presented the Chatthen Wireless Wi-Fi home alarm system [24], with the wearable SOS button, the SOS home siren and the dedicated App for Android and iOS, compatible with Tuya Smart and Alexa. The App can detect the alarm events locally and also remotely (in this last case, with an internet connection available and a paid monthly or annual plan).



Figure 1. Reachfar—SOS Bracelet V048: With fall alarm, SOS button and 4G GPS location [26].



Figure 2. Chatthen—Alarm Seniors Wi-Fi Home Alarm [24]: Compatible with Tuya Smart and Alexa.

2.2. Non-Wearable Fall Detection Systems

Non-wearable FDSs use powerful and expensive sensors such as visual cameras, radar, LiDAR, pressure sensors and capacitive touch-sensing floors. Table 1 shows eleven non-wearable FDSs, including the proposed assistive nighttime bed-leaving alert system, using different sensor technologies:

- Passive infrared sensor (PIR);
- Light-dependent resistor (LDR);
- Radar (mm-Wave);
- LiDAR (light detection and ranging);
- Vision camera (V-Camera);
- Pressure sensor (P-Sensor);
- Capacitive touch-sensing floor (C-Touch).

Modern vision camera-based systems process images locally using edge computing, converting the human silhouette into digital "skeletons"; this allows fall detection without ever transmitting or recording real images of the person. In Figure 3, the KamiCare Fall Detect camera [34] can be observed.

In Figure 4, the Scanalytics—Smart Floor fall prevention system [36] is depicted. This smart flooring system captures every footstep and movement, in real time.



Figure 3. KamiCare—Kami Fall Detect: Advanced AI-powered camera [34].

The millimeter-wave radar technology is the major current trend; it uses electromagnetic radio waves to detect movement and posture without the need for vision cameras, preserving privacy in sensitive areas such as bedrooms and bathrooms [39].

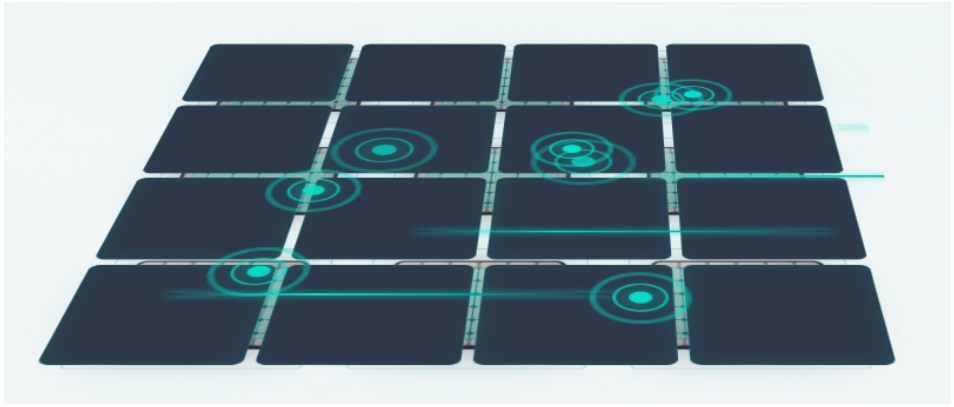


Figure 4. Scanalytics—Smart Floor: Intelligent sensing layer [36].

2.3. Artificial Intelligence-Powered FDSs

Artificial intelligence-enhanced fall detection systems apply Machine-Learning (ML) approaches [40–42] to distinguish real falls from everyday movements, offering higher accuracy and reliability than conventional sensors. This is crucial for protecting older adults, minimizing false alerts, and ensuring help arrives quickly when needed. Different AI algorithms can be used depending on the sensor type and desired complexity. Some relevant AI models are described next [43–48]:

- Classical machine-learning models, often used for wearable data: Support vector machines (SVM), random forests, k-Nearest Neighbors (k-NN);
- Deep learning models, ideal for radar and vision data: Artificial and Convolutional Neural Networks (CNNs), Long Short-Term Memory networks (LSTMs), recurrent neural networks (Gated Recurrent Units, GRUs);
- Radar-specific neural networks, process range-Doppler maps or point clouds;
- Hybrid models, combining temporal and spatial features.

Nowadays, it is possible to use edge computing devices to implement these AI models and algorithms.

2.4. Future Trends in Fall Detection Systems

Future trends in fall detection systems are evolving rapidly due to population aging, advances in new smart sensors, and the growing use of AI in home and clinical environments [44,49]. The strongest trends point toward systems that are more accurate, discreet, multimodal, and integrated into digital-health ecosystems. In the coming years, future systems are expected to include new technologies and solutions, such as the following:

- Fully camera-free systems focused on user privacy;
- Explainable AI to increase trust among caregivers and clinicians;
- Edge-AI devices and systems with local processing and less cloud dependence;
- New Plug-and-Play (PnP) systems for smart homes;
- New innovations in sensor fusion and data management;
- Better interoperability: Devices and systems will integrate directly with the Electronic Health Record (EHR), sending automated reports on the older adult's mobility to their attending physician;
- Predictive systems and solutions trying to anticipate falls based on gait patterns; the focus will shift from detection to prevention.

3. Proposed Hardware/Software Fall-Preventing System

The main idea behind this research and development work is to emphasize elderly fall prevention in bed-exit events at night, rather than simply alerting people to the problem after a fall has already occurred. Many homes and nursing homes are not well equipped with internet communication systems, for technical and/or financial reasons. The proposed system in this article does not require any contract with an internet provider, only a very small portable Wi-Fi router and a Local Area Network (LAN) to function correctly.

Figure 5 illustrates the high-level block diagram of the proposed hardware/software assistive system for detecting nighttime bed-exit events in older adults.

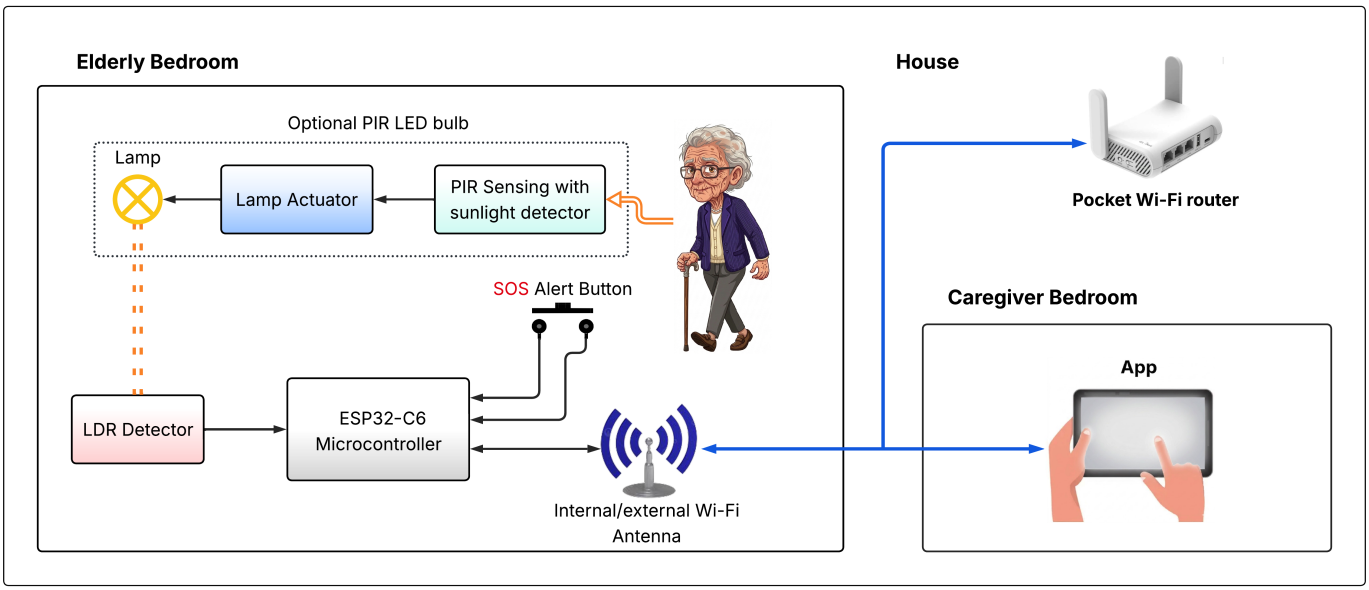


Figure 5. System block diagram.

The most problematic falls for elderly people living at home, with the help of one or more caregivers, occur in the middle of the night, for example, when the elderly person wakes up to go to the bathroom. In this situation, the bedroom should have an automatic lighting system so that when the elderly person wakes up at night, there is light to illuminate the way from the bedroom to the bathroom or another room in the house.

During the day, the automatic lighting system may be deactivated, as sunlight is usually sufficient to ensure visibility. During the day, the caregiver is also more attentive to the elderly person and their movements. At night, the caregiver should wake up, if necessary, to prevent the elderly person from falling. Typically, in a 24 h home care service contract, caregivers take turns throughout the week, with the elderly person having two, three, or more caregivers.

In the sensor and actuator layer, the system consists of a commercial PIR sensor, a solar light detector, and a lamp actuator. This implies adapting the bedroom's electrical installation to maintain the function of the on/off switch on the wall. Another optional solution that does not require modifications to the electrical installation is based on the use of a commercially available LED lamp with an integrated PIR sensor.

The developed hardware uses a light-dependent resistor (LDR) to detect if the lamp is on at night, in response to the elderly person's movement detected by the PIR sensor during the night. The LDR is connected to the ESP32-C6 microcontroller, which sends an alert via Wi-Fi to the Application Program (App) developed and installed on a tablet or smartphone, immediately alerting the caregiver.

The caregiver has full control of the App, being able to disable it or lower the alert sound volume if necessary. The system operates at night and automatically deactivates during the day, depending on the lighting conditions. However, an SOS alert button has also been implemented. This SOS alert button can operate 24 h a day and complements the developed system, also allowing the sending of a specific SOS alert message in the application, both day and night. Elderly people should be encouraged by their caregivers to use the alert button when they need the caregiver's help.

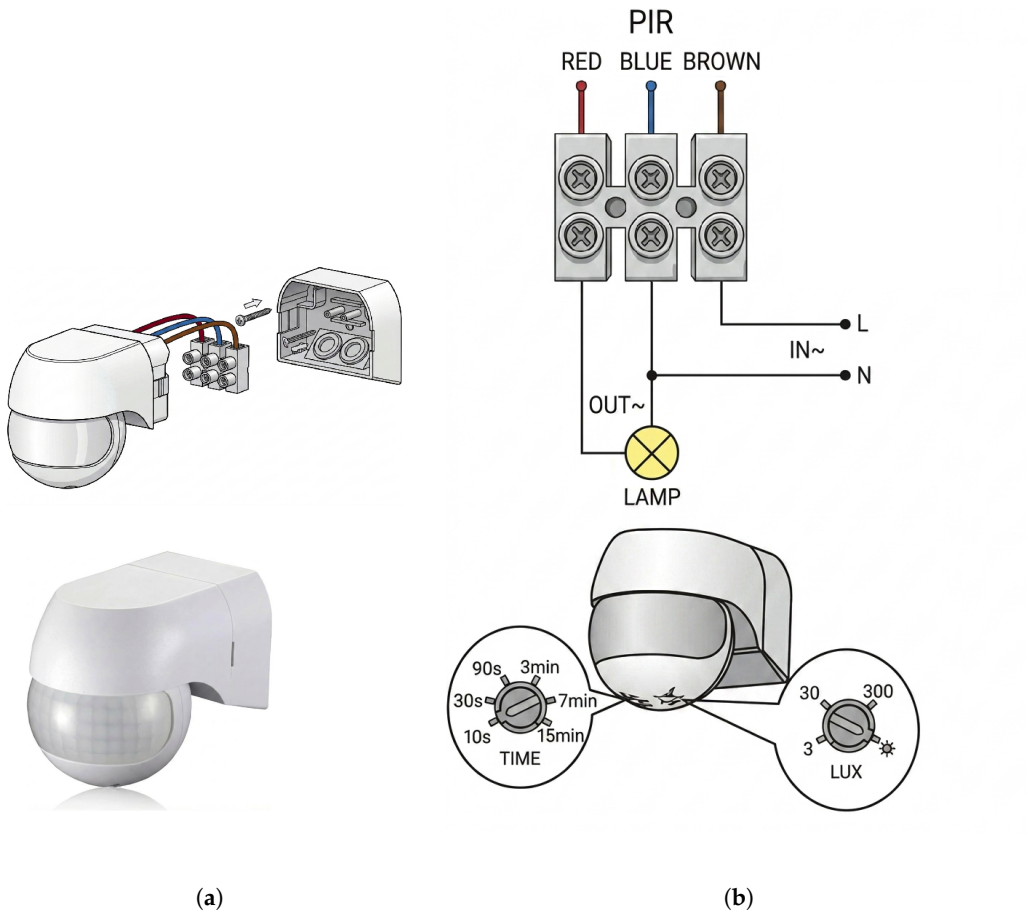
3.1. Motion Detector Light System

A PIR sensor detects electromagnetic radiation within the infrared spectral band, triggering the light when it detects human or animal movements. The commercial PIR sensor used is the PS-TECH PIR detector (Figure 6a), which is an IP44 motion detector for indoor and outdoor use. This PIR motion detector has the following dimensions: 6.5 cm (height) × 5.5 cm (width) × 8 cm (depth). It includes a 180° presence sensor for wall mounting with a range of 12 m and is suitable for LED lamps; it has twilight adjustment and a timer (10 s–15 min).

This detector uses "Zero Cross Switching" relay technology, which prevents false switching and voltage spikes, extending the lifespan of both the detector and the lamps; it is also suitable for LED and energy-saving lamps (up to 400 W) and incandescent lamps (up to 800 W).

This detector has a wide 180° angular coverage, with a linear range of up to 12 m, and is adjustable horizontally and vertically. For optimal performance, the recommended installation height should be in the range of [1.8 m; 2.5 m]. The Twilight Adjustment LUX knob allows deciding whether the detector should be activated only in total darkness, or in other ambient light conditions (3–2000 lx). Operating time can vary between 10 s and 15 min; its PS-TECH wiring diagram is shown in Figure 6b.

In this project, the electrical installation was supplemented to include the bedroom wall switch. A second wall switch was also installed to activate or deactivate the automatic light detection output. This second switch should be located in a higher position, so that only the caregiver can access it. The wall switch is connected in parallel to the L (phase) line to allow the wall lamp to function even when the automatic light detection output (OUT∼) is disabled. Figure 7 shows the complete wiring diagram for adapting the electrical system with a motion detector in the bedroom.



(**a**) (**b**)

Figure 6. The wall-mount PS-TECH PIR detector, adapted from the PS-TECH PIR instruction manual. (**a**) Wall-mount PIR detector [50]. (**b**) PIR detector wire diagram and available settings.

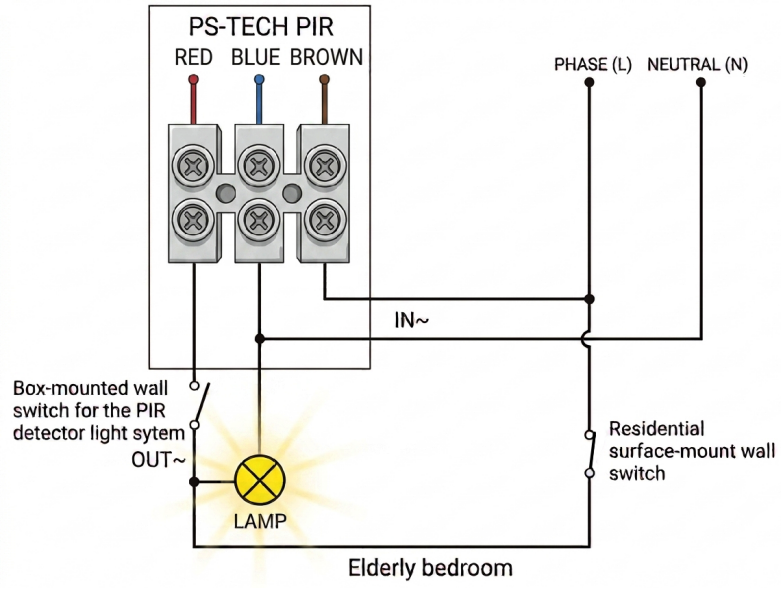
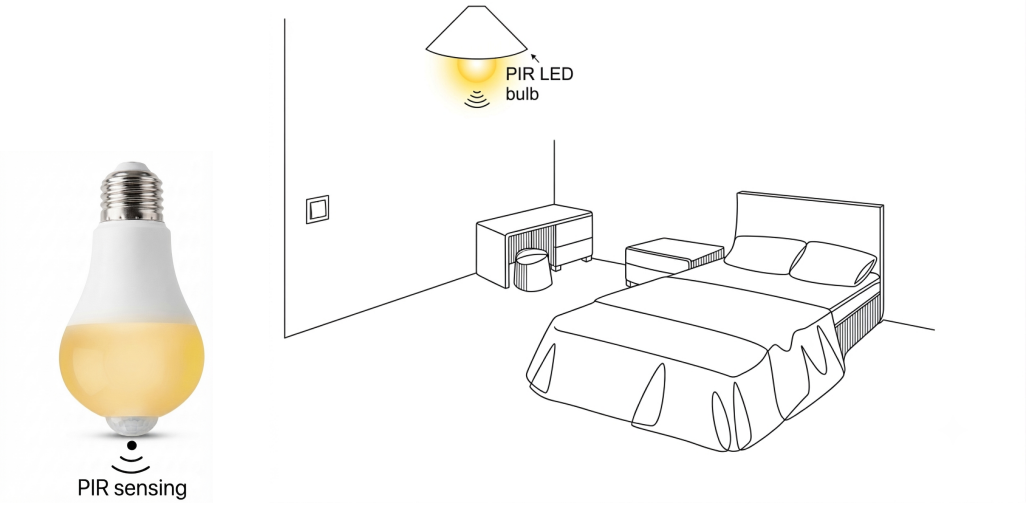


Figure 7. Electrical adaptation wire diagram for the elderly person bedroom PIR motion detector light system.

3.2. Optional PIR LED Bulb

Installing motion sensors in bedrooms can be simplified, significantly reducing installation time, with the use of an optional LED bulb with an integrated PIR motion detector/sensor. The Leikurvo E27 LED bulb [51] with motion sensor (Figure 8a) uses a

12 W warm white (3000 K) LED bulb with low energy consumption, featuring a passive infrared (PIR) motion sensor and intelligent infrared thermal detection technology.



(**a**) PIR LED bulb. (**b**) Elderly bedroom setup.

Figure 8. Elderly user's bedroom with the PIR LED bulb.

This LED (Light-Emitting Diode) bulb with a PIR motion sensor has an intelligent infrared detection mode, with a range of 5 m to 6 m and a height of 3 m to 4 m, lighting up for approximately 30 s after the motion detection. This E27 LED bulb provides between 500 and 1100 lm of light output and remains off during the day when the ambient illuminance exceeds 10 lx, which helps save energy and extend the bulb's lifespan. The LED bulb with a motion sensor has a wide detection angle of up to 110°. When motion is detected, the bulb lights up at dusk or at night. The day and night settings make it suitable for most indoor environments.

With the PIR LED bulb, nighttime fall prevention systems for the elderly can be easily installed without the need for any electrical adaptation, as illustrated in Figure 8b. The disadvantage is that the bulb cannot be manually turned on by the wall switch; it will only turn on automatically when it detects movement. Furthermore, configuring a PIR LED bulb to prevent false positives is considerably difficult task, as it may require repositioning the ceiling-mounted light fixture, as depicted in Figure 8b. The human infrared detection distance varies between 3 m and 5 m, the detection angle is approximately 120°, and the average delay time is 30 ± 5 s.

3.3. Hardware Developed Device

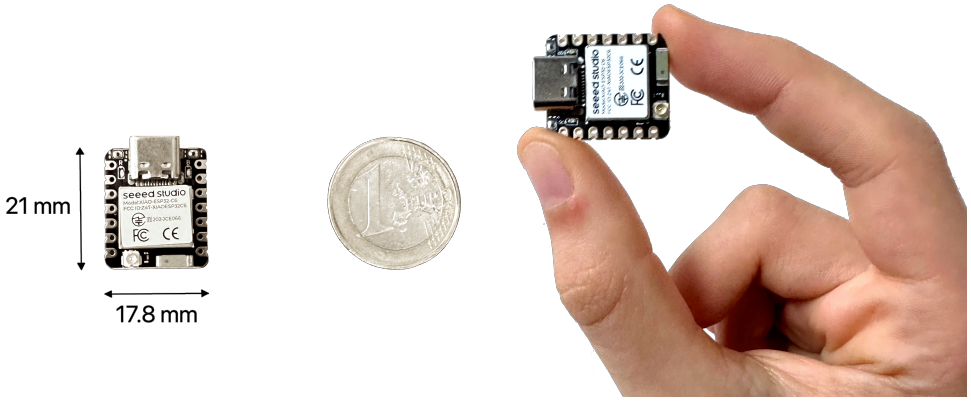
In this work, the developed hardware/software system helps to primarily prevent falls among elderly people during bed-exit events at night, when the caregiver is usually not in the elderly person's room, because it allows the detection of lights turned on as a result of detecting the elderly person's movement during the night, which will turn the elderly person's bedroom light on. To accomplish this task, it is necessary to use a microcontroller with Wireless Fidelity (Wi-Fi) mobile capability, that, at night, immediately senses the elderly person's bedroom light turned on.

3.3.1. XIAO ESP32-C6 Microcontroller

The Seeed Studio XIAO ESP32-C6 board (Figure 9a,b) incorporates a low-cost Microcontroller Unit (MCU) based on an RISC-V processor from Espressif Systems. This compact RISC-V MCU can be used in home automation, or other control and automation applications, among others, thanks to its support for various wireless connectivity options

(2.4 GHz Wi-Fi 6, BLE 5.0, Zigbee and Thread) [52]. Designed with a compact 21 × 17.8 mm form, and single-sided mounting of the XIAO Series, it is suitable for projects with limited physical space [53]. Encrypted on the chip, the XIAO ESP32-C6 ensures the desired level of security and a simplified embedded development experience. The most relevant features and advantages of the XIAO ESP32-C6 microcontroller board [54] are the following:

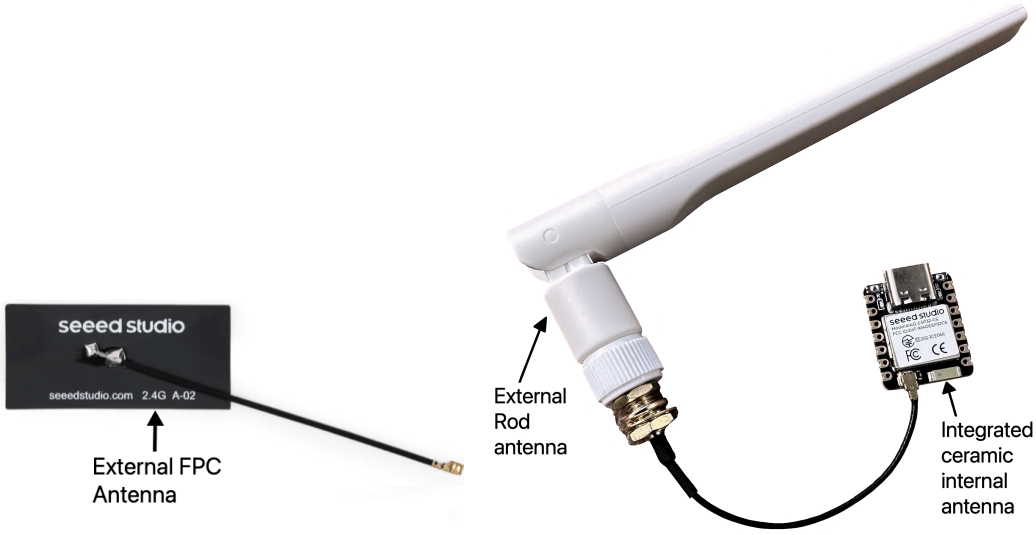
- Low-cost: The XIAO ESP32-C6 board usually ranges from approximately 6.99 € to 8.50 € across various European electronics retailers;
- Dual Reduced Instruction Set Computer (RISC)-V processors: It incorporates two 32-bit RISC-V processors [55,56], with the main processor running up to 160 MHz, and the low-power processor operating at up to 20 MHz;
- Connectivity: It combines 2.4 GHz Wi-Fi 6 (802.11ax), Bluetooth 5 (BLE-5), and IEEE 802.15.4 radio connectivity, enabling Zigbee and Thread protocols;
- Security encrypted on chip: The ESP32-C6 microcontroller SoC (System on a Chip) provides enhanced encrypted-on-chip security to smart home projects through secure boot, encryption, and a Trusted Execution Environment (TEE);
- RF performance: It has an on-board antenna with up to 80 m BLE/Wi-Fi range, with an interface available for an external UFL antenna;
- Power consumption: It has four working modes, with the lowest being 15 µA in deep sleep mode, and it also supports Lithium battery charge management;
- XIAO design: It remains the thumb-size XIAO form factor of 21 × 17.8 mm, and single-sided mount, making it ideal for space-constrained wearable projects;
- Integration with cloud platforms (Google Cloud, Microsoft Azure, AWS IoT and ESP Rain Maker), and also with the free Arduino Integrated Development Environment (IDE);
- Matter Native: It allows building Matter-compliant smart home solutions.



(**a**) (**b**)

Figure 9. The Seeed Studio XIAO ESP32-C6 ultra-compact 32-bit microcontroller board. (**a**) XIAO ESP32-C6 (21 × 17.8 mm coin-size dimensions). (**b**) Thumb-size XIAO ESP32-C6 microcontroller board.

The RF-Switch function [54], which allows switching between the XIAO ESP32-C6 integrated ceramic antenna and an external antenna (Figure 10), is performed by configuring GPIO (General-Purpose Input/Output) 14 (GPIO14). To enable this function, GPIO3 must be set to a low level, as this procedure activates RF switch control. The configuration process is as follows: (a) at GPIO14 low level (default setting), the XIAO ESP32-C6 device uses the integrated ceramic antenna; (b) at GPIO14 high level, the device switches to the external antenna. By default, GPIO14 is set to low, enabling the ceramic built-in internal antenna. To use an external antenna (FPC—Flexible Printed Circuit, Figure 10a—or rod type, Figure 10b), set GPIO14 to high.



(**a**) (**b**)

Figure 10. Antenna integration on the Seeed Studio XIAO ESP32-C6 board. (**a**) XIAO ESP32-C6 external FPC antenna. (**b**) XIAO ESP32-C6 external (Rod) and internal (ceramic) 2.4 GHz Wi-Fi antennas.

In Figure 11 is presented the example code for guidance on how to configure GPIO3, and also GPIO14 to enable the external antenna.

```
void setup() {
  pinMode(WIFI_ENABLE, OUTPUT);    //pinMode(3, OUTPUT);
  digitalWrite(WIFI_ENABLE, LOW);  //digitalWrite(3, LOW); //Enable the RF switch control
  delay(100);
  pinMode(WIFI_ANT_CONFIG, OUTPUT);     //pinMode(14, OUTPUT);
  digitalWrite(WIFI_ANT_CONFIG, HIGH);  //digitalWrite(14, HIGH); //Use an external antenna
}
```

Figure 11. XIAO ESP32-C6 RF switch feature C/C++ code.

3.3.2. Device Schematics

In Figure 12, the hardware schematics of the assistive developed device can be observed. The device is directly connected to the mains 230 V_{AC} power. The Hi-Link HLK-PM01 AC/DC converter [57] provides a regulated 5 V output used to power the XIAO ESP32-C6 microcontroller board [52]. The HLK-PM01 electronic converter complies with international safety and EMC (Electromagnetic Compatibility) standards (such as CE, EN55022, and IEC61000); it has built-in protection against short-circuits and overcurrents, making it certified for direct connection to the 230 V mains supply. The MOV-14D431K varistor provides protection against overvoltage transients such as power-line contact, lightning surges, and inductive switching events. Additional protection is provided by a 0.5 A fuse, which safeguards the circuit against excessive current. The 1N5817 Schottky diode provides protection against reverse current and power-supply polarity, preventing damage to the XIAO ESP32-C6 microcontroller board.

The sensing inputs include the light-dependent resistor (LDR) and a battery-free SOS alert push-button, mounted near the bedroom, providing continuous 24-h operation. An additional Normally Open (NO) PIR sensing input on pin 4, along with an external activation output on pin 5 for a dedicated 3.3 V relay module, can also be used when neither a wall-mounted PIR detector nor a PIR-based LED bulb is installed in the elderly person's bedroom. Figure 13a,b illustrate the complete Wi-Fi hardware developed together with the SOS alert button. The XIAO ESP32-C6 microcontroller board is housed inside the light gray device case (Figure 13b).

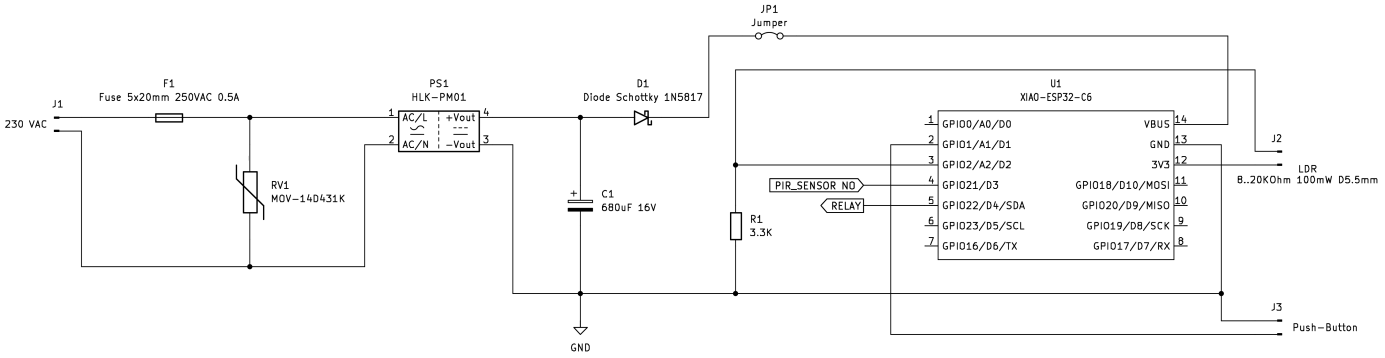
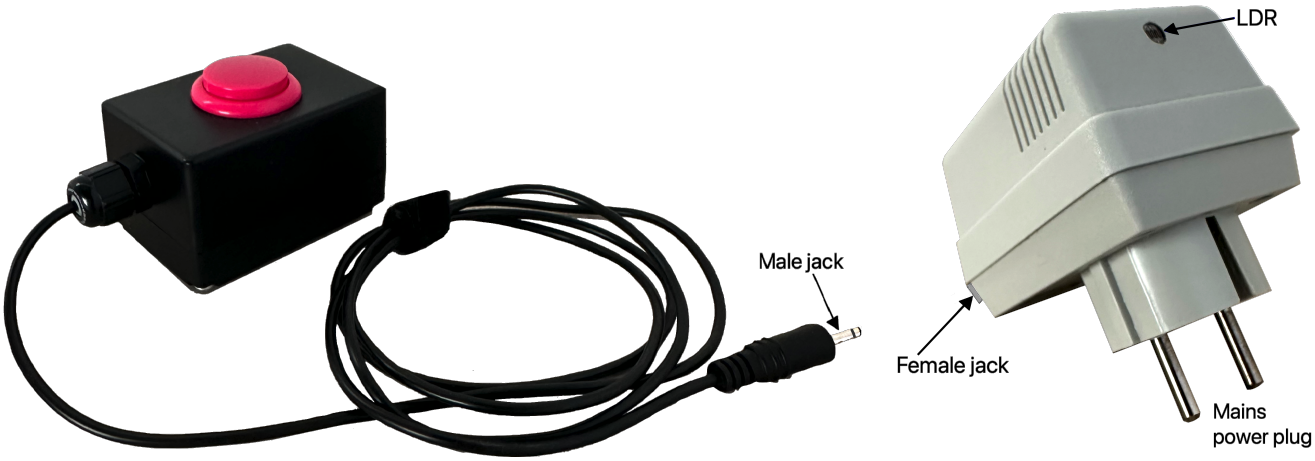


Figure 12. Complete electronic hardware schematics.



(**a**) (**b**)

Figure 13. The developed assistive Wi-Fi device for preventing elderly falls. (**a**) Battery-free SOS alert push-button, that attaches into the female jack of the device. (**b**) Wi-Fi device (ESP32-C6, FPC antenna and LDR).

The bill of materials is detailed in Table 2. The hardware device is budget-friendly, with electronics and materials estimated at approximately 28.4 €, the PIR detector adding approximately 15.2 € and a standard box-mounted wall switch adds an additional 2 € to 8 €. The developed Wi-Fi device (Figure 13b) was realized on a perforated circuit board (perfboard). In the future, a dedicated Printed Circuit Board (PCB) can be designed using, for example, the freeware tool KiCad [58]. Furthermore, manufacturing a prototype batch of 5 to 10 double-sided HASL (Hot Air Solder Leveling) Printed Circuit Boards (4 × 6 cm) in China, via fabricators like PCBWay, JLCPCB or NextPCB, usually costs between 10 € and 18 € total including standard shipping. The PCB's integrity validation can be performed using non-invasive methods [59].

Table 3 presents an estimated cost comparison between the proposed assistive solution and the existing available systems listed in Section 2.

When the LDR is used to activate the lamp at night in response to motion, a lamp-flicker effect can occur. In the absence of hysteresis, the sensor can produce rapid, contradictory commands in milliseconds: low light triggers the lamp to turn on, yet the resulting increase in illumination raises the LDR output and causes an immediate lamp turn off. This can initiate a self-sustaining flicker cycle, leading to visual discomfort and compromise the longevity of the lamp and associated components. Therefore, hysteresis is required to ensure system stability by compensating for the LDR's slow transient response. LDR hysteresis can be realized using a Schmitt-trigger stage or by applying software-defined

thresholds. In the ESP32-C6 microcontroller, hysteresis for the LDR was done through a software function, shown in Figure 14.

Table 2. Bill of materials (prices and availability may change) for the assistive Wi-Fi device, available from electronics retailers Mauser (Portugal) and Amazon (Spain).

Item	Qty.	Ref.	Seller	Source (accessed on 30 July 2026)	Cost
PS-TECH PIR detector	1	–	Amazon (ES)	https://amazon.es/-/pt/gp/product/B08P5N75MJ	15.2 €
U1 XIAO ESP32-C6 board	1	095-4212	Mauser (PT)	https://mauser.pt/095-4212	7.49 €
PS1 HLK-PM01 AC/DC	1	096-6877	Mauser (PT)	https://mauser.pt/096-6877	4.19 €
RV1 MOV-14D431K varistor	1	004-6013	Mauser (PT)	https://mauser.pt/004-6013	0.38 €
D1 1N5817 Schottky diode	1	007-0384	Mauser (PT)	https://mauser.pt/007-0384	0.15 €
F1 Fuse 0.5 A 250 V_{AC}	1	009-0986	Mauser (PT)	https://mauser.pt/009-0986	0.21 €
PCB fuse holder	1	019-0610	Mauser (PT)	https://mauser.pt/019-0610	0.26 €
C1 680 µF 16 V capacitor	1	004-1400	Mauser (PT)	https://mauser.pt/004-1400	0.31 €
R1 3.3 kΩ THT 1/4 W resistor	1	104-7461	Mauser (PT)	https://mauser.pt/104-7461	0.09 €
LDR 8–20 kΩ 100 mW	1	005-0045	Mauser (PT)	https://mauser.pt/005-0045	1.25 €
Push-Button with μ-switch	1	010-1064	Mauser (PT)	https://mauser.pt/010-1064	3.06 €
Female bullet terminal	2	011-0427	Mauser (PT)	https://mauser.pt/011-0427	0.24 €
Gland	1	302-3760	Mauser (PT)	https://mauser.pt/302-3760	2.55 €
Flanged nut for gland	1	302-3761	Mauser (PT)	https://mauser.pt/302-3761	0.36 €
3.5 mm mono jack socket	1	011-0349	Mauser (PT)	https://mauser.pt/011-0349	0.34 €
Wi-Fi device mounting case	1	095-1507	Mauser (PT)	https://mauser.pt/095-1507	3.06 €
SOS button mounting case	1	096-5305	Mauser (PT)	https://mauser.pt/096-5305	2.64 €
3.5 mm mono jack cable 1.5 m	1	019-0627	Mauser (PT)	https://mauser.pt/019-0627	1.78 €
Partial sum (excluding PIR)					28.4 €
Sum					43.6 €

Table 3. Cost comparison table (prices and availability may change) (estimates only).

Solution Type	Device/System	Est. hardware cost	Subscription
This article	4 × 6 cm PCB + PIR + box-mounted wall switch	∼56 €–70 €	None (Self-hosted)
Consumer Smartwatches	Apple Watch, Galaxy Watch, Fit3	150 €–500 €+	Optional
Medical Alert Wearables	MGMini Lite, Kanega, Opplà, Reacher	50 €–200 € (device)	Yes (20 €–50 €/mo)
mmWave Radar Sensors	Vayyar Home, Milesight VS373, Tuya Anti-Fall	70 €–350 €+ per room	Varies
Vision/AI Cameras	KamiCare, Voxela, Verso Vision	100 €–300 € per room	Usually Yes
Smart Floors & Bed Sensors	MariCare Elsi, Talius Bed Sensor	200 €–1000 €+	Enterprise B2B

The 12-bit ADC (Analog-to-Digital Converter) thresholds are set to 150 for the light-on threshold (which corresponds to 120.85 mV within the 0 to 3.3 V range) and 50 for the light-off threshold, corresponding to 40.28 mV. The system operates with a sampling period of 0.8 s for the LDR readings, it applies a debounce time of 150 ms, and the alarm timeout is set to 12 s; these parameters were defined and configured in the initial setup phase.

To ensure reliable detection, the ADC thresholds were empirically calibrated using a reference lux meter and controlled light variations to define the LDR's operational state transition points. A hysteresis band was integrated into the decision logic to mitigate noise-induced state flickering. To minimize sensitivity to lamp power and ambient-light leakage, the LDR was enclosed in a light-tight housing; this effectively isolated the sensor from external illumination and stabilized the Signal-to-Noise Ratio (SNR) across different physical placements.

To prevent false triggering from high-frequency noise, the software logic applies a 150 ms debounce period before confirming state changes; this 150 ms debounce window comfortably fits within the 0.8 s LDR sampling period, ensuring temporal margins are preserved. Because the debounce duration is significantly shorter than the LDR sampling interval (150 ms versus 0.8 s), the system reliably verifies state stability well before the

next acquisition cycle. Functioning as a low-pass filter, this configuration enhances signal integrity and ensures that only one state transition is registered per sampling period.

```
void hysteresis_LDR() {
  valor_LDR = analogRead(LDR);
  bool previous_luz = luz;
  if (valor_LDR > lightOnThreshold) {
    luz = true;
  } else if (valor_LDR < lightOffThreshold) {
    luz = false;
  }
  // Debounce the LDR state changes
  if (luz != previous_luz) {
    if (!ldrStateChanging) {
      ldrStateChanging = true;
      lastLdrDebounceTime = millis();
    } else if (millis() - lastLdrDebounceTime >= ldrDebounceDelay) {
      ldrStateChanging = false;
      // If lights are now OFF, ensure optional relay is OFF and reset motion detection
      if (!luz) {
        motionDetected = false;
        digitalWrite(RELE, LOW);
        delay(atraso_rele);
      }
    }
  } else {
    ldrStateChanging = false;  // Reset if the LDR value is stable within the thresholds
  }
}
```

Figure 14. LDR hysteresis function C/C++ code.

3.3.3. Implementing the HTML Web Server on XIAO ESP32-C6

Leveraging the ESP32-C6's networking wireless capabilities, the system operates as a local web server that handles nocturnal monitoring during bed-exit events and continuous SOS button status tracking. Figure 15 presents the HyperText Markup Language (HTML) page embedded in the ESP32-C6's flash memory, which acts as a dynamic front-end for user interaction.

The system's goal is to provide real-time updates of the light sensor and SOS button states, ensuring the browser interface remains current without user-initiated refresh actions.

The code presented implements a dynamic HTML page stored in the ESP32-C6's flash memory via the PROGMEM directive and a raw string literal, which permits embedding web content directly in the C/C++ code without manual handling of quotation-mark escaping. The interface relies on Asynchronous JavaScript and XML (AJAX) to asynchronously fetch updated sensor data, allowing the page to refresh its content in real-time without a full browser reload. Within the header, a JavaScript (JS) function generates an HTTP (Hypertext Transfer Protocol) GET request directed to a predefined server endpoint, the "/button" path. When the ESP32-C6 issues its response, the script captures the server-returned text and updates the interface element labeled "reqBot". In addition to rendering the data in the browser, the script pushes the server response into the App Inventor WebViewString interface, allowing the mobile client to process sensor updates or SOS-button triggers.

The system maintains real-time updates by triggering the data-fetch routine at one-second intervals via a software timer. The page adopts a minimalist layout, consisting of a single paragraph and an empty container into which the ESP32-C6 injects its output. The system architecture relies on a polling loop: the browser issues timed requests to read the microcontroller's pin state and then propagates the updated value to both the web page and the paired application, all handled seamlessly in the background.

```
// HTML page of the XIAO ESP32-C6 web server
const char MAIN_page[] PROGMEM = R"=====(
<!DOCTYPE html>
<html lang="pt">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <style>
        body {
        }
        span {
        }
    </style>
    <script>
        // Function to retrieve and update data from the XIAO ESP32-C6
        function updateData(endpoint, elementId) {
            var xhttp = new XMLHttpRequest();
            xhttp.onreadystatechange = function() {
                if (this.readyState == 4 && this.status == 200) {
                    document.getElementById(elementId).innerHTML = this.responseText;
                     if (elementId === "reqBot" && window.AppInventor) {
                        window.AppInventor.setWebViewString(this.responseText);
                    }
                }
            };
            xhttp.open("GET", endpoint, true);
            xhttp.send();
        }
        // Update data every 1 second.
        setInterval(function() {
            updateData("/button", "reqBot");
        }, 1000);
    </script>
</head>
<body>
    <p><span id="reqBot"></span></p><br>
</body>
</html>
)=====";
```

Figure 15. XIAO ESP32-C6 web server HTML code.

3.4. Setting the Local Wi-Fi Network

The system may operate on any new or existing Wi-Fi network, given that the ESP32-C6 microcontroller is compatible with 2.4 GHz Wi-Fi 6. To provision the wireless infrastructure, the system employs the GL.iNet GL-SFT1200 pocket-sized wireless router [60,61], depicted in Figure 16. The key technical specifications of this Wi-Fi router are as follows:

- AC1200 dual-band wireless router: (2.4 GHz) PHY (Physical Layer) rates up to 300 Mbps and (5 GHz) PHY rates up to 867 Mbps;
- Portable and compact construction, with a total weight of approximately 145 g;
- Gigabit wireless router featuring two 1 Gigabit LAN ports and one 1 Gigabit Wide Area Network (WAN) port;
- IPv6 support is provided, OpenVPN and WireGuard are preinstalled, and the device is compatible with more than 30 VPN (Virtual Private Network) providers;
- Supports WPA3 security standard for enhanced wireless protection;
- Support for Cloudflare encryption is provided to strengthen user privacy.



Figure 16. The ultra-compact GL.iNet GL-SFT1200 pocket Wi-Fi 6 router [60,61], measuring just 118 × 84 × 33 mm, available on Amazon (Spain) for around 41.7 €.

Figure 17 illustrates the router configuration [62]. WPA3 (Wi-Fi Protected Access 3) [63] introduces enhanced authentication and encryption mechanisms that reduce attack surface and provide stronger, more automatic protection for wireless networks. WPA3 defends against offline dictionary attacks by requiring a live authentication handshake for every password trial, which prevents attackers from using automated tools to validate large numbers of guesses without interacting with the network. It also employs forward secrecy (ephemeral key exchange), so compromise of long-term credentials does not expose prior session keys or past traffic. WPA3 substantially improves resistance to modern attack vectors and enforces stronger cryptographic protections, thereby preserving user privacy with no perceptible impact on the user experience.

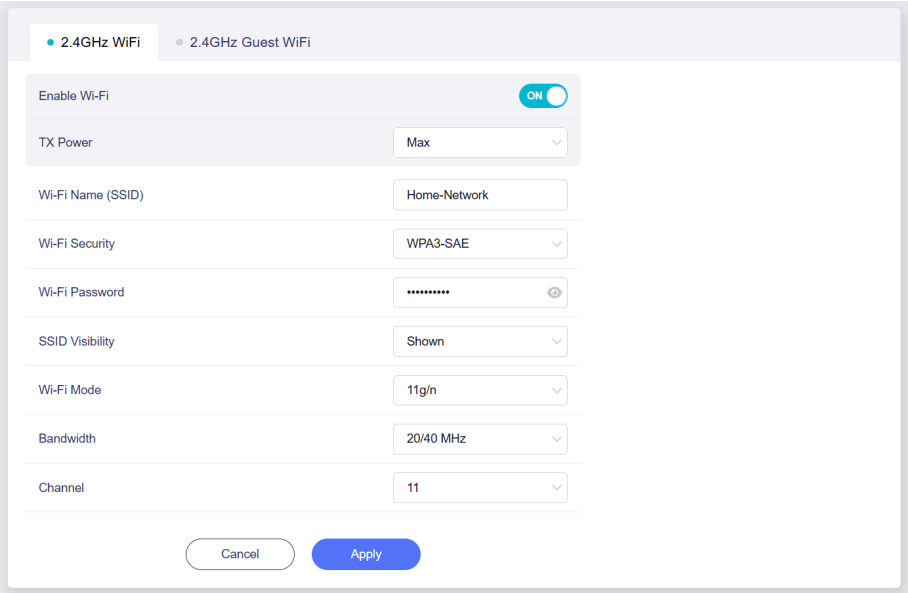


Figure 17. Configuration of the local Wi-Fi network on the GL.iNet GL-SFT1200 pocket router.

3.5. Developed Android App

MIT App Inventor [64] provides a block-based visual programming environment that abstracts low-level native Application Programming Interfaces (APIs), enabling rapid application prototyping without traditional development complexity. The block-based logic architecture facilitates creation of cross-platform Android and iOS Apps, preserving equivalent functionality on both smartphones and tablets. The platform supports IoT and AI integrations, enabling accelerated prototyping workflows that shorten the time from concept validation to deployable prototype. The platform democratizes mobile development and offers an extensible foundation that accelerates innovation in areas such as IoT, AI, and enterprise applications. The developed Android application (Figure 18a–f) activates its alert mode at night by referencing the device's internal clock, as the elderly user's bedroom generally receives sufficient natural daylight during daytime hours.

The caregiver can fully manage the application, including enabling or disabling the Wi-Fi Alert mode. When the elderly individual attempts to leave the bed, a Red Bell icon is displayed on the tablet or smartphone, and an audible alarm is activated to notify the caregiver. The visual and audio alert further identifies whether activation resulted from the SOS button or from PIR-based automatic lighting, implemented either through the wiring arrangement in Figure 7 or via the optional Leikurvo E27 PIR LED bulb installed in the ceiling fixture (Figure 8a,b). The SOS alert button can be configured with top-priority status and is able to trigger an alert at any time, regardless of the Alert mode slider state.

An online video, available at https://youtu.be/H4gvXsTnN4A (accessed on 1 June 2026) elucidate how the developed electronics healthcare system works. The source block-based code for the Android application is also available at GitHub: https://github.com/razevedoantunes/RAA-2026-MDPI-Electronics (accessed on 1 June 2026).

The App Inventor [64] visual development environment provides a cloud-based, block-oriented development platform that enables rapid cross-platform App creation for Android and iOS systems. By employing a user-friendly block-based logic architecture, the platform hides the complexities of text-based coding, facilitating rapid prototyping and integration with emerging technologies like IoT and AI.

In the implemented application, the MIT App Inventor WebViewer component encapsulates the web content, keeping it separate from the main application logic. The WebViewStringChange block (Figure 19) establishes a bidirectional communication mechanism between the App and the XIAO ESP32-C6 embedded web page. Practically, it removes this separation by continuously monitoring WebViewString.

Whenever the JavaScript (JS) code within the embedded page modifies this value, the block is triggered, enabling the application to respond immediately. Thus, it operates as an automated notification system that signals the arrival of new data from the web page. Because the PIR detector operates independently, its response time is not constrained by the 1 s sampling period of the web server embedded in the ESP32-C6 microcontroller. Hence, the delay between the lamp turning on and the sound and visual alert being issued will be at most 1.2 s due to the Wi-Fi 6 and the App stochastic latencies.

For Android distribution, the MIT App inventor platform executes a build process that produces an APK (Android Package Kit) suitable for device installation. When the build completes, the platform creates a time-limited QR (Quick-Response) code (commonly 2 h) that links to the APK for direct device download and installation, or for live testing (as shown in Figure 20).

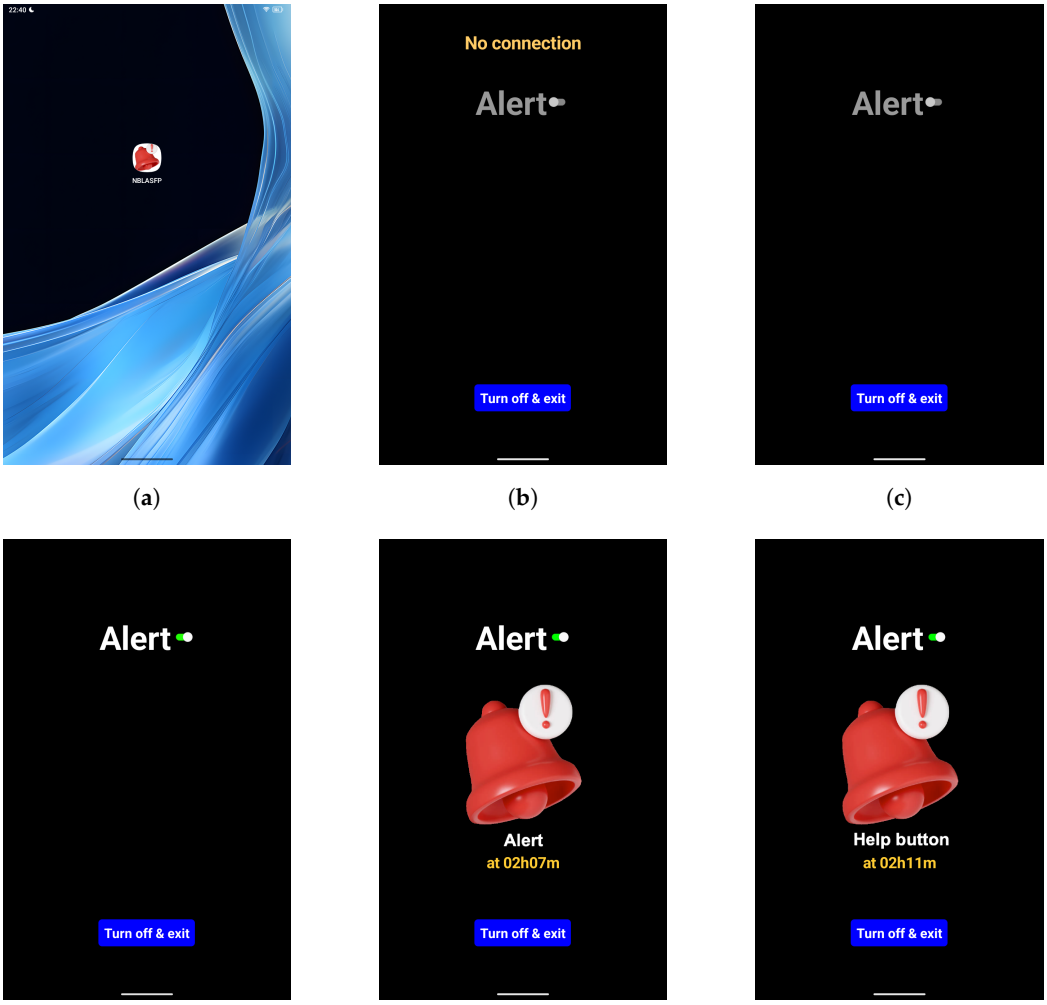


Figure 18. Tablet/smartphone Android App for nighttime bed-exit alerts in older adults. From top left to bottom right: (**a**) application icon; (**b**) startup interface; (**c**) Wi-Fi connection to the assistive device; (**d**) caregiver activating nighttime alert mode; (**e**) sound and visual alerts for the caregiver upon nighttime elderly person bed-exit detection; (**f**) sound and visual alerts for the caregiver, triggered by the optional 24 h Help/SOS button for the elderly.

The system operates strictly on a local Wi-Fi network, requiring no internet connection or cloud services. The MIT App Inventor application is deployed to Android devices via APK Sideloading—a standard Android method that ensures full local control over installation. During installation, the Android operating system automatically performs security and integrity checks on the MIT App Inventor APK package. The application communicates directly with the XIAO ESP32-C6 microcontroller using local IP addresses or mDNS (Multicast Domain Name System); suppressing all external internet traffic ensures absolute data privacy within the local network.

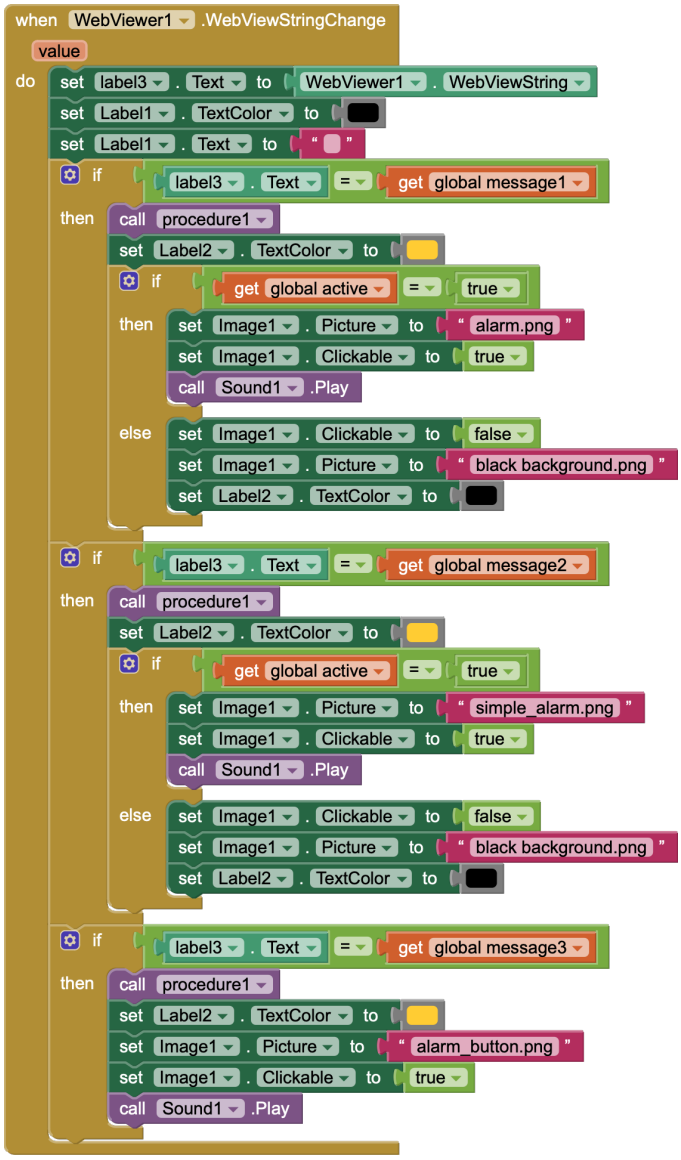


Figure 19. The WebViewStringChange App Inventor block.



Figure 20. Live testing with MIT App Inventor [65].

4. Results and Discussion

For the individual case study, the proposed hardware/software (HW/SW) alert system for nocturnal bed-exit events in older adults was validated under nighttime bedroom conditions. The system architecture combined a PIR sensor, a light sensor, and an ESP32-C6 microcontroller providing Wi-Fi connectivity, integrated with a caregiver-facing Android application. The PS-TECH PIR detector was positioned externally to the lamp. Its installation followed the manufacturer's manual guidelines. Specifically, positioning the PIR detector in front of highly reflective surfaces was avoided, as well as placing it near heat sources such as air conditioning units and hot air vents. The PS-TECH PIR detector was adjusted with a 3 lx ambient-light threshold and a 10 s activation time. Its detection field was fine-tuned to target nighttime bed-exit events, thereby mitigating false positives. Additionally, to prevent unintended activations, care must be taken to ensure that no pets are present in the elderly person's bedroom during the night.

Caregivers understand how the system works and protect the participant's nighttime privacy, stepping in only during alert or call situations, such as a bed-exit event or a button press. However, because passive infrared (PIR) sensors are susceptible to false triggers in multi-occupant environments—such as when a caregiver enters or multiple individuals share the room—the electrical system (Figure 7) is engineered to mitigate this constraint. Positioned near the bedroom entrance, the box-mounted wall switch (Figure 7) enables caregivers to manually override automatic lighting before the PIR sensor triggers, suppressing unwanted activations and offering direct operational control. Due to the physical limitations of a single passive infrared (PIR) detector, the proposed system cannot distinguish between caregivers, multiple occupants, or pets, making manual intervention an inherent limitation of the implementation.

Over the two-week period, the system detected 100% of the participant nighttime bed-exit events (≈2 per night), triggering exclusively nighttime automatic lighting whenever ambient illumination fell below the defined threshold. This feature increased instantaneous illumination within the room and lowered the hazards of dark-environment mobility, notably during bathroom trips. Furthermore, the system transmitted real-time notifications to the caregiver's smartphone or tablet via the Android mobile application. This mechanism ensured that the caregiver was instantly notified of nighttime activity events, enabling timely intervention when needed.

To analyze the performance and reliability of the bed-exit detection system, standard statistical metrics were used. The system's performance was evaluated using *Precision*, *Recall* (Sensitivity), and the *F*1-*score*, which are mathematically defined based on True Positives (TP), False Positives (FP), and False Negatives (FN), as detailed next.

$$Precision = \frac{TP}{TP + FP} \tag{1}$$

$$Recall = \frac{TP}{TP + FN} \tag{2}$$

$$F1\text{-}score = 2 \times \frac{Precision \times Recall}{Precision + Recall} \tag{3}$$

$$F1\text{-}score = \frac{TP}{TP + \frac{1}{2}(FP + FN)} \tag{4}$$

In the context of the developed bed-exit system, these metrics are associated with specific physical events: a True Positive (TP) occurs when the elderly person exits the bed and the system correctly triggers a caregiver alert; a False Positive (FP) occurs when the system triggers an alert but the elderly person remains safely in bed (e.g., as a result of rolling over or shifting position); and a False Negative (FN) occurs when the elderly person

leaves the bed but the assistive system fails to generate an alert, causing the highest risk in preventive care.

During a two-week pilot evaluation involving an individual participant, an average of 2 bed-exit events occurred per day, resulting in a total of 28 bed-exit events. All of these were successfully detected by the preventive system, yielding 28 True Positives ($TP = 28$). Concurrently, no missed events were observed ($FN = 0$) and no false alarms were recorded during the monitoring period ($FP = 0$). Consequently, substituting these experimental parameters yields a score of 1.0 (100%) across all three evaluation metrics, showing the reliability of the developed assistive system within this initial pilot testing phase. The reported high performance is preliminary and limited to an individual participant.

The proposed solution attempts to minimize false alarms; in this case study, empirical data collected during the testing period revealed that no false positives were recorded. However, it is critical to note a specific contextual factor regarding the typical target demographic: elderly individuals commonly have lower body mass, and emit less body heat compared to the average adult. These physiological differences are key factors that the low-cost assistive system with the PIR motion detector accounts for, ensuring that the absence of false positives remains consistent under these specific conditions.

Figure 21 presents an illustrative timeline diagram depicting the intervals between a nocturnal bed-exit and the subsequent caregiver notification, respectively. The ESP32-C6 web server's update cycle is configurable and was settled to 1 s. The bed-exit notification latency refers to the time elapsed between t_1 and t_6. To calculate the mean, variance, and the maximum latency for the bed-exit end-to-end trials, 30 repeated trials were conducted using a precision chronograph. The results are summarized in Table 4.

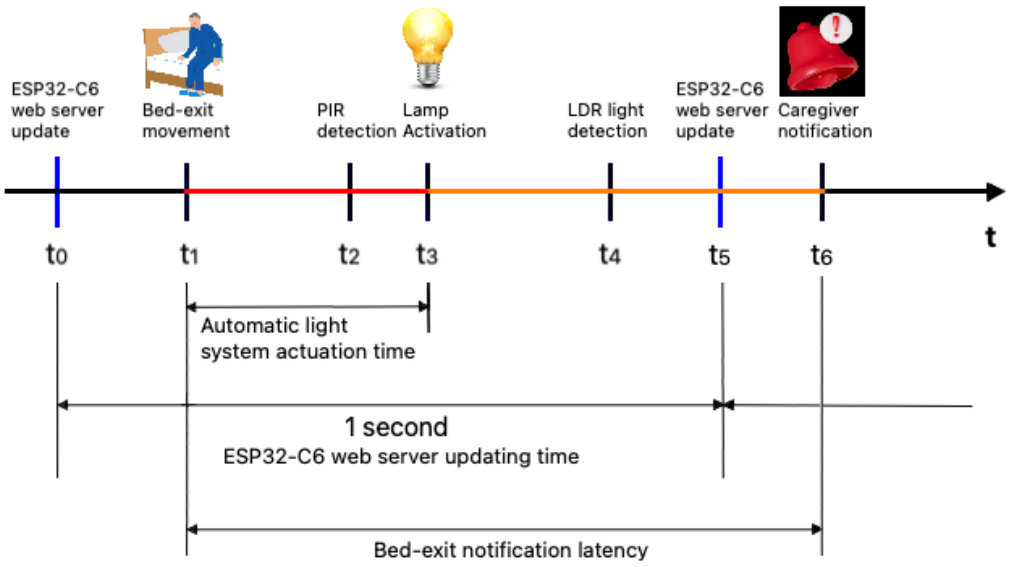


Figure 21. Nocturnal bed-exit detection: Conceptual timeline from PIR detection and lamp activation to final caregiver notification.

Table 4. Bed-exit notification latency (t_1 to t_6).

Metric	Value
Mean Latency	0.92 s
Max. Latency	1.69 s
Variance	0.14 s^2

The maximum notification latency on the Android App was approximately 1.69 s. Because the application currently needs foreground operation to receive real-time alerts, the Android device ought to remain unlocked. To mitigate the energy impact of an always-on display during extended deployment, a dedicated tablet was integrated into the setup.

Communication between the sensor unit and the mobile application remained consistently stable during the entire test period, indicating that the XIAO ESP32-C6-based platform is appropriate for this category of Active Assisted Living (AAL) applications. Since the system operates on a local network with a relatively low load, the combined processing and communication time was always shorter than the 1 s predefined sampling interval. In an atypical occurrence of a Wi-Fi 6 communication fault during a given cycle, the system continues to operate normally in subsequent cycles, aligning with Espressif Systems' manufacturer specifications—the ESP32-C6 prioritizes architectural efficiency over raw speed for superior network resilience. By implementing Wi-Fi 6 features such as Target Wake Time (TWT), the chip reduces power draw and mitigates channel contention in congested spaces. Coupled with hardware-level radio coexistence for Wi-Fi 6, Bluetooth 5, and Zigbee/Thread, this architecture aims to provide the operational stability required for fault-tolerant IoT applications.

The questionnaire findings for the elderly and caregiver participants, presented in Table A1 (Appendix A), indicate that the proposed system is a viable assistive solution for early intervention in elderly care, especially during nighttime periods, when fall risk is highly elevated. A notable advantage identified in this case study was the full suppression of unnecessary nighttime alerts for the caregiver, made possible by the integrated use of motion and light sensors, which allowed the assistive system to adapt more accurately to the real usage context. In contrast to more sophisticated computer-vision-based non-private systems, this solution provides a simpler and more cost-effective approach while offering enhanced privacy preservation.

The quantitative data from the questionnaires (Table A1, Appendix A) for both the elderly participant and the 24 h care company caregivers strongly suggest that the devised solution could reduce anxiety and the fear of falling. Given that this case study included a single elderly participant, the results should be regarded as preliminary. Despite the promising initial results observed in this case, comprehensive validation across multiple users, caregivers, and heterogeneous home settings is needed to more fully assess system reliability, user experience, and performance scalability. Broader participant testing and rigorous validation are essential to confirm overall reliability. Future work will resolve current methodological constraints by establishing an independent ground-truth baseline. This validation setup will pair infrared night vision with manual video annotation for accurate event logging, with all devices synchronized to a common time reference. Lastly, integrating formal uncertainty quantification will allow to strictly benchmark performance metrics and verify system resilience across a larger and diverse participant group.

5. Conclusions and Future Work

In this work, the hardware/software (HW/SW) developed prototype represents a cutting-edge example in the engineering of compact and multifunctional assistive devices for the human-centered Society 5.0 concept. The conceived system monitors elderly person bed-exit events in real time and immediately alerts the caregiver if a bed-exit event is detected or the SOS push-button is pressed, so that prompt assistance to the elderly user can be provided. Fall prevention is also a key requirement; unlike solutions that trigger alerts only after an impact, this system detects nocturnal bed-exit events in real-time and issues immediate caregiver notifications.

This innovative assistive solution for Active Assisted Living (AAL) completely eliminates the need for contractual or prepaid cloud services common in commercial products, while the custom hardware module with the compact Flexible Printed Circuit (FPC) external antenna, mounted inside the light gray housing device (Figure 13b), extends reliable Wi-Fi coverage to every room. The proposed nighttime bed-leaving system for elderly people is low-cost (the hardware device is budget-friendly, estimated at around 28.4 € plus minimum price per PCB (10 €/5 = 2 €), with the PIR detector adding approximately 15.2 €) and Plug-and-Play (PnP), requiring minimal wiring and no specialized installation expertise. The unit operates passively as a non-wearable sensor and requires no onboard batteries. This non-intrusive approach preserves privacy, eliminates direct contact with hardware, and removes any burden of active compliance from elderly users. In contrast, Ultra-Wideband (UWB) architectures depend on wearable tags and fixed anchors, while inductive systems require users to carry or wear metallic objects for detection. The developed system operates entirely over the local Wi-Fi LAN without relying on external internet services or cloud subscription fees, eliminating the need for an Internet Service Provider (ISP) subscription and lowering operational expenses.

The Espressif Systems ESP32-C6 has emerged as a modern "Swiss Army knife" among microcontrollers, offering a compact design, robust wireless connectivity and an extensive peripheral support, thereby making it suitable for many different application domains. Despite its minimal footprint, this low-cost 32-bit RISC-V microcontroller features a rich set of integrated peripherals and interfaces, along with support for smart-home ecosystems based on the Matter standard [66,67]. Unlike proprietary architectures such as Intel or ARM, which involve companies to pay high licensing fees, RISC-V is an open-source architecture. Anyone can freely download the RISC-V architecture documentation [68] and design their own chip at no cost. It is often described as the "Linux of the hardware world".

In the future, the aim is to implement a distributed system with multiple microcontrollers and integrated sensors, incorporating sensor fusion techniques such as Kalman filtering, for example, combining motion, pressure and EM (electromagnetic) sensing data to enhance nighttime bed-exit detection. Electromagnetic (EM) sensing is emerging as a robust, non-visual alternative for privacy-preserving monitoring. While its efficacy is well-established in industrial applications—such as non-cooperative inductive metal detection for wireless electric vehicle (EV) charging [69]—the technology is increasingly vital for context-aware sensing, serving as an intelligent safeguard against thermal hazards caused by metallic foreign objects (MFOs) during wireless power transfer.

Electromagnetic (EM) sensing encompasses a broad spectrum of non-invasive technologies—including passive infrared (PIR), Wi-Fi Channel State Information (CSI), Ultra-Wideband (UWB), and mmWave radar—that extend far beyond traditional inductive methods. By combining advanced technological integration with human-centric social well-being, these privacy-preserving modalities offer a compelling foundation for next-generation healthcare within the Society 5.0 paradigm.

While PIR sensors offer an energy-efficient solution based on heat and motion detection, mmWave radar provides high-precision tracking and an advanced predictive matrix, though it requires higher energy consumption and greater algorithmic complexity. To further enhance system performance, additional EM sensing modalities could be integrated. For example, flexible inductive coils integrated under the mattress surface enable continuous presence detection by sensing body-mass-induced shifts in electromagnetic field impedance. This solution can be complemented by a pressure-sensitive pad, embedded beneath the fitted sheet at the hip or shoulder region, which enables precise monitoring by detecting pressure release to signal a potential bed-exit.

To further enhance system efficacy and operational robustness, future iterations will leverage the advanced Physical Layer (PHY) capabilities of the ESP32-C6 System on a Chip (SoC). Specifically, we plan to incorporate Channel State Information (CSI) analysis, transitioning beyond traditional Received Signal Strength Indicator (RSSI) metrics to enable high-resolution spatial and motion monitoring. By capturing subcarrier amplitude and phase dynamics, the system can comprehensively characterize the propagation environment, maintaining resilient operation despite multipath fading and localized interference. Furthermore, we intend to leverage the IEEE 802.11ax (Wi-Fi 6) Fine Timing Measurement (FTM) protocol to enable precise, Round-Trip-Time (RTT)-based distance estimation without compromising system scalability. This integration elevates the platform from a conventional communication link to a high-precision sensing and positioning system capable of sub-meter ranging. By exploiting these Physical Layer hardware capabilities, we anticipate a marked improvement in system reliability and spatial resolution, paving the way for robust deployment in dense, dynamic indoor wireless environments.

Future research should also further assess long-term deployment, user acceptance, and the system's capability to detect and appropriately respond to real fall events. While this study serves as a proof-of-concept, subsequent work must address long-term reliability by implementing an independent ground-truth framework—integrating infrared night monitoring with manual video annotation for precise event logs. Additionally, we plan to implement AI-Taguchi-Analysis of Variance (ANOVA) approaches to conduct stress tests, optimize parameters, and monitor the device's long-term robustness. Upcoming new developments may also include enabling remote alarm notifications through the MQTT (Message Queuing Telemetry Transport) protocol (which necessitates internet connectivity), integrating a dedicated PIR motion sensor straight into the hardware in place of ambient-light activation, adopting sensor-fusion approaches, and porting the application to Apple's iOS and iPadOS using Xcode [70,71] with extended AirPlay 2 support [72–74] for streaming alert audio.

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Institutional Review Board Statement: Ethical review and approval were not required for this study under Regulation (EU) 2016/679 (GDPR) and Portuguese law (Law n.º 21/2014, of 16 April, as amended), as all data utilized were fully anonymized, publicly available, and contained no identifiable personal data. The study was conducted in accordance with the Declaration of Helsinki.

Informed Consent Statement: Written informed consent (Appendix A) for participation and article publication was obtained from the elderly participant and Home24 Almada, the 24 h senior care company (https://home24.com.pt/work/apoiodomiciliario-almada/) (accessed on 1 June 2026) involved in this study.

Data Availability Statement: An online video elucidating how the system works is available at https://youtu.be/H4gvXsTnN4A (accessed on 1 June 2026). The block-based code for the Android application is available at GitHub https://github.com/razevedoantunes/RAA-2026-MDPI-Electronics (accessed on 1 June 2026).

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Abbreviations

The following abbreviations are used in this manuscript:

AAL	Active Assisted Living
AC	Alternating Current
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
AJAX	Asynchronous JavaScript and XML
ALS	Ambient Light Sensor
ANOVA	Analysis of Variance
APIs	Application Programming Interfaces
APK	Android Package Kit
App	Application Program
B2B	Business-to-Business
BLE	Bluetooth Low Energy
CNNs	Convolutional Neural Networks
CSI	Channel State Information
C-Touch	Capacitive Touch
DC	Direct Current
EHR	Electronic Health Record
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EV	Electric Vehicle
FDS	Fall Detection Systems
FPC	Flexible Printed Circuit
FTM	Fine Timing Measurement
GPIO	General-Purpose Input/Output
GPS	Global Positioning System
GRUs	Gated Recurrent Units
HASL	Hot Air Solder Leveling
HTML	HyperText Markup Language
HTTP	Hypertext Transfer Protocol
HW/SW	Hardware/Software
IDE	Integrated Development Environment
IoT	Internet of Things
ISP	Internet Service Provider
JS	JavaScript
k-NN	k-Nearest Neighbors

LAN	Local Area Network
LDR	Light-Dependent Resistor
LED	Light-Emitting Diode
LiDAR	Light Detection and Ranging
LSTMs	Long Short-Term Memory networks
MCU	Microcontroller Unit
mDNS	Multicast Domain Name System
MFOs	Metallic Foreign Objects
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
NO	Normally-Open
PCB	Printed Circuit Board
PHY	Physical Layer
PIR	Passive Infrared
PnP	Plug-and-Play
QR	Quick-Response
RISC	Reduced Instruction Set Computer
RSSI	Received Signal Strength Indicator
SNR	Signal-to-Noise Ratio
SoC	System on a Chip
TEE	Trusted Execution Environment
THT	Through-Hole Technology
TWT	Target Wake Time
VPN	Virtual Private Network
UWB	Ultra-Wideband
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WPA3	Wi-Fi Protected Access 3

Appendix A. Questionnaires, Statement of Consent Form and Feedback

Elderly Questionnaire

Thank you for participating in this study. Please answer the following questions based on your experience with the system in your bedroom.

1. The automatic bedroom lighting made me feel safer when getting out of bed at night.

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

2. The automatic lighting helped reduce my "fear of falling" when walking in the room at night.

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

3. I felt that my privacy was fully preserved while using this system (no cameras or invasive sensors).

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

4. Knowing that the caregiver would be alerted immediately reduced my anxiety about being alone at night.

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

Figure A1. Elderly participant questionnaire.

Caregiver Questionnaire

Thank you for participating in this study. Please complete this brief questionnaire based on your experience using the proposed alert system.

1. The system's immediate Wi-Fi alerts reduced my anxiety regarding the elderly person falling at night.

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

2. The dedicated Android application was easy to use and understand.

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

3. The system allowed me to provide immediate assistance whenever the elderly person got out of bed during the night.

- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

4. Overall, how much did the system improve your peace of mind during the night?

- [ ] Significantly
- [ ] Moderately
- [ ] Slightly
- [ ] Not at all

Figure A2. The 24 h care company caregiver questionnaire.

By signing below, you agree that the anonymous answers from your questionnaire can be shared and published in scientific articles to help improve care for other elderly individuals.

Statement of Consent

I understand the information above. I voluntarily agree to participate and give my consent for the anonymous results to be published.

Participant's Name/Signature: _____ Date: ____ / ____ / 2026

24 hour Care Company: _____ Date: ____ / ____ / 2026

Figure A3. Statement of consent form.

Table A1. Qualitative questionnaire feedback.

	Elderly Participant	24 h Care Company Caregivers
Question 1	Strongly Agree	Agree
Question 2	Strongly Agree	Strongly Agree
Question 3	Strongly Agree	Strongly Agree
Question 4	Strongly Agree	Moderately

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