HealthSonar: A System for Unobtrusive Monitoring of Elders and Patients with Movement Disorders

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***Abstract*—This work presents the HealthSonar, a novel unobtrusive, privacy-focused, health monitoring system for elders and patients with movement disorders, capable of tracking the quality of their sleep, identifying sleep apnea events, evaluating their mobility and detecting falls. The system comprises a impulse radio ultra-wideband (IR-UWB) radar-based device, a web portal, a web dashboard and a mobile application. Due to its nature, HealthSonar is perfectly suited for care homes, and generally for clinical environments, where residents are in need of continuous monitoring, especially during their sleep, as well as during their presence in hazardous rooms, such as bathrooms.**

***Index Terms*—ultra-wideband radar; health monitoring; sleep monitoring; gait analysis; fall detection**

I. Introduction

The world's older population is rising, along with the number of patients suffering from sleep, neurological and movement disorders [1]–[4]. Impaired mobility, in particular, can result in falls, which in turn can result in life-threatening injuries, especially in older people. A practical solution, offering a unified approach for monitoring sleep, evaluating gait and identifying falls, could be of great interest, specifically for care homes and clinical environments. As of now, to the best of our knowledge, there is no such practical unified solution offering all those features.

Lately, progress in ultra-wideband (UWB) radar technology has resulted in the development of affordable, practical and accurate radar sensors [5] that can be used as a platform for building health monitoring solutions. Specifically, because of their high accuracy, penetrating 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. Some of them are, respiratory and heart rate extraction, sleep monitoring, presence detection, fall detection, people counting, gesture recognition, baby monitoring, assisted living of elderly people, as well as mobility monitoring [5], [6]. 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 one would be privacy-intrusive. Moreover, regarding sleep, radars offer unparalleled opportunities for contactless sleep monitoring as their penetrating abilities result in posture recognition even in low temperatures where people would be covered with blankets [7]. Given radar sensors 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 to human health [5].

In this work, we present a novel health monitoring system, the HealthSonar, based on UWB radar technology. The system itself can be used easily in a plethora of clinical scenarios and even as a general tracker for improving the quality of life of healthy people, but its applicability in clinical environments and care homes is particularly noteworthy. Specifically, in Section II the various hardware and software parts of the HealthSonar system are presented and in Section III its functionality is described. Next, in Section IV the innovative aspects of the system are discussed along with possible future directions for its improvement. Last but not least, in Section V some concluding remarks are presented.

II. The HealthSonar system

The HealthSonar system was created to fill the gap in accurate, unobtrusive, privacy-focused, continuous and particularly contactless, health monitoring. More specifically, the system was created to serve elders (especially those with deteriorated mobility) and patients with movement or sleep disorders in tracking the quality of their sleep, identifying sleep apnea events, evaluating their mobility and detecting fall events.

 ISBN: 978-1-68558-105-3

Fig. 1. A prototype of the HealthSonar device.

Moreover, the system also detects human presence, which is a prerequisite and important step for choosing when the sleep monitoring or the fall detection pipelines will initiate.

The development of the system was propelled by the recent advances in IR-UWB radar technology, especially the small sizes of the available sensors and their affordable prices. Those features rendered them commercially viable options to be used as platforms for building health monitoring devices. The HealthSonar system consists of the following "components": (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 with different users in mind, such as elders, patients, nurses, care workers or attending physicians. It was also designed to provide different administrative and monitoring utilities to each one of the aforementioned groups. The HealthSonar system is meant to be straightforward and easy to use, while still being customizable for advanced, mainly research, use cases. It is important to note that HealthSonar was built as a centralized, extensible system, as a result multiple devices can be connected and administrated at once, in order to cover the needs of a care home, or generally of a clinical environment. On the other hand, the system is modular enough to be usable as a single unit, ideal for home use applications, or even research purposes. Last but not least, HealthSonar is operational with minimal user interaction and after its first setup, it can continually monitor either a bed for sleeping individuals or a bathroom for human activity. Given its lack of a battery, as it will be described below, the system does not even need the users to manually check its power level at regular intervals.

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 the prototype of the HealthSonar monitoring device in Fig. 1. The front side of the device can be seen on the left half of Fig. 1, while the back side can be seen on the right half. The case for the prototype was produced using additive manufacturing techniques. The device comprises an Aria Sensing LT102 IR-UWB radar sensor, embedded within the top part, and a Raspberry Pi 4 Model B board encased within the bottom base. The specifications of the Aria Sensing radar module can be found in Table I. On the top, back and side of the device, various connection ports can be seen. The radar connects to the Raspberry Pi board via 1 external USB cable.

TABLE I
ARIA SENSING LT102 RADAR SPECIFICATIONS.

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

The radar sensor identifies micro motions (such as the oscillation 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 HealthSonar device is not powered by a battery, but through a wall socket, as a result it can work indefinitely without any user interaction for charging purposes. The intended placement of the device is: (1) next to a bed, on top of a nightstand, enabling nighttime sleep monitoring, (2) mounted on a bathroom wall, enabling fall detection, or (3) mounted on top of a tripod, or other suitable furniture, for general mobility evaluation. The system's intended use is depicted in Fig. 3 and includes 2 HealthSonar devices, one placed on top of a nightstand and one on the bathroom wall.

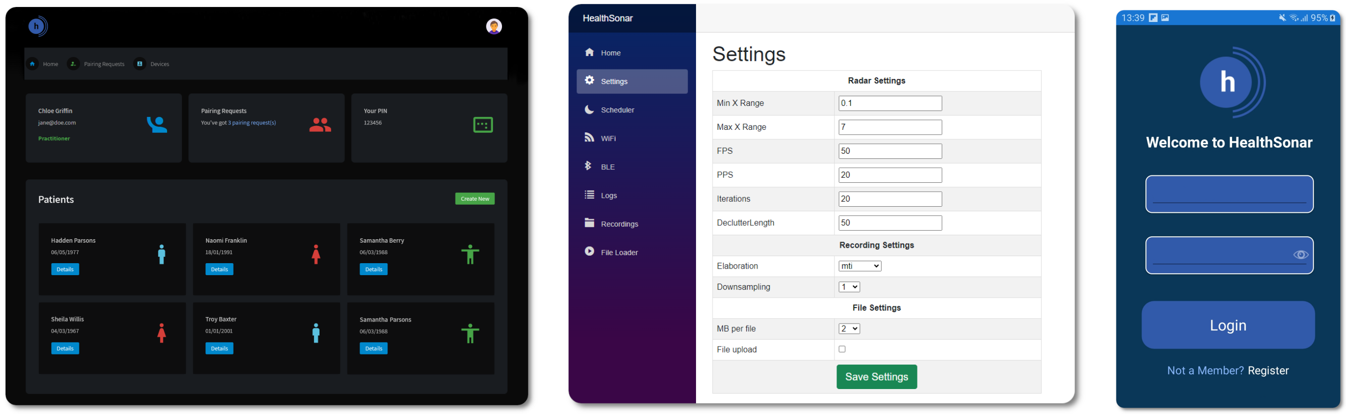
B. The web dashboard application

The web dashboard (see Fig. 2a) is a web application that runs on the cloud and can be accessed through the Internet. Its purpose is to act as the central hub for managing multiple (or more aptly, at least one) connected HealthSonar devices. The dashboard is meant to be used by care home workers or nurses as an administrative and overview tool.

The functionality of the dashboard is: (1) Manually initiating and terminating recording sessions. (2) Manually selecting data for upload to the cloud storage. (3) Accessing telemetry data (logs) for connected devices. (4) Accessing system information (metadata) about each device. (5) Assigning users (e.g., elders, patients) to specific devices. (6) Viewing the connection status of each available device. (7) Managing the recorded stored data of all connected devices. (8) View reports and notifications for the extracted health analytics.

C. The web portal to the radar

The web portal to the radar (see Fig. 2b) is a web application that runs locally on the HealthSonar device itself and can only be accessed through the local network that the device is



(a) (b) (c)

Fig. 2. (2a) The main screen of the web dashboard. (2b) The settings page of the web portal. (2c) The mobile app's login screen.

connected to, without the need for an Internet connection. Its purpose is to facilitate direct communication with, and access to, one specific HealthSonar device, while also serving as the main configuration tool of its settings.

Generally, the web portal shares a similar purpose with the mobile application, that will be described below (see Section II-D), although the latter is not able to configure the radar. The portal is meant to be used by care workers or nurses, that have been trained in its use, as a tool for setting up the radar device, for rapid implementation of various testing scenarios and data gathering (e.g., sleep or mobility evaluation scenarios), or for easy access to stored radar data.

Specifically, the functionality of the web portal is: (1) Setting up the radar 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. As a result, the web portal is intended as a tool for advanced, trained users, that understand the consequences of having direct access to the HealthSonar device's settings and storage, and specifically the effects of changing the internal parameters of the radar.

An example of an ideal use case for the web portal would be that of a clinical trial, or generally any research endeavor, in which the portal would be the main tool of the researchers for configuring the radar based on the needs of specialized scenarios, as well as for accessing the resulted data. It should be noted that, under normal circumstances, the web portal should not be used, as the HealthSonar device is delivered to a user preconfigured. As a result, no tinkering with advanced settings is needed, while the HealthSonar's full functionality can be achieved with the user-friendlier web dashboard and mobile application. This is the main reason that the web portal's user interface is not as polished as the web dashboard's as its target user group.

D. The mobile application (mobile app)

The mobile application (see Fig. 2c) facilitates the initial setup of the system and provides, to the end user, sleep and mobility extracted metrics based on data acquired with the HealthSonar device, enables the user to evaluate their mobility and receives notifications for fall events. The end users of the mobile app are the ones being monitored by the HealthSonar device (usually those are the elders and patients). The functionality of the mobile app, apart from setting up the system during its first use, revolves around providing detailed analyses about sleep quality (through sleep staging and sleep duration), sleep-related events (such as obstructive sleep apnea), mobility metrics indicating deteriorated gait, or a higher fall risk, as well as real-time notifications in the event a fall takes place within the bathroom. Note that the aforementioned presented mobility metrics are calculated using data generated through a TUG test, which the users need to manually initiate through the HealthSonar mobile app itself. As a result, the initiation of a TUG test session is one more feature of the mobile application.

Contrary to feature-rich mobile applications for commercial sleep and fitness trackers, the HealthSonar app is built around user-friendliness and targeted functionality, taking into account, first and foremost, the needs and experience of their users, those being elders and patients. Said groups of people, are not accustomed to technology, or they are not capable of operating an app extensively due to impaired dexterity (for example patients with Parkinson's disease). As a result, in such cases, the most concise, and focused, user experience should be preferred, with the HealthSonar app being, intentionally, a reporting tool.

E. System's data storage and processing

The radar data acquired during the HealthSonar system's operation are either stored and processed locally on the radar-based monitoring device, or uploaded to the cloud for storage and further processing. Whether the storage and processing is done offline or online is determined by how time-critical the resulting analytics are for the user.

The gait monitoring and, crucially, the fall detection pipelines should provide their outputs as close to real-time as possible. Nurses and physicians should receive the results of a TUG test when it concludes in order to plan ahead based

 ISBN: 978-1-68558-105-3

on the mobility state of the test's subject. The results of a TUG test can indicate a high risk of falls in the future, thus such information is necessary in order to take preventative steps and arrange medical interventions before any misadventure takes place. Moreover, nurses and caregivers should receive notifications for a fall immediately in order to take timely action. Falls can lead to serious injuries, and given that they can go unnoticed if the faller is unable to move, real-time notifications can be a matter of life and death. As a result, all processing for those tasks is done locally on the radar-based device itself in order to avoid the time-consuming data uploading procedure or any Internet connection issues that may lead to problems in data uploading altogether. Nevertheless, as the TUG test raw radar data can be useful for research purposes, or simply for further custom analysis, there is the option to upload them to the cloud for storage and future use. This can be done via the web dashboard application.

On the other hand, sleep monitoring, does not provide time-critical data to the users. Generally, nighttime monitors are meant to gather data while a person is asleep, conclude the recording when they wake up, followed by processing the stored data and presenting them in a report when available. Note that, although sleep apnea events identified by the HealthSonar system during a person's sleep can be serious, they are not time-critical information and there is no advantage in sending real-time notifications to alert either the person sleeping or nurses and caregivers. As a result, the sleep monitoring pipeline includes automatically uploading the stored data to the cloud, as soon as the user wakes up, where they will be further processed and presented in a sleep report via the mobile app or the web dashboard.

Last but not least, presence detection is a necessary step prior to sleep monitoring and fall detection. As a process, it does need to run in real-time but it does not generate any data for further processing, apart from an event indicating that the sleep or fall pipeline should initiate. Hence, presence detection has to run locally on the HealthSonar device but no data are stored (for long-term use) or uploaded to the cloud.

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 is accessed through the web dashboard and the mobile application with the goal of bringing into contact the device with the cloud. The functionality offered by the API serves a pivotal role in the use of the HealthSonar and enables building its overall ecosystem. The facilitated communication is conducted in a secure manner to safekeep the sensitive user data.

G. HealthSonar: Customizable, extensible

The HealthSonar system was built to be customizable and extensible. As a result, the system can be used as a single

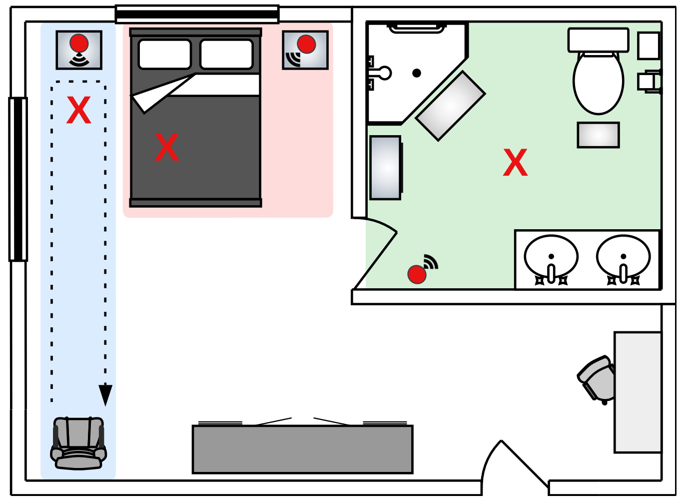


Fig. 3. Three suggested scenarios with the HealthSonar system inside a typical bedroom with a bathroom. **Green area**: A falling detection scenario. **Red area**: A sleep monitoring scenario. **Blue area**: A suggested Timed Up and Go (TUG) test scenario.

unit or as a "network" of radar-based devices, with all the radar's parameters able to be finely-tuned depending on the application at hand. The term "network" does not denote that the devices are connected with each other, but with a service offering centralized management of all the active HealthSonar devices of the organization using them. The centralized management is conducted via the web dashboard application.

The HealthSonar system is customizable enough to offer a plethora of options regarding how to use it and which features are needed for a certain application. More specifically, one can use at least one radar-based device along with all its accompanying software (namely, web portal, web dashboard, mobile app), or only with the ones they need. For research purposes, the web portal could offer complete functionality and elevated access to the device's embedded radar parameters, although the administrator should be knowledgeable regarding the theory and operation of IR-UWB radars.

On top of that, HealthSonar is extensible and can be deployed with one, or with as many radar-based devices is necessary. The extensibility is particularly important for care homes, and generally for clinical environments, as their needs change over time based on the number, and needs, of their residents or inpatients. The ease of extending, or even shrinking, the "network" of connected HealthSonar devices, can also help the organizations utilizing it to better-manage their human resources easily based on their needs. In a moment's notice, routine, yet important monitoring tasks, could be easily arranged to be performed by the HealthSonar system itself, leaving the personnel free to provide other vital tasks.

III. PRESENCE, SLEEP, MOBILITY AND FALLS

The HealthSonar system uses the IR-UWB radar module in order to capture rich micro and macro body movements that

 ISBN: 978-1-68558-105-3

are subsequently used for monitoring health through: (1) detecting human presence within a space (2) studying nighttime sleep (staging, duration), (3) identifying sleep-related events (sleep apnea), (4) evaluating mobility (gait evaluation), and (5) detecting sudden, dangerous fall events. A description regarding the applications of the HealthSonar system (presence detection, sleep monitoring, gait evaluation and fall detection) can be found in more detail in the subsequent Sections III-A, III-B, III-C and III-D.

The performance of the HealthSonar system in those applications was evaluated, in a sleep lab of Evangelismos General Hospital (ethical committee's approval number 198/06-06-2022), with patients suffering from sleep disorders, in the neurology clinic of the University Hospital of Ioannina (ethical committee's approval number 7/21-03-2023), with patients suffering from movement disorders, as well as in-house, with healthy individuals, through experimental setups similar to the ones depicted in Fig. 3.

A. Presence detection

Presence detection is the cornerstone of the HealthSonar's features as it is a necessary step taking place prior to both sleep monitoring and fall detection. Presence detection is a procedure running constantly (apart from when the device is used for mobility evaluation), by default, on the HealthSonar device, as it is a prerequisite for initiating either the sleep monitoring or the fall detection pipeline.

Through presence detection, the HealthSonar system is capable of detecting whether someone is lying on a bed with the intention of sleeping, resulting in automatically initiating the sleep monitoring pipeline, based on the absence of activity and the monitoring of vital signs. On top of that, presence detection enables the bathroom wall-mounted HealthSonar device to identify whether someone is using the bathroom, resulting in automatically initiating the fall detection pipeline based on abrupt decreasing changes in signal's energy.

B. Sleep monitoring

Sleep monitoring is an important aspect of the HealthSonar system's functionality. Monitoring sleep in enabled for a nightstand-mounted HealthSonar device by the presence detection pipeline. More specifically, after the system detects a person lying on the bed, and until they move away from it, the sleep monitoring pipeline is initiated and runs continuously gathering data. Once the person moves away from the bed, the sleep monitoring routine comes to a halt and the generated data, which up to this point were stored locally on the HealthSonar device, are uploaded to the cloud for further processing, leading to the extraction of rich sleep-related metrics pertaining to sleep staging classification (including wake/sleep identification) and sleep apnea events detection that are presented either through the web dashboard or the mobile application. Contrary to the fall detection and gait evaluation pipelines, the processing of the gathered sleep data takes place on the cloud as there is no imminent need for the user to receive the extracted nighttime metrics in real-time. It is important to note that, during the sleep monitoring routine, the respiratory rate and the heart rate are calculated as they are a necessary preprocessing step prior to sleep staging and sleep apnea detection.

C. Gait evaluation

The HealthSonar system evaluates the gait of an individual based on the Timed Up and Go Test (TUG) [8], a well-established, standardized test, used for assessing various aspects of one's mobility, such as gait, balance and risk of falling [9], [10]. Performing a "classic" TUG test requires minimal instrumentation, namely an armchair (it is important for the chair to have arms), a mark for the $3\,\mathrm{m}$ distance and a stopwatch, although there are versions of the TUG test where extra instrumentation is used to better track the performance of the participants, (iTUG tests) [9]. A participant starts the test while sitting on the armchair, then, after being instructed, proceeds to stand up unaided, walk for $3\,\mathrm{m}$, turns around the mark $180°$, walks back to the armchair and sits down, thus, ending the test. The performance of the participant is timed with the stopwatch, and the total time of the test is used as the final score.

In order to evaluate gait using the HealthSonar device, a modified version of the TUG test is utilized. The modification lies in the use of a 3 to $5\,\mathrm{m}$ walking path instead of the "classic" $3\,\mathrm{m}$, as it leads to the acquisition of more gait data, and as a result to a richer representation of the participant's mobility state. A suggested setup for a TUG test scenario with the HealthSonar can be seen in Fig. 3, where the device placed on top of the nightstand can be positioned in such a way as to monitor the path in front of the armchair. Note that due to the use of the radar-based device, this modified TUG test is considered instrumented (iTUG). The test results in the generation of a body of rich gait data, which are used to extract a set of gait metrics useful for the evaluation of a person's mobility. Those are, the total walking duration, the turning duration and the average gait speed [11].

The gait evaluation pipeline of the HealthSonar device does not run automatically, but is initiated manually through the mobile app (or the web portal to the radar for advanced, or custom use cases) by arranging a TUG test session. After the TUG test is finished, the resulting data are stored and processed locally on the HealthSonar device itself and the gait evaluation metrics are presented to the user via the mobile app through a Bluetooth connection. Note that there is the option to manually upload the generated TUG test data to the cloud storage though the web dashboard for future use.

D. Fall detection

Fall detection is a pipeline initiated through the presence detection feature of the bathroom wall-mounted HealthSonar device. The detection of fall events was designed to run for the bathroom area as it constitutes one of the most hazardous areas for elders and patients [12], [13]. Due to its nature, the fall detection pipeline is run locally, and continually (in case the presence detection procedure indicates there is a person using the bathroom), on the HealthSonar device as it needs to monitor for falls in real time. In the event of a fall, the system will identify it and sent a notification to both the web dashboard, as well as to the mobile phone application in order to notify caregivers to attend to the faller's needs. Fall detection is a crucial feature for any system facilitating assisted living of elders and patients as falls can result in serious, even fatal, injuries, thus their identification in real time can lead to timely interventions preventing further serious consequences for the faller.

IV. Discussion

In this work, a complete, unified, assisted living solution, the HealthSonar, targeted at monitoring sleep, evaluating gait and identifying falls was presented. The innovative nature of the solution lie in the fact that it is cheap, easy to use and home-based, while offering all the aforementioned features combined. As far as we know, currently no other alternatives exist that tick all those "boxes". The HealthSonar system was designed and built in-house, from the ground up, into a fully functioning assisted living monitor. The system was designed to be operated with minimal to no interaction from the user. Apart from the installation and the first setup, it was of paramount importance for HealthSonar to be unobtrusive while continually monitoring its surroundings, either for sleeping individuals or falls. As a matter of fact, it is possible for the user to bypass using any of its software application and "ignore" the system altogether. In that case, a treating physician or a nurse can be responsible for reading reports about the user's sleep, as well as receive notifications regarding falls. It is important to note that the device has no battery and can be permanently connected to a wall socket, thus existing on top of the nightstand (or the wall) indefinitely.

As of now, the functionality of the HealthSonar system is significant, yet future directions could extend it in various ways. One of the most useful, lie in the improvement of the mobility evaluation to include the identification of freezing of gait events in patients with Parkinson's disease. Moreover, as already mentioned, fall detection within the bedroom area could also be explored in the future based on the feedback we will gather from more users of the system. Last but not least, the heartbeat extraction, being a preprocessing step for sleep monitoring, could be further improved. Last but not least, the device was built as a prototype, thus technical limitations prohibited the design and construction of a more refined case for the inner hardware. As a result, in a future version, the device could be redesigned from the ground up, and one particularly useful addition would be a screen showing the time, the weather or the news of the day. This feature would be useful for the nightstand-mounted device, as it would then serve as a dashboard showing useful information.

V. Conclusions

The population of elders and patients with sleep and neurological disorders is rising, leading to a growing need of accurate continuous health monitoring, mainly revolving around sleep and mobility. Continuous, privacy-preserving, contactless, monitoring solutions, such as the HealthSonar, have the potential to disrupt the way clinical organizations (care homes, clinics, hospitals, etc.) monitor their residents, by providing a stream of health analytics, while helping them preserve human resources from repetitive, yet necessary tasks such as continuous health monitoring.

Acknowledgment

This research was funded by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH–CREATE–INNOVATE (project name: HealthSonar, project code: T2EDK-04366)

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