Titolo rivista/libro: Digital Health Technology for Better Aging

Titolo articolo/sezione: Monitoring in the Physical Domain to Support Active Ageing

Autore/i: E. Denna,M. Civiello, S. Porcelli, A. Crivello, F. Mavilia, F. Palumbo

ISBN: 978-3-030-72663-8

DOI: 10.1007/978-3-030-72663-8_4

Anno: 2021

Volume:

Editore: Springer

Pag. iniziale: 55

Pag. finale: 76

Monitoring in the Physical Domain to Support Active Ageing

E. Denna, M. Civiello, S. Porcelli, A. Crivello, F. Mavilia, and Filippo Palumbo

Abstract Monitoring system have been customized to collect data and to analyse several aspects of the users' life, the reason of this custom solution came from the needs to join physical activity of the user, life usage, social interaction and mind activities, all these features are not present in standard devices all together, so we arrived to a new system architecture where the monitoring system is the first front end versus the user. This chapter describes the general monitoring system architecture and provides insight into the contribution and role of sensors. Such sensing solutions are not only designed to match the needs and requirements of the user but also to reduce intrusiveness and usage complexity. By doing so the system is designed around the life of its users and maximizes the effectiveness of data collection. Example from NESTORE project are taken as reference.

1 Design Requirements and Guidelines

The monitoring system has been designed according to some precise requirements coming from different workshops that took place in different sites, with several champion users. Due to the target users characteristics, workshops led to identify some basic user needs: the monitoring system needed to be composed by not invasive devices, with a user friendly interface and easy to be used, and at the same time able to collect several data to track different activities of the user and some of his/her biometric parameters.

Keeping in mind the physical requirements and the user design requirements coming from the workshop, the monitoring system resulted to be composed by 6

E. Denna (✉) · M. Civiello
Flex Design Medical S.r.l., Via Ernesto Breda 176, 20126 Milan, Italy
e-mail: enrico.denna@flex.com

S. Porcelli
Institute of Biomedical Technologies, National Research Council, Segrate, Milan, Italy

A. Crivello · F. Mavilia · F. Palumbo
Institute of Information Science and Technologies, National Research Council, Pisa, Italy

G. Andreoni and C. Mambretti (eds.), *Digital Health Technology for Better Aging*, Research for Development, https://doi.org/10.1007/978-3-030-72663-8_4

Fig. 1 Graphic representation of Nestore wearable and environmental monitoring system

devices, each one able to satisfy one or more requirements and to always meet the user requirements:

The wristband is Bluetooth 4.2 connected with the apps in the user smartphone, while the beacons are Bluetooth 4.2 connected to the wristband itself, so all the data of these devices are transferred to the app on the smartphone, while the sleep monitor and the smart scale are Wi-Fi connected by the user router, transferring data directly to the cloud.

The monitoring system architecture is represented in the following figure (Fig. 1).

The user smartphone and tangible interface complete the set of devices used by the Nestore user and they are present in his house. User smartphone is used also to take pictures of food and beverages consumed by the user to track his/her nutrition consumption and habits. This additional operation is considered part of the monitoring system, while the tangible interface is not.

From all the variables present in the Table 1, a final group of variables will be monitored during specific test exercises the user will be asked to complete at identified moments. The required exercises are:

- 6 min walking test
- 30-s Chair Raise Test.

During these tests, several variables will be monitored to obtain precise information to be analysed and described in the table below (Table 2):

All these data are transferred to the cloud where algorithms will process and elaborate to provide lifestyle suggestions to the user.

The following figures better depict the wearable wristband and environmental monitoring system components (Figs. 2, 3, 4, 5 and 6):

Table 1 Devices of the Nestore monitoring system

Device	Physical requirements	Technical requirements	User requirement
Wearable wristband 	Continuous monitoring of variables: Steps Distance Activity recognition Sedentariness Stairs Energy expenditure Data report: Start/stop time and duration Exercise intensity Target heart rate Cardio-respiratory score Peak heart rate Post exercise heart rate recovery Activity energy expenditure Total steps Total distance Difference in altitude Data as time series: Timestamp with time zone info Steps Cadence Distance Exercise heart rate Grade	Battery level	The wearable wristband looks like a common smartwatch for fitness monitoring, so it doesn't't' look like a medical device. The user interface is based on a colour LCD display with few simple and big icons and fonts, reporting essential information. The feedback to the user is given by a motor vibrator inside the wearable and user interaction is granted with a single multifunction button. The battery recharging operation is managed by a wireless charging station provided as accessory
Environmental beacons 	User activities inside his/her home	RSSI Battery level Motion detection House temperature	Devices attached in the user house that don't limit or interfere with the normal life of the user in his/her house. No user interface and feedback are present, the battery is expected to last 1 year

(continued)

Table 1 (continued)

Device	Physical requirements	Technical requirements	User requirement
Social beacons 	Social interaction activities	RSSI Battery Level	Devices provided to user friends and relatives. They look like a common keychain. No user interface and feedback are present, the battery is expected to last 1 year
Sleep monitor 	Sleep duration Sleep quality		Transparent to the user because it is attached and powered under his/her bed, so no battery recharging operation is required to the user It is Wi-Fi connected to the user router
Smart scale 	Weight Body mass	Wi-Fi and battery indicators are provided by the display of the scale	It is a commercial scale powered by commercial batteries and Wi-Fi connected to the user router

In the following paragraphs the single physical devices will be analysed from a more technical point of view.

2 Wearable Wristband Architecture Overview

The wearable is designed as a bracelet. In the present section, there is a description of its technical implementation examined according to the Industrial Design and Mechanical, Hardware and Firmware engineering structure.

The wearable has the following features (Fig. 7).

Table 2 Variables of the test exercises

Test exercise	Variables
6 min walking test	Data report: Start/stop time Peak heart rate Post exercise heart rate recovery Activity energy expenditure Total steps Total distance Difference in altitude Data as time series: Timestamp with time zone info Steps Cadence Distance Exercise heart rate Grade
30-s chair raise test	Data report: Start/stop time Peak heart rate Post exercise heart rate recovery Activity energy expenditure Total repetitions Data as time series: Timestamp with time zone info Acceleration Repetition Pressure

Fig. 2 Wearable device: to be worn daily, to monitor basic vital parameters (i.e.: Heart Rate, energy expenditure, steps count etc.) and to provide the first user interface

Fig. 3 Ad-hoc charging station for the wearable device: the device is suitable to wireless charge the wearable device. Design and functionalities have been realized to optimize the usage

Fig. 4 Social (black) beacons and Environmental (white) beacons: devices suitable to monitor respectively the user social interactions and the user in-house habits during daily life activities. They provide two environmental parameters: house temperature and humidity

Fig. 5 Off-the-shelf smart scale (https://www.withings.com/uk/en/body-plus): the device is able to measure not only the weight of the user, but also additional useful data such as muscle, bone and fat mass and body water. The device is Wi.FI connected directly to the Cloud

Fig.6 Off-the-shelf sleep monitoring sensor: the device can monitor the user sleep activity and quality mapping movements during the sleep. The device is Wi.FI connected directly to the Cloud (https://www.murata.com/en-eu/products/sensor/accel/sca10h_11h/sca11h)

Feature	Solution
Body position	Wrist
Sensors	Accelerometer, Barometer, PPG
Form Factor	Wrist-band
User Interface	Button, TFT display,Motor vibrator
Connectivity	BTLE
Power	Rechargeable battery

Fig.7 Wearable device features

2.1 Industrial Design and User Interface Solution

During the workshops conducted in the first period of the project, users expressed a clear preference for a small and discreet wristband that could be well integrated with people's lifestyles and existing accessories, with a minimal and simplified UI.

The wristband design respects the following characteristics:

- **DISCREET**. During the workshops conducted, users expressed concerns that people might label and stigmatize them when noticing them wearing a strange new device or a device that looked like medical. The wristband should, therefore, have a sober aesthetic that doesn't catch people's attention.

Designers examined some possible solutions like:

- hiding the UI when not in use, for instance by using a lens or a particular material or finish on top of the display.
- simple and approachable overall shape, not too styled or characterized.
- neutral or desaturated colours
- In alternative, disguise the wristband as something else, such as a generic bracelet or fashion/sport accessory.

Finally, a simple and linear black case was designed and ad-hoc produced, in order to seem sober and not out of the ordinary design language of the most known smart watches/wristbands actually present on the market.

- **EASY TO WEAR**. As elderly people develop dexterity problems the more they grow old, particular attention should be given to the strap design, in order to guarantee a quick and effortless operation.

Possible solutions examined were:

- prioritizing simplified locking mechanism that does not require high accuracy of movements such as Velcro or magnetic attachments.
- Potentially explore a closed-loop design that doesn't require feeding the strap through small elements etc.
- Minimize the number of steps of the overall operation.

For these purposes, an ultra-light, soft and magnetic bracelet has been chosen as the best solution.

- **EASY TO MANAGE**. From the user workshops, it was clear that elderly develop strong habits that are hard to change. The solution should adapt to their routines rather than disrupt them. Particular attention should be therefore given to the charging experience, a key aspect in the wearable usage that, if not designed well, could negatively affect the overall experience or even lead to discontinuity in usage. Cleanability is another key aspect that shall be well addressed.

The possible solutions were:

– Create a solution that feels natural and requires little to no attention from the user, such as a docking, to be positioned on the bedside that wirelessly charges the wristband overnight.
– Consider using magnetic attachments between the two elements to aid positioning and provide a quality feeling.
– Easy separation of wristband body and bands could also aid cleanability (potentially in the washing machine) which in terms will result in higher user acceptance.

For these purposes, an ad-hoc charging station was designed and produced. The station is simple and intuitive to use, and a magnetic alignment system has been inserted to avoid any mistake in the positioning of the bracelet onto the station. Thus, the user is guided, by the magnetic alignment system, to get the right position of the wearable onto the station.

Furthermore, an easy and intuitive UI has been designed, in order to adapt to what users already utilize every day with their smartphones.

- **COMFORTABLE & COMFORTING**. Many users tend to dislike wearable devices the more they grow old: during the workshops, many mentioned not even wearing classic watches because uncomfortable or having to wear one because someone dear gifted them. The solution should therefore well integrate with their lifestyle and routines, as well as be physically ergonomic and enjoyable to wear.

The possible solutions identified were:

– using softer and ‘warmer’ materials for the wristband body, such as textile or PU,
– having an organic and ergonomic shape that well adapts to the user’s wrists.
– Particular attention shall be given to balancing the tightness of the wristband necessary to properly monitor heartbeat related variables and the comfort expected by the users.

Given the impediments identified with textile and PU wristbands (excessively thick and uncomfortable to be worn with a single hand), Flex selected a metallic wristband with a magnetic clasp that firmly stacks without any effort required to the user.

- **CUSTOMIZABLE**. Healthy elderly people are still quite active socially and give much importance to their look and public image. Moreover, as Nestore users will be of both sexes and different cultures, the wristband shall be able to adapt and be personalized based on individual tastes and needs. Being able to customize elements of the User interface could also be a highly appreciated feature that could make users feel more understood and valued as individuals.

Possible solutions:

– offering swappable bands that could be picked at the moment of purchase or offering a few variants as main to allow choice based on the occasion or need. This approach will also simplify maintenance and be expandable for future updates.
– allowing, through the smartphone APP, to customize the wearable UI both visually as well as in terms of haptic/sound feedbacks.

For these purposes, Flex selected a standard size (20 mm) for the wristband alignment to the wearable case. The users are free to change their wristbands with every off-the-shelf wristband that respect that standard measure.

- **SIMPLE & EMOTIONAL UI**. During the workshops, most users expressed preferences for a coach with a friendly and supportive personality, someone that understands them and motivate them with positive messages rather than stressing their misbehaviours and leverage on a sense of guilt. Moreover, users were not particularly fond on receiving complex information on the wristband (whose small form factor also would pose serious problems on the readability of the messages due to the natural decay of eyesight). The User interface shall, therefore, be simplified displaying less information in a clear way and adopt a more emotional tone of voice that could be perceived as more motivating and natural by non-technical users.

The possible solutions identified were:

– prioritize simple human language over technical stats
– leverage on haptic feedbacks to communicate simple messages through different patterns without having to look at the device.
– Communicate activities progress in a visual way through progress bars or circles or even colours.
– Utilize icons and visuals to provide context to the messages.
– Minimize user interactions avoiding the need to press buttons to trigger activities.

For these purposes Flex identified the usage of a vibramotor as both helpful and discreet. It lets the user receiving feedbacks without requiring any user active interaction.

2.2 Technology Selection

The data collection solution involves a selection of the suitable technology for the Nestore application. There are several sensors to be selected for the scope according the available alternatives.

Starting from the wristband device, the proper technology to be used for heart rate monitoring is the Photoplethysmography (PPG) that is an uncomplicated and inexpensive optical measurement method. PPG is a non-invasive technology that uses a light source and a photodetector at the surface of skin to measure the volumetric variations of blood circulation. A more precise method is the ECG monitoring based on electrical pulse sensor, but this system is more used in medical application and even if it is possible to reduce the number of the electrodes, the user should attach the electrodes to his skin by some wires, resulting in an uncomfortable solution.

The physical movements of the user including step and climb are normally obtained by a combination of accelerometer and precise barometer that combine movement and ligth air pressure difference. The feature in the technology is mainly given by the algorithms used that shall consider and filter false movements and increase the precision of the measure. Some of these algorithms, like fall detection, step count and climbing measurement shall be calibrated and personalized around the hardware designed. Of course, also the Nestore algorithm of the device have been tuned to obtain the desired accuracy.

The other functionalities of wristband are implemented with standard technologies for wireless connection and user interface: Bluetooth communication, vibramotor, colour LCD and wireless charger.

The technologies used for beacon is mainly related to the proximity sensing, used either for the social than for the environmental. There are several options for proximity detection from optical solution, microwave, ultrasound or magnetic sensors. Due to the Bluetooth connection already implemented in the wristband, Nestore leverages on the RSSI of the Bluetooth protocol to detect the proximity between the beacon and the wristband.

Sleep monitoring and Smart scale are commercial solutions selected for Nestore according the requirements of not invasiveness.

In the following chapters a detailed technical description of the device implementations will be presented.

2.3 Wristband Mechanical Description

This section describes the mechanical implementation of the wearable wristband device and his accessories.

Mechanical dimensions have been chosen in order to design and produce a case with a display and one button to get the simplest user interface, to respect the user requirements expressed during the Workshop user study. The charging base is designed with Renesas proprietary low power wireless technology, to meet miniaturizing and power budget efficiency needs. Renesas uses circa 100 mW instead of 5 W consumed by a standard C or WMA protocols.

The bracelet consists of a rigid part containing and protecting the electronics components and a soft and adjustable bracelet for maximum wearability comfort guaranteeing the correct positioning and therefore the correct functioning of the PPG sensor.

Compatibly with the mandatory electronics components, Flex designed and produced the smallest and most comfortable dimensions possible. The PPG sensor protrudes of 1.5 mm, to guarantee the correct positioning and functioning (Fig. 8).

The bracelet case is made of biocompatible plastic materials (polycarbonate) and was produced with injection moulding technology.

Injection moulding is an industrial production process in which a plastic material is melted and injected under high pressure into a closed mould, which is opened after solidification of the manufactured article. Usually injection moulding is a suitable process for a high volume of production; nevertheless, in this case, with a limited production quantity, was selected because it ensures high quality of the parts in respect to other technical solutions (e.g.: 3D printing).

Concerning the rigid part of the bracelet: since the PPG sensor needs to be glued on the plastic case, Flex chose a polycarbonate material to guarantee the tightness between the two parts. This choice was supported, furthermore, by the good mechanical properties of the polycarbonate.

The wristband is metallic with a magnetic clasp and it was chosen to ensure the best comfortability and wearability easiness (Fig. 9).

Fig. 8 Wearable case CAD file view

Fig. 9 Metallic bracelet clasp detail

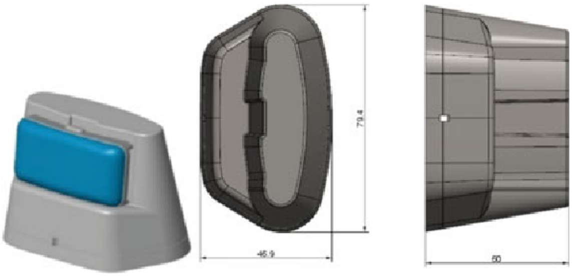

Fig. 10 Charging station CAD files view

2.4 Mechanical Drawing for Charging Station

The approach for the construction of the loader was to keep small dimensions and ensuring a good solidity to keep the charger and device during charging in position and avoid accidental drops. The charger has a micro USB interface (Fig. 10).

As gathered during the requirements identification phase, the mechanical team, in collaboration with the ID team, investigated the idea of an error-proof interface. The main goal was to identify a solution that avoids misplacing the device onto the station.

A magnetic alignment system was inserted in both the case and the station. The alignment between the magnets guides the user to place the wearable in the correct way, thus ensuring the proper recharging.

2.5 Hardware Solution

The hardware electrical architecture of the wristband is described in the block diagram below:

To monitor all the required variables, the electronics is equipped with three sensors:

- A Valencell module (Benchmark wrist 1.2) implementing the Heart Rate and PPG function
- A 3-axis accelerometer (LIS3DH—ST) suitable for step count, distance and exercise detection
- A barometer (ICP-10100—TDK) providing useful information for floor climbing and exercise, combined with accelerometer information.
  The user interface is composed of two main elements:
- A colour TFT display that is used for an easy user interface, and can also be versatile and upgradable to provide even more complex information too, if required in the future
- A vibro-motor, common in all wearable devices and smartphones or smartwatches that can provide haptic feedbacks (Fig. 11).

- One mechanical button that can be used for power on–off and for general interactions

The communication with the router and with the other smart accessories is done by a customized BTLE interface with an integrated antenna. All the logic functions are managed by a microprocessor CC2640R2F of Texas Instrument that leverages on a Serial NAND to store and buffer the data to be transmitted via BTLE.

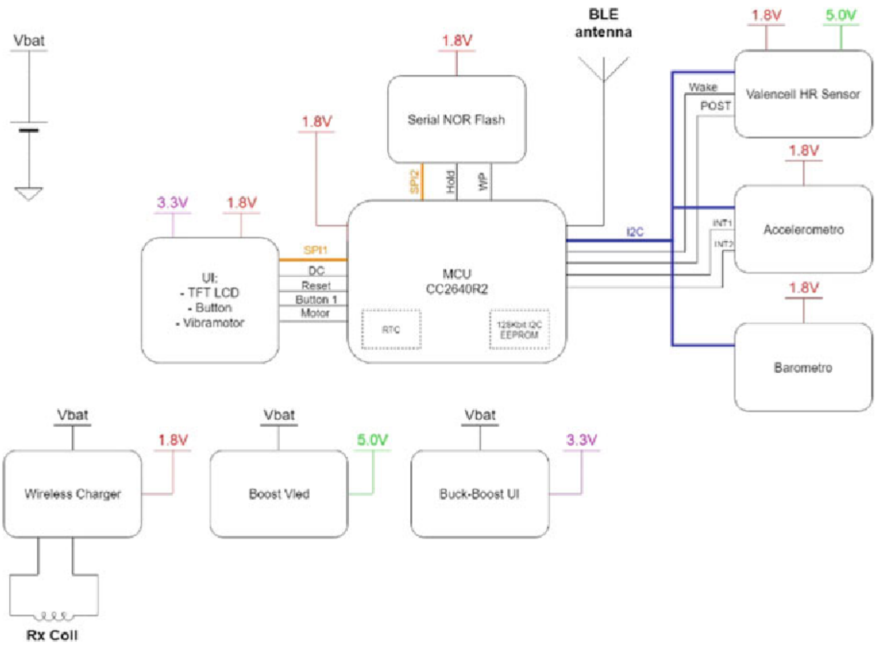

Fig. 11 Block diagram of wearable electrical architecture

The wristband is powered by a rechargeable battery of Li+ polymer in the order 95mAh. The recharging operation is realized with a couple of TX-RX device of Renesas where the TX is inside an external docking station powered by a standard wall adapter with micro-USB connector, typical for mobile applications and easy to use.

The battery duration esteem is based on the Nestore user scenario. It has been necessary to make some assumptions about the time the users might spend in performing usual daily activities. The table below summarizes the number of hours daily spent for different purposes (Fig. 12)

The following graph describes the power budget computation based on the composition estimation of the power consumption. The actual battery duration is around 1 day of usage, around 20 h, depending on the utilization (Figs. 13 and 14).

Day time division	Hours
Sleep hours	7 h
Physical Activity hours	2 h
Wake-up hours	15 h

Fig. 12 Use case scenario for a standard daily utilization of the wearable device

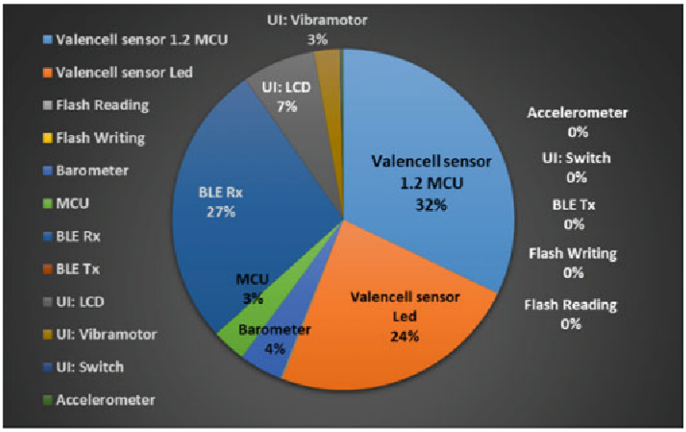

Fig. 13 Graphical representations of components percentage power consumption distribution

		Worst case	Best case	Actual status
Heart rate sensor		Always on during the day; disabled during sleep time	Always on during the physical activity. During the other hours of the day: 30 seconds on and 30 seconds off; when the device is not worn or in charge	1 minute on and 2 minutes off during the utilization. Disabled when the device is not worn or in charge
Flash	Writing	Writing any 265 bytes of data, corresponding to 0.5ms any 5 seconds	Writing any 265 bytes of data, corresponding to 0.5ms any 5 seconds	Range considered: from 6 to 9 times a day. Disabled when the device is not worn or in charge
	Reading	3times per day during synchronization; total read byte 3.1 Mbyte, esteem reading time: 6 seconds	3 times per day during synchronization; total read byte 3.1 Mbyte, esteem reading time: 6 seconds	Range considered: from 6 to 9 times a day. Disabled when the device is not worn or in charge
Barometer		Always on during the day; disabled when the device is not worn or in charge	Always on during the day; disabled when the device is not worn or in charge	Always on when the device is worn. Disabled when the device is not worn or in charge
MCU		Normally in sleep mode, it wakesup to Collect, store, process transmit sensor data and visualize information on the screen	Normally in sleep mode, it wakesup to Collect, store, process transmit sensor data and visualize information on the screen	Normally in sleep mode, it wakesup to Collect, store, process transmit sensor data and visualize information on the screen
BLE	TX	3 times per day to transmit data from flash memory during synchronization	3 times per day to transmit data from flash memory during synchronization	The range actually considered: from 6 to 9 times a day. Disabled when the device is not worn or in charge
	RX	400 ms any 2 seconds to receive data from beacons	220 ms any 3 seconds to receive data from beacons	330 ms for each BLE transmission channel (3 in total) every 3 seconds. Total: 990ms
UI	LCD	Overall 10 minutes on per day	Overall 10 minutes on per day	Overall 10 minutes on per day
	Vibro-motor	Overall 1 minute on per day	Overall 1 minute on per day	Overall 1 minute on per day
	Switch	Overall 2 minutes on per day	Overall 2 minutes on per day	Overall 2 minutes on per day

Fig. 14 Power consumption analysis

2.6 Charging Station

Here following the block diagram of the charging station used to wirelessly recharge the wearable device (Fig. 15).

All the hardware architecture is based on Renesas TX board working on 175 kHz power less than 1 W and an off-the-shelf coil to couple with the RX. A LED is present

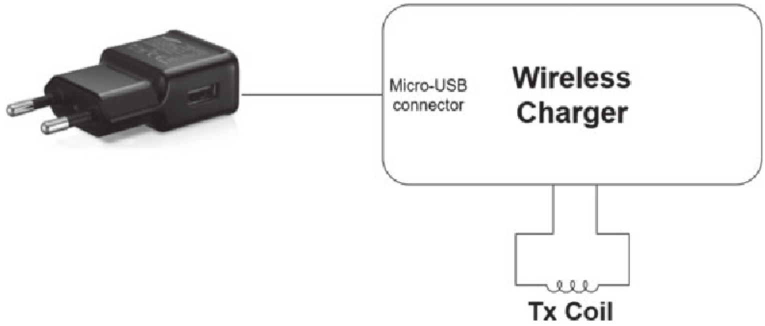

Fig. 15 Charging station block diagram

to indicate the charger activity. The connection to the main power is realized by a standard wall-plug adapter with a standard USB cable with micro connector.

3 Environmental Sensors for Physical Activity

The NESTORE environmental monitoring system is an ensemble of wireless sensors able to sense the variables indicated by the domain experts. Furthermore, it has the aim of detecting the interaction of the user with his circle of friends and caregivers and the environment itself, while monitoring the status of the environment, in terms of indoor thermal comfort. For this reasons, we call *environmental* device any sensor deployed in the user's vital space, while *wearable* the wristband worn by the user during his daily activities.

In order to build the integrated NESTORE environmental monitoring system, we first performed a technology selection to satisfy not only the requirements coming from the domain experts related to the user profile (to cover as much variables as possible), but also the ones coming from the co-design activities in terms of unobtrusiveness. The integrated system should be unobtrusive under diverse perspectives: (R1) user interaction—the user should not wear additional sensors or explicitly interact with the environmental device; (R2) number of device—the user's living environment should not be filled with lot of visible devices; (R3) installation and maintenance—it should be easy to deploy and maintain the device without additional effort from the user.

We focus now on the environmental technologies used to cover the variable indicated by the medical experts of NESTORE, in terms of: sleep monitoring [1, 2], weight monitoring [3], indoor user's behaviour and environmental status monitoring [4–6], and social interaction detection [7–9].

Figure 16 shows the ensemble of devices and technologies chosen to build the NESTORE environmental monitoring system.

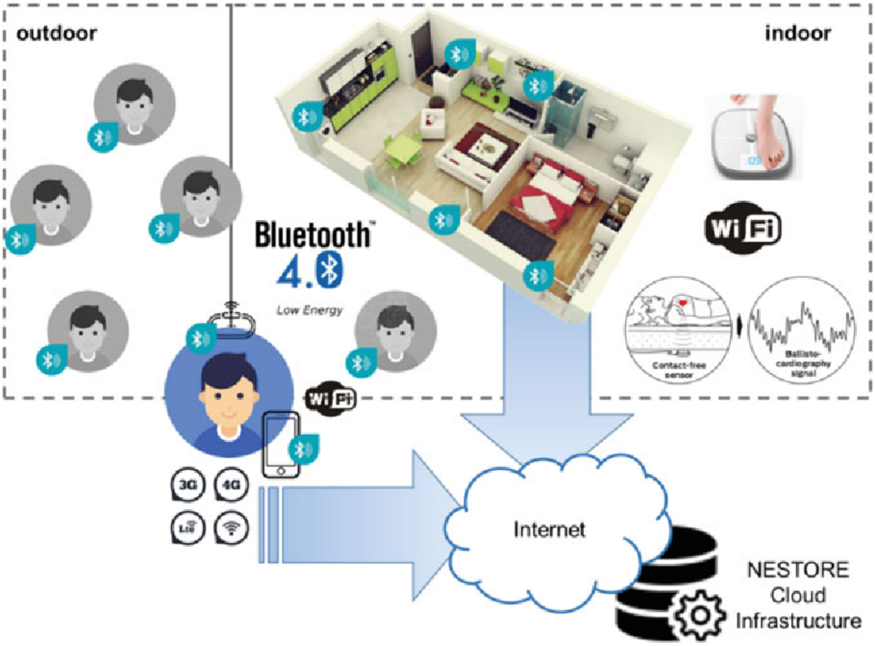

Fig. 16 The technologies used in the NESTORE environmental monitoring system

3.1 BLE Beacons

The Bluetooth Low Energy (BLE) beacons are emitters that periodically send beacons (called advertisements in BLE) with a specific rate and power. They are received by other BLE devices located nearby (e.g., the NESTORE wristband). When the receiver hears a beacon, it estimates the Received Signal Strength Indicator (RSSI), a value expressed in a decibel scale (dbm), which can be related to the distance of the receiver from the transmitter.

The set of NESTORE devices based on BLE connectivity is composed by the wristband, a charging station, and five social and five environmental beacons. The choice of BLE allows us to provide different kind of services to the user with the same devices (i.e., social interaction detection, indoor behavioural index, and indoor thermal comfort) using the inherent capabilities offered by this technology. We exploit the characteristics of the BLE technology in terms of type of customizable BLE messages (the BLE devices embed different sensors like accelerometers, humidity and temperature sensors, which information is transmitted in the advertisement's payload) and possibility to infer proximity using the Received Signal Strength of the received BLE advertisements.

Besides the social interaction and indoor thermal comfort detection, in the physical activity domain, we use BLE beacons for unsupervised user habits detection. By monitoring the activation of the sensors embedded in the BLE beacons, indicating the opening/closing of doors and room occupation of the user during his time spent at home, it is possible to retrieve heterogeneous and multivariate time-series over long periods. These time-series are used to learn recurrent behaviours of the user in her/his daily activities by analysing the time variations of several parameters like the room occupied by the user and qualitative activity level. More details can be found in [10].

3.2 Ballistocardiography

Despite being used commonly in sleep medicine, the term "sleep quality" has not been rigorously defined [11]. Usually it refers to well defined questions in dedicated questionnaires. One of the goals of NESTORE is to find a measurable sleep quality index starting from sleep related physiological characteristics. The main variables influencing sleep quality are Heart Rate (HR), Heart Rate Variability (HRV), Respiratory Rate (RR), and Respiratory Rate Variability (RRV).

From a technological point of view, there are very few ways to monitor sleep quality, among them we find polysomnography (PSG), actigraphy [2], and ballistocardiography (BCG). Being one of the main requirements of the NESTORE system its unobtrusiveness, we easily chose BCG as best candidate.

Ballistocardiography is a method for the measurement of the mechanical forces originated from the body [12]. This phenomenon was first studied in 1877 by Gordon and further investigated through the 1900s century. However, BCG was not accurate enough for medical use until recent improvements in the signal processing methods. The new ways to assess BCG signal have produced reliable results when compared with the traditional ECG measurements [13].

The rationale behind the performed sensor selection is the possibility to collect data without an explicit interaction of the user with 3rd party applications or the device itself. For this reasons, among the possible BCG solutions available on the market, we have chosen a device able to transmit data over WiFI (in order to not have a dedicate application on the user's smartphone) and that allows us to gather data with available open API. The cost has also been kept in mind. We also performed a preliminary study about their usability and performance. From the usability point of view, we considered how the device is installed, if the user has to manually start and stop the data collection and how he can view his own data. These considerations lead to the choice of the Murata SCA11H (https://www.murata.com/en-eu/products/sensor/accel/sca10h_11h/sca11h) sensor, also because it allows to design our own user interface to be integrated in the NESTORE dashboard. Also the performance analysis confirmed the Murata SCA11H as the best candidate, being the sensor that instead of providing an already aggregated and usually unreliable information about user's sleep quality it collect a more rich set of raw data, like HR, HRV, RR, and RRV.

3.3 Smart Scale

In order to collect information about the user's body composition, we integrated in the NESTORE system a smart scale able to detect the variables indicated by the domain experts (e.g., weight, percentage of fat mass, percentage of muscle mass, percentage of water, percentage of bone mass). All of the considered devices uses Bioelectrical Impedance Analysis (BIA) to calculate the body composition [14]. BIA actually determines the electrical impedance, or opposition to the flow of an electric current through body tissues which can then be used to estimate total body water (TBW), which can be used to estimate fat-free body mass and, by difference with body weight, body fat.

For the selection of the best candidate smart scale solution we considered the easiness of installation and use (no need to manually synchronize a mobile app and the device after a weighing), but also the availability of APIs to gather the collected data. For these reasons, we choose Withings Body+. It has been chosen on the basis of the availability of open APIs provided by the Withings development community. It comes with a full specification and documentation available on a dedicated website: https://developer.withings.com/oauth2/.

4 Firmware Solution

The wearable device is an embedded system that must have real-time performances and execute a lot of different tasks:

- It acquires data from different sensors, manages their data and stores them in a dedicated flash memory
- It executes different integrated algorithms to compute elaborated data starting from the sensor raw data
- It manages the Bluetooth Low Energy connections
- It manages the receiving of advertising messages of beacons devices
- It manages the bi-directional communication with the smartphone for data exchange
- It provides the user with feedback using a display and a motor-vibrator
- It responds to the user input (button pressing).

Generally, the best firmware solution for embedded devices that require pre-emption consists of using a RTOS (Real-Time Operating System). This approach permits to write an application characterized by different tasks clearly defined and prioritized. The tasks division and prioritization can greatly enhance the system's real-time performance, the modularity and portability of the code. Furthermore, many RTOS generally have some middleware stacks already implemented and the RTOS approach is often suggested when the system needs to integrate a Bluetooth Low Energy protocol for optimizing all operations.

Therefore, the design of an RTOS based firmware solution resulted appropriate for the Nestore wearable device development.

The FW application of the wearable device is divided into different tasks by functionality:

- Sensors task: It manages the peripherals on which the sensors are connected, the sensors initialization, the sensor reading procedure and the communication termination. Furthermore, it manages the algorithms that elaborate raw data coming from the sensors and orchestrates the general configuration, operation and power management of the system
- Flash task: It manages the data storing in the embedded non-volatile memory
- Bluetooth task: It manages the Bluetooth Low Energy communication
- User Interface task: It manages the feedback to the user driving the motor-vibrator and the display.

The wearable device covers two different Bluetooth roles to communicate with beacons and with the user smartphone.

4.1 For the Beacons

The wearable shall be a "BLE-observer", while the beacons shall act as "BLE-broadcaster":

the beacons advertise their specific data in broadcast permitting to every BLE device in scanning mode in the near area to receive their advertisement messages. The wearable going in receiving status scans for these advertising messages catching the beacons information without establishing a connection with them.

4.2 For the Smartphone

The wearable shall be a "BLE-peripheral", while the smartphone shall act as "BLE-central": the wearable advertises its presence like the beacons. When receiving the advertisement, the smartphone sends a scan request to the wearable. The wearable responds with a scan response.

This process is called "device discovery": the smartphone and the wearable start sharing a bi-directional connection. When the connection is established, the wearable functions as a slave exposing its services and characteristics to the user smartphone.

4.3 Data Management

Data collected by the wearable come both from its embedded sensors and from the beacons.

These data are elaborated and buffered by the sensor manager and then stored in the flash memory. The elaborated data can also be sent by the sensor manager to the UI task to give feedback to the user using vibration patterns and/or displaying texts and images on the screen (Figs. 17 and 18).

The data are read from the flash memory by the flash manager and sent through BLE to the user smartphone.

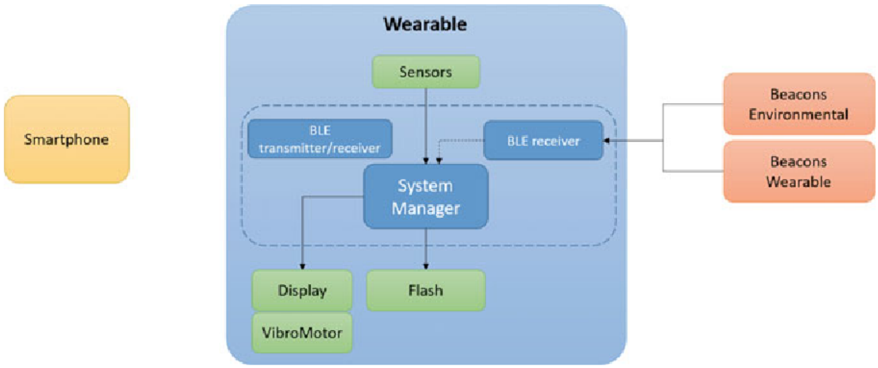

Fig. 17 Schematic of the wearable data collection process

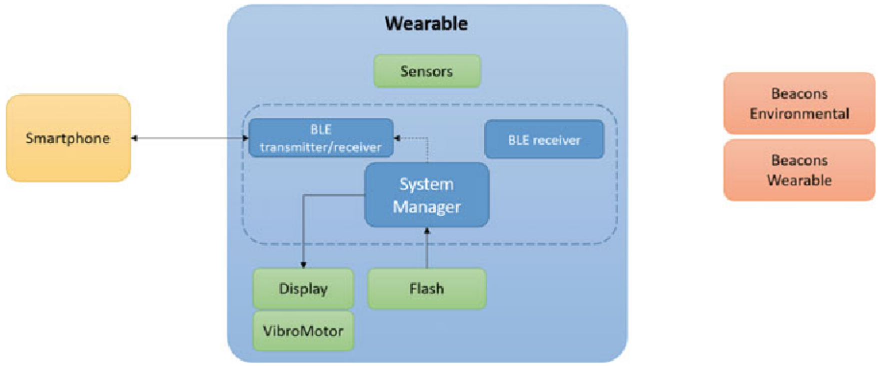

Fig. 18 Schematic of the wearable data transmission process

References

1. Crivello A., Palumbo, F., Barsocchi, P., La Rosa, D., Scarselli, F., & Bianchini, M. (2019). Understanding human sleep behaviour by machine learning. In *Cognitive infocommunications, theory and applications* (pp. 227–252). Springer.
2. Alfeo, A. L., Barsocchi, P., Cimino, M. G., La Rosa, D., Palumbo, F., & Vaglini, G. (2018). Sleep behavior assessment via smartwatch and stigmergic receptive fields. *Personal and Ubiquitous Computing, 22*(2), 227–243.
3. Bacciu, D., Chessa, S., Gallicchio, C., Micheli, A., Pedrelli, L., Ferro, E., et al. (2017). A learning system for automatic berg balance scale score estimation. *Engineering Applications of Artificial Intelligence, 66,* 60–74.
4. Barsocchi, P., Crivello, A., Girolami, M., Mavilia, F., & Palumbo, F. (2017). Occupancy detection by multi-power bluetooth low energy beaconing. In *2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN)* (pp. 1–6). IEEE.
5. Palumbo, F., La Rosa, D., & Ferro, E. (2016). Stigmergy-based long-term monitoring of indoor users mobility in ambient assisted living environments: the doremi project approach. In S. Bandini, G. Cortellessa, & F. Palumbo (Eds.), *Artificial intelligence for ambient assisted living (AI*AAL.it)* (pp. 18–32). No. 1803 in CEUR Workshop Proceedings—AI*IA Series, Aachen.
6. Barsocchi, P., Crivello, A., Mavilia, F., & Palumbo, F. (2017). Energy and environmental long-term monitoring system for inhabitants' well-being.
7. Mavilia, F., Palumbo, F., Barsocchi, P., Chessa, S., & Girolami, M. (2019). Remote detection of indoor human proximity using bluetooth low energy beacons. In *2019 15th International Conference on Intelligent Environments (IE)* (pp. 1–6). IEEE.
8. Baronti, P., Barsocchi, P., Chessa, S., Mavilia, F., & Palumbo, F. (2018). Indoor bluetooth low energy dataset for localization, tracking, occupancy, and social interaction. *Sensors, 18*(12), 4462.
9. Crivello, A., Mavilia, F., Barsocchi, P., Ferro, E., & Palumbo, F. (2018). Detecting occupancy and social interaction via energy and environmental monitoring. *International Journal of Sensor Networks, 27*(1), 61–69.
10. Palumbo, F., Baronti, P., Crivello, A., Furfari, F., Girolami, M., Mavilia, F., et al. (2019). Exploiting BLE beacons capabilities in the NESTORE monitoring system. In S. Bandini, G. Cortellessa, & F. Palumbo (Eds.), *Artificial intelligence for ambient assisted living (AI*AAL.it)* (pp. 66–84). No. 2559 in CEUR Workshop Proceedings—AI*IA Series, Aachen.
11. Crivello, A., Barsocchi, P., Girolami, M., & Palumbo, F. (2019). The meaning of sleep quality: A survey of available technologies. *IEEE Access, 7,* 167374–167390.
12. Pollock, P. (1957). Ballistocardiography: A clinical review. *Canadian Medical Association Journal, 76.*
13. Inan, O., et al. (2015). Ballistocardiography and seismocardiography: A review of recent advances. *IEEE Journal of Biomedical and Health Informatics, 19*(4), 1414–1427.
14. Schmidt, A., Döring, T., & Sylveste, A. (2011). Innovations in Ubicomp Products. *IEEE Pervasive Computing, 10*(4), 6.