Building a Smarter Care Home: A Deep Dive Into HealthSonar's Architecture for Assisted Living

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***Abstract*—This study introduces HealthSonar, an innovative, unobtrusive and privacy-preserving health monitoring system, designed for the continuous monitoring of elderly individuals and patients with movement disorders, such as Parkinson's disease. HealthSonar offers a suite of features, including sleep quality tracking, sleep apnea event identification, mobility assessment, real-time fall detection and fall notification. The system itself comprises an impulse-radio, ultra-wideband radar device, a web portal, a dashboard, and a mobile application. HealthSonar is particularly well-suited for use in potentially hazardous areas of care homes and hospitals (such as bathrooms), where continuous monitoring of their residents/inpatients is essential, especially during nighttime. To demonstrate the system's utility, a care home deployment is presented, detailing the installation of the radar-based device, the monitoring procedure of the residents as well as the management of the system. Through this application, it is effectively demonstrated that HealthSonar can be seamlessly integrated into clinical settings improving the quality of life of elders/patients, preventing injuries and reducing the workload of their personnel as well as of the overall healthcare system in general.**

Index Terms*—ultra-wideband radar; health monitoring; sleep monitoring; gait analysis; fall detection; care home monitoring; assisted living.

I. Introduction

THIS work builds upon the foundation laid by a preceding study [1] which introduced a novel health and wellness monitoring system, the HealthSonar, based on ultra-wideband (UWB) ambient sensing radar technology, perfectly suited for monitoring elders and patients with sleep, neurological and movement disorders.

The world's older population is rising, along with the number of patients suffering from sleep, neurological and movement disorders [2]–[5]. More often than not, these two groups share similar health problems, usually revolving around sleep and mobility. Impaired mobility, in particular, can result in falls, which are common, yet serious, incidents that can lead to life-threatening injuries, or permanent disability. Falls and their associated costs are expected to surge significantly over the next two decades, posing a growing burden on the healthcare systems over time [6]. Current technologies fall short of addressing the growing need for practical wellness and health monitoring systems, particularly for the expanding elderly and patient populations. Ideal systems would monitor sleep, evaluate mobility, and identify falls – functionalities crucial for this demographic. A practical solution, targeting a holistic approach to wellness, could be of even greater interest, specifically for care homes and clinical environments, where residents are primarily elders and patients, in need of constant monitoring and care, for various health emergencies.

As of now, to the best of our knowledge, there is no single unified solution offering sleep monitoring, mobility monitoring and fall detection. Existing approaches, usually offer only a fraction of those features and lie in the use of either medical-grade diagnostic equipment (such as polysomnography), camera-based systems, or wearable solutions (such as actigraphy) [7]–[10]. Those systems can be expensive, cumbersome, privacy-invading, or solely geared towards clinical use. There are commercially available devices, such as smartwatches and fitness trackers, offering similar functionality, but their wearable form significantly limits their usability. This is especially true for sleep tracking purposes, as a wearable solution would be cumbersome leading to user discomfort. Furthermore, current commercial devices often rely on complex on-device interfaces, alongside web and mobile applications with intricate functionalities. The primary challenge lies not with the applications themselves, but rather with the nature of the employed user interfaces (UIs). These UIs frequently neglect to incorporate design principles that cater to the specific requirements of elderly users and patients, thereby creating substantial barriers to adoption and use within these populations. For elderly users, unfamiliar with technology, clear and well-documented user interfaces (UIs) are essential. Patients with movement disorders, on the other hand, benefit from larger icons and minimal interactive elements to accommodate dexterity limitations.

Lately, progress in ultra-wideband (UWB) radar technology has resulted in the development of affordable, practical and accurate radar sensors [11]. These sensors can serve as a platform for building wellness and health monitoring solutions capable of addressing the needs of both elders and patients. Specifically, because of their high accuracy, penetration capabilities and reliability, UWB radars can track micro and macro motions, even through different weather conditions and obstacles (such as walls and furniture), making them ideal for a diverse set of applications. Among these are respiratory and heart rate extraction, presence detection, fall detection, people counting, gesture recognition, baby monitoring, assisted living of elderly people, as well as mobility monitoring. What is more, UWB radar technology provides an unobtrusive, contactless, low-consumption and privacy-focused approach, perfectly suited for devices meant to be used for long periods of time, inside the most private areas of people's homes, such as bedrooms, bathrooms etc. Due to their nature, radar-based devices are a suitable choice for applications pertaining to sleep, where a wearable solution would inevitably cause discomfort, while a camera-based solution would be privacy-intrusive [12]. Moreover, radars offer unparalleled opportunities for nighttime activity/movement monitoring as their penetrating abilities result in motion evaluation and posture recognition even in low temperatures where people would be covered with blankets during sleep [12]. Given radar-based devices are constantly emitting energy in the form of radiation, a logical concern would be that of safety regarding their continual use. Thankfully, UWB radars are safe to use, due to their low emitted power levels of non-ionizing radiation that are harmless for human health [11]. The contactless nature of radar-based devices unlocks new possibilities for continuous monitoring in assisted living and general wellbeing applications. Unlike wearable sensors that can be forgotten, misplaced, or uncomfortable for long-term use, radar-based devices offer a passive monitoring solution that seamlessly integrates into daily routines. This facilitates unobtrusive tracking of activity levels, sleep patterns, and even subtle changes in movement, empowering individuals in both assisted living and wellness contexts to gain valuable insights into their well-being.

UWB radars have been used extensively for wellness and health monitoring in research settings for various applications. In the context of this work, we are mostly interested in the state-of-the-art research about UWB radar technology applied to vital signs extraction, sleep monitoring, presence detection, fall detection and mobility monitoring. The extraction of the respiratory and heart rate using devices based on UWB technology [13], [14], takes advantage of the ability of radar sensors to capture micro motions, in this case the oscillating motion of the chest resulting from the movement of the lungs and heart. By analyzing the subtle changes in the reflected radar signal caused by these micro motions, sophisticated algorithms can accurately extract respiratory and heart rate information. This contactless approach eliminates the need for uncomfortable or intrusive wearable sensors, offering a more natural and user-friendly way to monitor vital signs. Sleep monitors based on UWB radars, have been developed either as medical-grade diagnostic equipment with the goal of substituting the gold standard, yet cumbersome and expensive, polysomnography (PSG) or as general wellness tools for evaluating the quality of one's sleep. In either case, vital signs are commonly paired with additional features obtained from radar data, such as body posture or night movement [15]–[17]. This allows for applications such as detection of obstructive sleep apnea events [13], [18], [19] (the most frequent breathing disorder occurring during sleep [20]), differentiation between sleep and wake states, or classification of sleep stages [12], [16], [21], among others. UWB radars are gaining traction as ambient sensors in assisted living environments. They excel at human presence detection and fall identification, promoting safety and well-being for residents [22]–[24]. Radar-based devices are privacy-oriented and are ideal for installation in areas such as bedrooms and bathrooms, where fall incidents are relatively common for elders and patients with movement disorders. Last but not least, UWB technology has been applied to human mobility evaluation [25]–[27], a task that up to now primarily relied on wearables, such as devices based on inertial measurement units (IMUs) and instrumented insoles, or highly specific laboratory equipment, such as pressure sensitive mats and walkways. In applications like human presence detection, mobility monitoring, and fall detection, UWB radar sensors leverage their ability to remotely and precisely capture large-scale human movements (macro-motions), even through objects. This distinctive capability translates into rich spatiotemporal data, providing valuable insights into a person's movement patterns and location over time.

Within this work, we outline the different elements composing the HealthSonar system, its structure, and its diverse functions. Additionally, we present a detailed application of the system in a care home catering to elders or patients with movement disorders, such as Parkinson's disease. A care home application was specifically chosen because both residents and employees can greatly benefit from a system like HealthSonar, which was specifically designed and built with such an environment in mind. The system can be easily deployed in a plethora of other scenarios, even as a general wellness tool for improving the quality of life of both healthy individuals and patients, but its applicability in clinical environments and care homes is particularly noteworthy.

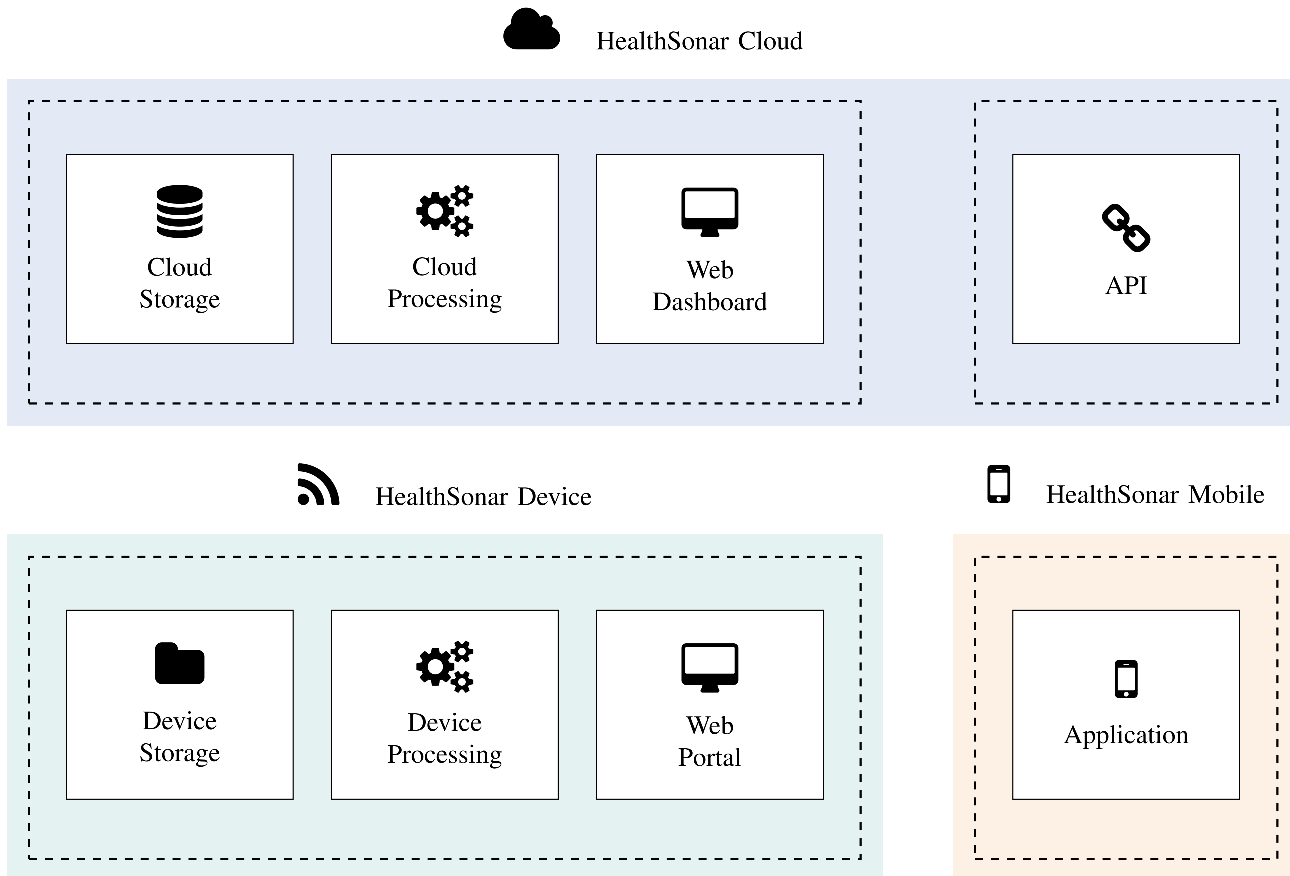


Fig. 1: The architecture of the HealthSonar system.

II. The HealthSonar system

The HealthSonar system was developed to fill the gap in continuous, accurate, unobtrusive, privacy-focused and contactless health monitoring, designed to support elders (focusing on those with deteriorated mobility) and patients with sleep, or movement disorders. It achieves this by tracking the quality of their sleep, identifying sleep apnea events, evaluating their mobility and detecting fall incidents. The development of the system was propelled by recent advances in IR-UWB radar technology, especially the small size of available sensors and their affordable price, rendering them commercially viable options to serve as platforms for building health monitoring devices. The HealthSonar system consists of the following "components" (see Figure 1):

1) a radar-based monitoring device,
2) a web dashboard application,
3) a web portal to the radar device,
4) a mobile application (or app),
5) a Cloud data processing service.
6) a Cloud data storage service, and
7) an API for communication purposes.

The system was developed as an ecosystem catering to different users serving different purposes, thus it was designed for use by (1) elders and patients, (2) caregivers (for example, family members or nurses and healthcare professionals of a care home), as well as by (3) attending physicians (for example, neurologists or sleep experts of hospitals and clinics). It was also designed to provide different administrative and monitoring utilities to each one of the aforementioned groups based on their roles. The HealthSonar system is meant to be straightforward and easy to use, while still being customizable for advanced, mainly research, use cases. Prioritizing the needs of the target audience, uncompromising usability was a core principle throughout the design process.

It is important to note that HealthSonar was built as a centralized, scalable system. As a result, multiple devices can be connected and administrated at once in order to cover the needs of large organizations serving many residents or inpatients. On the other hand, the system is modular enough to be usable even as a single unit, ideal for home use applications, or research purposes.

A. The radar-based monitoring device

The cornerstone of the HealthSonar system is the radar-based monitoring device, which was designed, developed and produced, in-house, by PD Neurotechnology Ltd. You can see a HealthSonar prototype in Figure 2. The case for the prototype was produced using 3D computer-aided design (CAD)

TABLE I: The specifications of the Aria Sensing LT102 radar module, the heart of the HealthSonar system.

General specifications	Values
Radar's operating frequency	6.5 GHz to 8.5 GHz
Temperature operating range	$-40\,°C$ to $85\,°C$
Radar module's dimensions	36 mm×68 mm
Maximum power consumption	220 mW at 5 V
Integrated antenna aperture	$\pm60°$ by $\pm60°$
Typical detection range	12 m

and additive manufacturing techniques. The device comprises an Aria Sensing LT102 IR-UWB radar sensor, and a Raspberry Pi 4 Model B board. The radar module connects to the Raspberry Pi board via 1 external USB cable. The radar sensor identifies micro motions (such as the oscillations of the chest) and macro motions (such as the human gait), translating them into data, while the Raspberry Pi board is the main processing unit of the device. The specifications of the Aria Sensing radar module can be found in Table I. The HealthSonar device is powered through a wall socket instead of a battery, allowing it to operate indefinitely without requiring any user interaction for charging. The intended placement of the device is:

1) Next to a bed, on top of a nightstand facing the sleeping individual, enabling nighttime sleep monitoring.
2) Mounted on a bathroom wall, maximizing the coverage of the area, enabling human presence and fall detection.
3) Mounted on a tripod, with its line of sight facing a strip of the room, for general mobility evaluation.

B. The web dashboard application

The web dashboard (see Figure 3a) is a could-based web application accessible via the internet. It serves as the central hub for managing multiple (or, more aptly, at least one) connected HealthSonar devices. Tailored for healthcare professionals across care homes, hospitals, and other healthcare settings, the web dashboard offers a comprehensive suite of tools for patient data monitoring, device management, and overall system administration. Its functions include:

1) Manually initiating and terminating recording sessions.
2) Manually selecting data for upload to Cloud storage.
3) Accessing telemetry data (logs) for connected devices.
4) Accessing information (metadata) for each device.
5) Assigning the system's users to specific devices.
6) Viewing the connection status of each available device.
7) Managing the recorded data of all connected devices.
8) Viewing sleep/mobility reports and notifications.

C. The web portal to the radar

The web portal to the radar (see Figure 3b) is a web application hosted on the HealthSonar device itself, accessible solely via the local network the device is connected to. It facilitates direct communication with, and access to, a specific HealthSonar device, serving as the primary tool for configuring its settings. While the web portal shares a similar purpose with the mobile application (see Section II-D), it uniquely offers configuration capabilities for the radar, which the mobile app does not.

Contrary to the web dashboard and mobile application, the web portal is designed for a more technical audience. Trained healthcare professionals or researchers in various healthcare and research environments, including care homes, hospitals, and medical research facilities, utilize the web portal as a tool for setting up the radar device, quickly scheduling and implementing sleep or mobility evaluation scenarios, gathering health and mobility data, as well as easily accessing stored data. Specifically, the functionality of the web portal is:

1) Connecting the device through Wi-Fi.
2) Configuring the settings of a device.
3) Initiating and terminating a recording.
4) Setting up a scheduler for a recording.
5) Accessing previously-stored radar data.

The web portal is intended for advanced, trained users who understand the consequences of directly accessing the HealthSonar device's settings and storage, particularly the effects of changing the internal parameters of the radar sensor. A clinical trial, or generally a similar research endeavor, would be the perfect use case for the web portal, enabling highly specialized configuration of the radar based on the needs of specific scenarios, as well as for accessing the generated data.

It should be noted that, under normal circumstances, access to the web portal should not be necessary (it would even be ill-advised), as the HealthSonar device is delivered to a user preconfigured with optimal settings. The full functionality of the system should be accessed through the web dashboard and mobile application. Throughout the design phase of the companion applications, an austere design language was purposely chosen for the web portal's user interface in order to discourage routine use. On the contrary, the web and mobile applications offer better usability through a "polished", "clean" and "friendly" user interface, encouraging their use.

D. The mobile application (mobile app)

The mobile application (see Figure 4) facilitates the initial setup of the system and provides reports based on data acquired by the HealthSonar device. It also enables elders/patients to evaluate their mobility and caregivers to receive notifications for fall incidents. Specifically, the mobile app was designed for use by elders/patients and their caregivers as a tool for:

1) Setting up and configuring the system before its first use.
2) Tracking sleep quality (e.g., sleep staging, duration).
3) Identifying sleep-related events (such as sleep apnea).
4) Evaluating mobility using gait assessment techniques.
5) Tracking gait quality, including fall risk indicators.
6) Receiving real-time notifications in the event of a fall.

Evaluating mobility is conducted using a Timed-Up and Go (TUG) test (see Section III-C), which is manually scheduled through the mobile application. Unlike feature-rich mobile apps accompanying commercial sleep and fitness trackers, the HealthSonar app prioritizes user-friendliness taking into account, first and foremost, the needs and experience of their

Fig. 2: A prototype of the HealthSonar device. On the left picture, the front side of the device can be seen, while on the right, the back side. The bottom part of the device houses the Raspberry Pi 4 and the top part contains the Aria Sensing LT102 radar module. Various connection ports are located on the top, back, and sides of the device. The radar connects to the Raspberry Pi board via an external USB cable.

users. The mobile application caters to users with two main limitations: unfamiliarity with technology, common among elders, and impaired dexterity experienced by patients with movement disorders like Parkinson's disease. Recognizing these limitations, the HealthSonar app is designed towards providing a user experience that is both concise and focused. This is achieved by intentionally designing it primarily as a reporting tool.

E. System data storage and processing

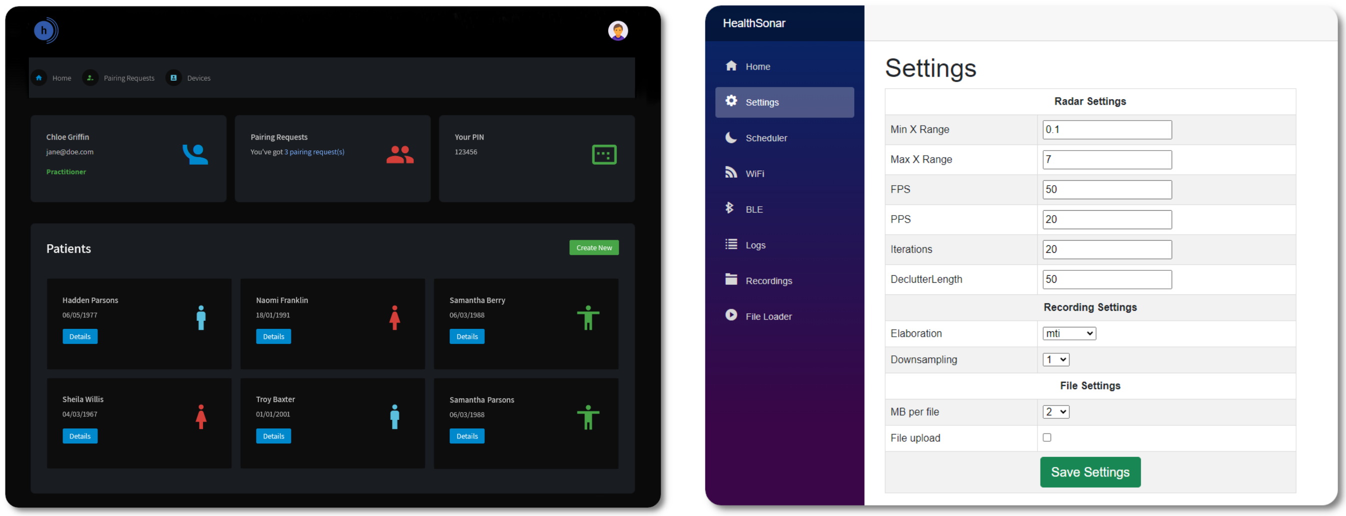
The radar data acquired during the operation of the HealthSonar system are stored and processed either locally on the monitoring device or on the Cloud after being uploaded. The decision depends on the time-critical nature of the resulting analytics for the health of the user. Local, on-device, storage and processing delivers near real-time outputs, crucial for situations where immediate action might be necessary. On the contrary, uploading to the Cloud, while valuable for long-term analysis, can introduce delays.

The fall detection and, to some degree, the mobility evaluation pipeline, leverage on-device storage and processing, producing their outputs as close to real-time as possible. Fall detection is a cornerstone of any assisted-living solution, but its effectiveness hinges on delivering real-time alerts immediately following the detection of a fall. Falls present a significant risk of serious injury, particularly for elderly individuals and patients with movement disorders. These populations are more vulnerable due to a combination of factors: increased fragility and the possibility of falls going unnoticed if they are unable to move and call for help afterwards.

Real-time fall notifications can be a matter of life and death, providing precious time for caregivers to attend to the needs of the faller, potentially saving their live. Similarly, mobility evaluation (TUG test) benefits from producing results with minimal latency, mainly for two reasons. First, physicians conducting mobility evaluations require the resulting information as soon as the evaluation concludes, ideally while the patient is still present. This allows physicians to tailor treatment plans based on the patient's current condition and discuss them directly. Revisiting a patient's case at a later time would be impractical. Second, the results of a TUG test indicate a high risk of future falls. While this information is not strictly time-sensitive, early awareness allows for timely medical interventions and preventative measures to be taken, potentially avoiding serious future injuries. However, recognizing the potential value for research and custom analysis, the system allows users to upload the raw TUG test radar data to the Cloud for future use. Uploading is easily managed through the web dashboard application.

On the other hand, the sleep monitoring pipeline rely on Cloud storage and processing since time-critical feedback to the users is not required. Nighttime monitors typically work silently in the background, collecting data throughout your sleep. Upon waking, they automatically stop recording and process the data to generate a sleep report accessible through a mobile or web application. HealthSonar follows the same approach, automatically collecting sleep data throughout the night and concluding recording upon waking. It then generates a sleep report accessible via its mobile app and web dashboard.

Last but not least, presence detection acts as a prerequisite step for both sleep monitoring and fall detection, necessitating its real-time execution on the HealthSonar device. Unlike sleep monitoring and mobility evaluation, presence detection does not generate data for long-term analysis. Instead, it acts as a



(a) (b)

Fig. 3: (3a) A screenshot depicting the web dashboard's homepage layout, optimized for user-friendliness and clear presentation of health monitoring data. Designed to meet the demands of healthcare professionals in diverse settings like care homes and hospitals, the web dashboard provides a powerful toolkit for patient data monitoring, device management, and overall system administration. (3b) A screenshot depicting the Settings page of the radar's web portal. This page caters to trained users with advanced technical knowledge, allowing them to configure specialized radar parameters. These configurations are primarily intended for researchers conducting specialized studies. To ensure optimal performance out of the box, the HealthSonar device is preconfigured for typical use, eliminating the need to access the web portal under normal circumstances. To discourage routine use, a utilitarian, bare-bones user interface was chosen.

trigger, signaling the system to launch the appropriate pipeline (sleep or fall) when a user's presence is detected.

F. Application Programming Interface (API)

The communication between the Cloud services and the "local" parts of the HealthSonar system is enabled by an application programming interface (API). The API acts as the middleman for data access and integration between databases, web services and the device itself as well as the mobile application. More specifically, the API provides functionality enabling secure and stable communication between the HealthSonar device and the Cloud, safeguarding sensitive user data and guaranteeing data integrity. The functionality offered by the API serves a pivotal role in the use of the HealthSonar system and enables building, maintaining and scaling its overall ecosystem. The API opens the door for future innovation. It allows third-party developers to create applications that connect with the HealthSonar system. This not only empowers users with a wider range of tools to manage their health data, but also fosters a vibrant ecosystem of applications that leverage HealthSonar's features for personalized health insights and experiences.

G. HealthSonar: Customizable, Scalable

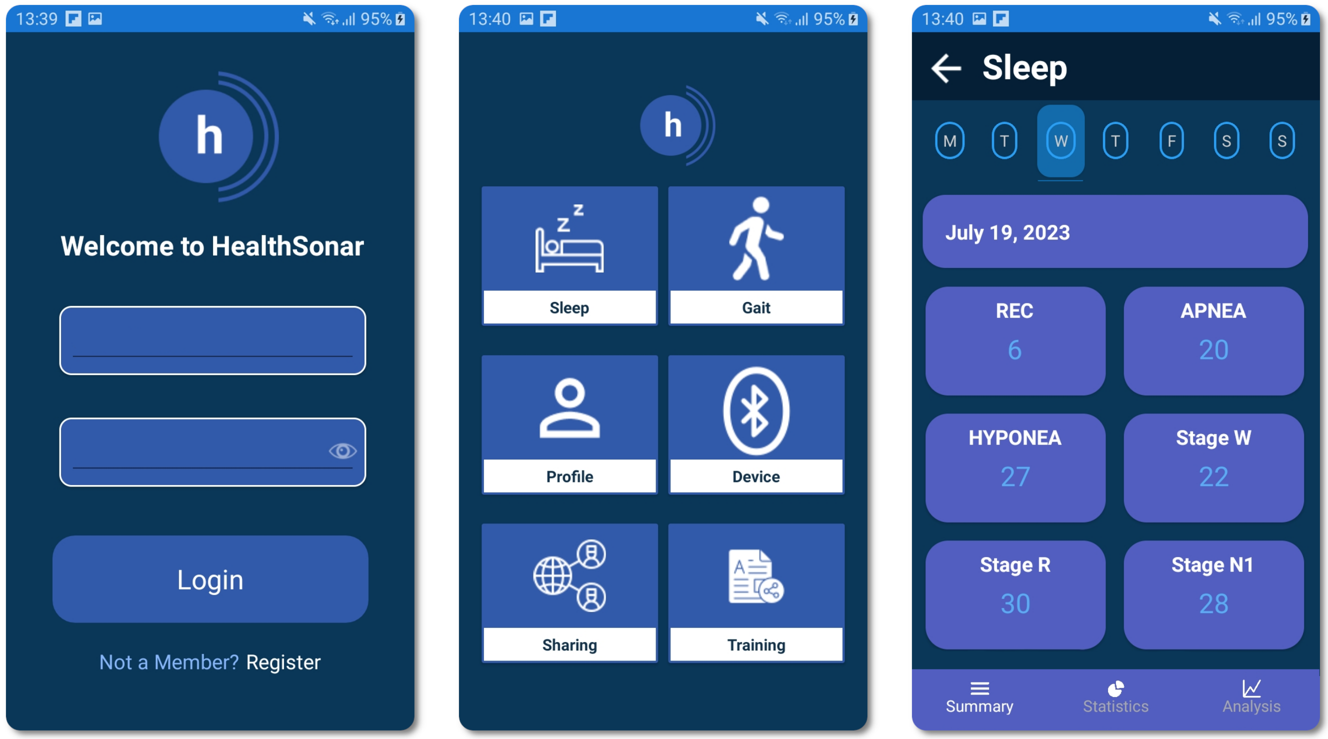
The HealthSonar system offers high customizability and scalability. This flexibility allows it to function effectively as a single unit or as a network of radar-based devices. Notably, the term "network" refers to a collection of HealthSonar devices managed by a central service, not a cluster of interconnected devices themselves. Each device's radar parameters can be precisely adjusted to suit the specific application. Centralized management of all active devices within an organization is conveniently facilitated through the web dashboard application.

The HealthSonar system provides extensive customization options, allowing users to tailor its functionality to their specific needs. Users can choose to utilize at least one radar-based device along with the accompanying software components (including the web portal, web dashboard, and mobile app) based on their requirements. For research purposes, the web portal offers comprehensive functionality and grants elevated access to the embedded radar parameters. However, administrators should possess knowledge regarding the theory and operation of IR-UWB radars.

Furthermore, the HealthSonar ecosystem as a whole boasts extensibility and can seamlessly integrate with one or multiple radar-based devices as needed. This adaptability is particularly crucial for care homes and clinical environments, where requirements evolve based on the number of residents or inpatients. By effortlessly expanding, or reducing, the connected network of HealthSonar devices, organizations can efficiently manage their human resources according to demand. Routine monitoring tasks can be swiftly automated by the HealthSonar system, freeing up personnel to focus on other critical responsibilities.

III. Sleep, Mobility, Presence and Falls

The HealthSonar system leverages the IR-UWB radar module to capture rich micro and macro body movements. These



(a) (b) (c)

Fig. 4: Various screens of the HealthSonar mobile application. (4a) The login screen. (4b) The main menu. (4c) The sleep analytics. The app provides a user-friendly interface to the HealthSonar system, assisting users in configuring the device before its first use, as well as providing sleep metrics, sleep-related events, mobility metrics and real-time fall notifications.

captured movements provide valuable data for health and well-being monitoring, offering insights into mobility, posture, and potential sleep disturbances. HealthSonar offers the following functionalities:

1) Human presence detection within a space.
2) Nighttime sleep monitoring (e.g., quality, duration).
3) Sleep-related events identification (e.g., sleep apnea).
4) Mobility evaluation (e.g., gait, balance, fall risk).
5) Fall detection in high-risk environments.
6) Real-time fall notifications enabling timely action.

A comprehensive description regarding the features of the HealthSonar system (i.e., presence detection, sleep monitoring, mobility evaluation and fall detection), as well as the necessary setup, including suggestions, for its proper use per application can be found in Sections III-A, III-B, III-C and III-D.

The performance of the HealthSonar system was evaluated in the sleep lab of Evangelismos General Hospital (with patients suffering from sleep disorders), in the neurology clinic of the University Hospital of Ioannina (with patients suffering from), as well as in-house (with healthy individuals), through experimental setups similar to the ones described in the aforementioned sections (those are depicted in Figure 5). The results of the performance evaluation of the HealthSonar system have been published in peer-reviewed journals and conference proceedings [26], [28]–[31].

A. *Presence detection*

Presence detection serves as the essential foundation for both sleep monitoring and fall detection within the HealthSonar system. This crucial process runs continuously and locally on the device itself, acting as a prerequisite before activating either the sleep or fall detection pipelines.

By detecting human presence, HealthSonar can determine whether someone is lying in bed for sleep. If so, it automatically initiates the sleep monitoring pipeline to capture sleep data. Similarly, presence detection allows the bathroom-mounted HealthSonar to identify when someone is using the bathroom, triggering the fall detection pipeline as a precautionary measure.

B. *Sleep monitoring*

Sleep monitoring is a core function of HealthSonar. When the presence detection pipeline identifies someone lying in bed, it automatically initiates sleep monitoring. This continuous process gathers detailed data throughout the sleep period. Once the user leaves the bed, the monitoring stops, and the locally stored data is uploaded to the Cloud for in-depth analysis.

Unlike fall detection or mobility evaluation, sleep data processing leverages the Cloud infrastructure of the HealthSonar system. This is because real-time sleep metrics aren't crucial during the night. Instead, HealthSonar extracts valuable sleep insights upon data upload, including sleep stage classification (identifying wakefulness and sleep periods) and sleep apnea event detection. Users can then access these metrics through the web dashboard or mobile application.

For accurate sleep staging and apnea detection, HealthSonar calculates respiratory rate and heartbeat during sleep monitoring. These metrics serve as essential preprocessing steps for an advanced and thorough sleep analysis (such as, sleep staging and sleep apnea detection) conducted in the Cloud.

C. Mobility evaluation

The HealthSonar system evaluates the mobility of an individual based on the Timed Up and Go Test (TUG) [32], a well-established, standardized test, used for assessing various aspects of one's mobility, such as gait, balance and risk of falling [33], [34]. Performing a TUG test requires minimal instrumentation, namely

1) an armchair (the arms are crucial for the test),
2) a reference marking the 3 m walking distance and
3) a stopwatch, (with variations being the iTUG tests [33]).

A participant begins the test seated in the armchair. Following instructions, they stand up unaided, walk for 3 meters, turn around 180 degrees at the reference marking the turning point, walk back to the chair, and sit down to complete the test. The performance of the participant is timed with the stopwatch, with the total time serving as the final score of the test.

HealthSonar utilizes a modified version of the Timed Up and Go (TUG) test to assess gait. The key difference lies in the walking path length. Instead of the standard 3 meters, HealthSonar utilizes a variable walking distance ranging from 3 to 5 meters. This extended path allows for the collection of a richer set of gait data, such as the total walking duration, the turning duration and the average gait speed [26], resulting in a more comprehensive representation of the participant's mobility. Note that due to the use of the radar-based device, this modified TUG test is considered instrumented (iTUG).

Mobility evaluation in HealthSonar, unlike presence detection and sleep monitoring, is user-initiated through the mobile app (or the web portal to the radar for advanced or custom use cases). The instrumented Timed Up and Go (iTUG) test, is typically infrequent and periodic, often conducted following a physician's recommendation. This test requires a controlled setting, specific procedures, and the HealthSonar device itself as the instrumentation properly setup for accurate results. Following completion of the TUG test, the collected raw gait data is stored and processed locally on the HealthSonar device. The extracted mobility evaluation metrics can then be presented to users through the mobile app or web dashboard. The web dashboard provides an additional option for users to manually upload the generated iTUG test data to Cloud storage for potential future use or analysis. This can be beneficial for identifying long-term trends or sharing data with healthcare professionals.

A typical setup for a HealthSonar iTUG test scenario can be seen in Figure 5. The placement of the HealthSonar device should allow for the effective monitoring of the path in front of the armchair during the testing process.

D. Fall detection

HealthSonar's fall detection functionality builds upon the presence detection capabilities of the HealthSonar system, ideally installed on a bathroom wall. This targeted approach focuses on the bathroom, a high-risk area for falls among elderly and patient populations [35], [36]. Due to the critical need for real-time monitoring in high-risk areas, fall detection runs continuously on the HealthSonar device itself. This local processing ensures timely response in case of a fall event.

Upon detecting a fall, the system automatically sends notifications to both the web dashboard and mobile app, alerting caregivers, physicians or other relevant healthcare professionals and enabling them to swiftly address the fallen individual's needs. Fall detection is a crucial feature in assisted living environments for elders and patients. Falls can lead to serious or even fatal injuries. Real-time identification allows for prompt intervention, potentially preventing further harm to the fallen individual.

IV. The care home application

The HealthSonar system's diverse and rich feature set allow it to be used by various user groups for a plethora of use cases. However, it is particularly well-suited for clinical environments and assisted-living scenarios as they take advantage of all its features and functionality. One of those scenarios, is a care home, housing elders or patients with movement disorders. The specific needs of a care home are similar to those of any clinical environment, such as a hospital or a clinic. Consequently, the presented application can be seamlessly implemented in any clinical environment with minimal modifications. For the purposes of this work, we consider a care home, with several rooms, each one resembling the layout depicted in Figure 5. The specific arrangement of each room is not crucial, while the only requirements are usually already met by a typical room (a nightstand and an armchair).

A. Device installation

For full coverage of a room, providing comprehensive monitoring, two HealthSonar devices are recommended. The first device is placed on a nightstand, primarily for sleep monitoring. When an iTUG test needs to be conducted, this same device can be conveniently repositioned to effectively monitor the subject's walking path (covering a 3-to-5 meter straight line walking distance. The second device is mounted on a bathroom wall, strategically positioned for optimal coverage of the area for fall detection. The targeted placement of the device prioritizes the bathroom since it is regarded as the most hazardous space for elders and patients in the context of falls associated with an elevated likelihood of resulted serious injuries [35], [36]. Refer to Figure 5 for a visualization of the suggested device placements for various functionalities: sleep monitoring, mobility evaluation (iTUG test), and fall detection.

B. Monitoring procedure

After installing the HealthSonar device, healthcare professionals can set it up for use through the mobile app with

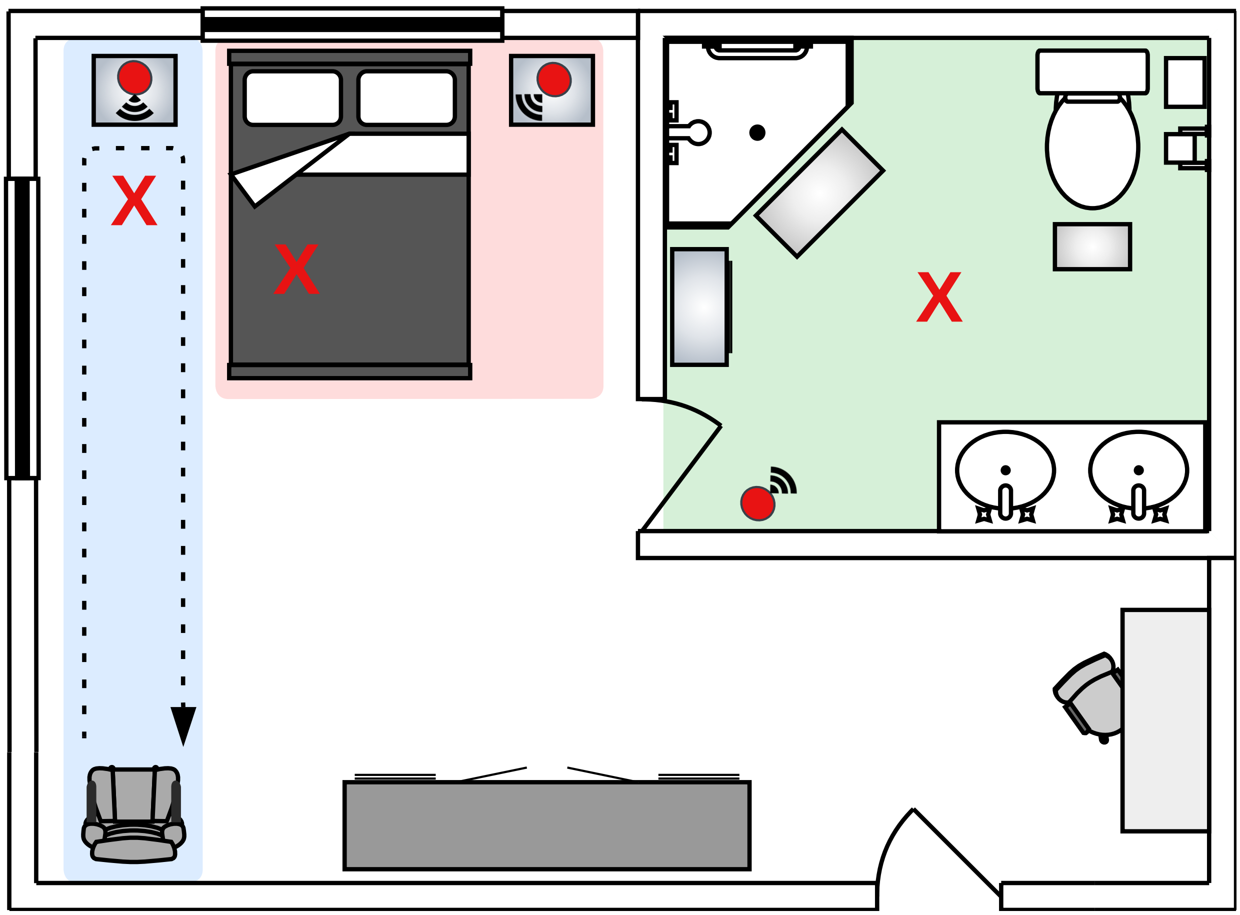


Fig. 5: Three illustrative scenarios showcasing the HealthSonar system's application within a typical bedroom of a care home or a similar clinical environment. **Green area**: A falling detection scenario. **Red area**: A sleep monitoring scenario. **Blue area**: A suggested Timed Up and Go (TUG) test scenario.

minimal effort. This involves registering an account for the resident and linking it to the device. Once configured, the device is ready for use.

Residents themselves don't need to interact with the device physically, as it's operational is contactless and unobtrusive. However, they can optionally access the HealthSonar system through a mobile app to view their sleep and mobility reports.

Sleep monitoring and fall detection run continuously in the background. Presence detection allows the system to automatically initiate these monitoring sessions. Manual session initiation is also available if needed.

C. Managing the system

The HealthSonar system is designed to be straightforward and user-friendly for busy care home personnel. It integrates seamlessly into their existing routines, requiring minimal additional time or effort.

Healthcare professionals leverage the web dashboard for comprehensive monitoring and resident data management. The dashboard provides functions for:

1) **Device Overview**: Gaining a quick view of all installed HealthSonar devices, including activity status, data upload status, and user registration.
2) **Device Management**: Assigning devices to residents, handling recorded data, accessing system information, and manually setting up recording sessions.
3) **Resident Analytics**: Reviewing detailed reports on resident sleep patterns (sleep stages, sleep apnea events) and gait metrics (total walking duration, turning duration, average gait speed). Leverage historical data to personalize care plans by evaluating residents' condition progression.
4) **Fall Notifications**: Receive real-time notifications regarding fall incidents taking place in residents' bathrooms, allowing for prompt intervention and injury prevention.

V. Discussion

The rising number of elders and patients with sleep disorders (like insomnia and restless leg syndrome), neurological conditions (like Parkinson's disease), and movement disorders (like gait abnormalities) highlights the need for improved monitoring solutions. These groups face similar challenges, primarily related to sleep quality and mobility. Continuous, unobtrusive, and privacy-focused monitoring can offer valuable insights into sleep quality (e.g., sleep duration, fragmentation) and mobility state (e.g., gait patterns, fall risk assessment), potentially leading to earlier interventions and improved health outcomes.

This work presents HealthSonar, a complete and unified assisted living solution designed and built from the ground up. It goes beyond a proof-of-concept, functioning as a comprehensive, multifunctional system for sleep monitoring, mobility evaluation, and fall detection. HealthSonar ensures streamlined operation and reliable data collection through its fully integrated elements, unlike systems relying on disparate hardware and software components. HealthSonar is comprised of

1) A prototype device, fabricated using additive manufacturing techniques (see Section II-A).
2) A suite of custom-developed software applications (see Sections II-B, II-C and II-D).
3) A set of novel algorithms implementing the system's functionality (see Section III).

The system is designed to be operated with minimal to no interaction from the user. Following installation and initial setup (see Section IV-A for device installation details), the radar-based device seamlessly runs in the background, unobtrusively monitoring sleep and detecting falls. Users can entirely bypass the software components and remain unaware of the system's operation. In such cases, healthcare professionals can access sleep reports and receive fall notifications. HealthSonar is entirely maintenance-free. Eliminating the need for batteries, the device can be permanently plugged into a wall socket, functioning continuously atop a nightstand or mounted on a wall. The system has been tested to function as intended under realistic conditions (see Section III).

Highlighting the versatility of the HealthSonar system, this work demonstrated its effectiveness in a care home setting. This adaptable scenario readily integrates into diverse clinical settings, requiring minimal adjustments to deliver comprehensive health/wellness monitoring.

Our presented approach for sleep monitoring, mobility monitoring and fall detection within a care home offers a comprehensive solution for clinical environments. However, the HealthSonar system's design allows for further customizations to address evolving healthcare requirements and potentially even entirely new applications. As an example, our use case prioritizes continuous fall detection in bathrooms, recognizing them as high-risk zones for falls in elderly and patient populations. This targeted approach maximizes effectiveness while minimizing intrusiveness in residents' living spaces. If necessary, continuous fall detection can be extended to bedrooms or other areas based on individual needs and risk factors.

As of now, the functionality of the HealthSonar system is significant, yet future development could extend it in various directions.

1) **Advanced Mobility Evaluation**: Enhance the mobility evaluation to identify freezing of gait events in Parkinson's patients. This could significantly improve patient care and early intervention strategies.
2) **Bedroom Fall Detection**: Based on user feedback, explore implementing continuous fall detection within the bedroom area to provide a more comprehensive monitoring solution.
3) **Refined Heartbeat Extraction**: Incrementally improve the heartbeat extraction algorithm, a crucial preprocessing step for sleep monitoring, to ensure the accuracy of sleep data analysis.

While the software for HealthSonar (web/mobile app, radar portal) is considered feature-rich and fully-realized, delivered as a robust wellness monitoring application suite, the current prototype prioritizes functionality over design aesthetics. However, future iterations can explore a more refined design, potentially incorporating elements such as a user-friendly screen. This display could show time, weather, or news headlines, transforming the nightstand device into a versatile dashboard with additional functionalities.

VI. Conclusions

The increasing number of elders and patients with sleep and neurological disorders necessitates improved health monitoring solutions, particularly for sleep and mobility. This work presented HealthSonar, a novel contactless and unobtrusive system designed to enhance the well-being of elderly individuals and patients with sleep and movement disorders in assisted living settings. HealthSonar prioritizes user privacy while providing continuous sleep and mobility monitoring, as explored through a care home application scenario.

The presented care home scenario exemplifies HealthSonar's centralized management, enabling healthcare professionals to simultaneously monitor the health status and analytics of multiple residents. This seamless integration significantly improves workflow efficiency. For residents, HealthSonar provides a hassle-free experience with completely unobtrusive monitoring, eliminating the need for physical or digital interaction.

Continuous, privacy-preserving monitoring solutions like HealthSonar have the potential to revolutionize the way clinical organizations (care homes, clinics, hospitals, etc.) monitor their residents. By providing a continuous stream of actionable health data and analytics, HealthSonar empowers these organizations to optimize care delivery while alleviating the burden of repetitive and time-consuming tasks like continuous health monitoring.

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