Wearable System for Elderly People Monitoring in Multi-Resident Scenario

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***Abstract*—We discuss a wearable system that is part of a larger project aiming at monitoring the activities/wellness of elderly people in a multi-resident scenario. Each subject wears an active badge equipped with a microcontroller that manages a number of on-board sensors, while a dedicated software has been developed for data communication and storage and integration with other environmental sensors either fixed or mounted on a robot. Preliminary results are reported that confirm the effectiveness of the approach we have followed. In particular, the implemented badge has been successful in monitoring the movements of a test subject both during bed rest and when moving around in other environments, providing the correct information on his posture and environmental conditions (temperature and humidity).**

***Index Terms*—Sensors integration, communication protocols, multi-resident.**

I. INTRODUCTION

With the advancement of the Internet of Things (IoT) and the increasing accessibility of smart devices, sensing technologies have become useful in many applications, including smart support for independent living for older adults [1]. Monitoring the daily activities and habits of older individuals is crucial for assessing their health and ability to live independently [2]. While non-invasively tracking the activities of a single resident in a smart home is relatively straightforward, monitoring multiple residents remains a challenge. In single-resident scenarios, sensor data directly correspond to the individual's activities. However, in multi-resident environments, this association is often unclear: if two motion sensors in different rooms activate simultaneously, it indicates the presence of two individuals, but their identities and respective locations remain unknown. This lack of direct association complicates activity recognition and necessitates effective sensed data binding to specific individuals. To address this issue, several tracking methods have been employed in smart home environments:

- **Vision-based approaches** [3]: utilize biometric data (e.g., facial recognition, height) from cameras to identify residents. However, privacy concerns limit their widespread adoption.
- **Tag-based methods** [4], [5]: Involve wearable devices with unique identifiers (e.g., RFID, Bluetooth Low Energy (BLE), ZigBee). These require strategically placed scanners within the home to detect and locate the wearers.
- **Signature-based techniques** [6]: Rely on sensors such as microphones, passive infrared (PIR) motion sensors, ultrasound, and ultra-wideband (UWB) to generate unique signatures for individuals. While promising, accuracy can be highly dependent on environmental factors.

To improve multi-resident monitoring, researchers have explored data association techniques [7] and artificial intelligence (AI) algorithms [8]–[10]. Smart home sensors can collect data on residents' movements and routines, providing insights into their functional status and enabling timely interventions when necessary [11]. Maintaining an active lifestyle is vital for older adults to prevent health issues, sustain independence, and enhance their overall well-being. Various technologies [12] have been used to monitor older adults' activities, including PIR sensors [13], cameras [14], pedometers [15], and accelerometers [16]. While pedometers are widely used for activity tracking, they only measure step count and often underestimate steps in cases of slow or irregular gait, which is common among older adults. Accelerometers overcome these limitations by capturing movement frequency and intensity (e.g., light, moderate, vigorous) through raw acceleration data [17]. While wearable devices offer continuous monitoring, passive systems such as PIR sensors and cameras allow residents to go about their daily routines without the need for body-worn devices. However, privacy concerns arise with camera-based monitoring, making PIR sensors a more widely accepted alternative [18]. Research has demonstrated that PIR sensor data can effectively map daily activities, detect mobility patterns, and assess behavior changes over time [19]. This enables early identification of potential health concerns and facilitates proactive interventions [20]. This paper introduces an innovative multi-resident activity detection system that integrates wearable sensors and signature-based technologies to identify and track residents while monitoring their activities in a shared living space. Key advantages of this approach include: ease of use and deployment; low cost and non-invasiveness; respect for privacy; robustness and reliability. Although the system is composed of wearable sensors and sensors fixed to the infrastructures, in this work the wearable part, implemented in the form of a Smart Badge (SB), will be discussed.

II. DESCRIPTION OF THE SYSTEM

A. Description of the project

The aim of the project (Age-SenseAI project) is to develop an innovative sensory ecosystem for measuring the activities and comfort of elderly individuals in multi-resident settings through sensor networks, robots, Data Fusion (DF), and Artificial Intelligence (AI) techniques. The project will implement and explore the following objectives:

1) Develop an innovative sensory ecosystem consisting of a network of non-invasive sensors installed in the environment, worn by users, and integrated into a mobile robot. This ecosystem will measure activities (behavioral changes, Activities of Daily Living - ADLs, and pre-fall events) and comfort levels of elderly individuals in multi-resident settings using DF and AI techniques. This project will go beyond the current state of the art, by developing an innovative sensory ecosystem featuring:
   - A sensor network installed in the environment and on a mobile robot.
   - DF techniques to reduce complexity and uncertainty.
   - AI techniques to distinguish activities and comfort levels for each resident.
   - Explainable AI (XAI) methods to identify the sensors that provide the most relevant information and the possible presence of redundant sensors, in such a way to optimize the sensor network.
   - A data visualization and representation interface for guiding caregivers' assistance and support.
2) Validate the developed solution in a Living Lab with real users, following the guidelines provided by the European Network of Living Labs and ensure the replicability of the developed ecosystem on both social and industrial levels. This objective focuses on developing a solution that meets user requirements. Additionally, a commercial assessment will be carried out to explore potential interest in the solution among local and regional communities.

B. Active Badge

The active badge system is intended as a platform for experimentation with sets of easily available low-cost sensors that can provide, directly or indirectly, information about the wearer of the badge and on the surrounding environment. Candidate sensors were selected among those available in the form of small size breakout boards. With this choice, one can potentially experiment with different sets of sensors without the need for the design and realization of a dedicated printed circuit board. At the same time, the sizes of the components on breakout boards are such that many of them can be fitted in a small space and connected to a microcontroller using standard buses such as I2C or SPI. A picture of one of the badges used in this study is reported in Fig. 1. The gray frame hosting the breakout boards and components has been obtained via 3D printing. The size is comparable to that of standard badges and the weight is sufficiently small to expect negligible discomfort for the users. Since an accelerometer is included (g in Fig. 1) to possibly extract information about posture and other motion related activities, the badge should be strapped to the torso, possibly using Velcro strips on the back, with matching patches on a fitted T-shirt worn by the subject. The badge includes a rechargeable battery (a) together with a charge manager circuit (b) allowing the recharge via the integrated micro-USB connector (c). The mechanical switch (d) on the side of the badge allows for turning off the badge by disconnecting the battery. The ESP32-s3 miniaturized board (a) hosts the ESP microcontroller and a miniaturized antenna for WiFi and Bluetooth connection. We resorted to an "ESP32-S3 Mini Development Board" produced by Waveshare, since the programming circuit via USB-C cable is available as a separate board that can be connected only during development and disconnected when not needed, thus resulting in the small footprint noticeable in Fig. 1. The miniaturized 128×32 pixel LCD panel (i) is intended as a debugging tool during the development of the system and it is expected to not be included in the deployed systems. The board labelled (f) includes a temperature and humidity sensor (AHT21) and an air quality detector (ENS160) that allow to obtain information on the environment in close proximity of the subject wearing the badge. A high-resolution barometric pressure sensor (bme280) is also present (h) that can be used to obtain indirect information about changes in the elevation of the badge with submeter sensitivity. This means that we can potentially infer if the subject wearing the badge is standing or is sitting or, in a worst-case scenario, is laying on the floor. A three axes accelerometer board is also present hosting the LSM6DS3 sensor (g). The LSM6DS3 also incorporates a gyroscope, but we have still selected this device (leaving the gyroscope disabled) because of its easy availability and the small size of the breakout board. The accelerometer can provide information about the posture of the subject (hence the need to avoid wearing the badge with a lace and positioning it as integral with the torso as discussed before). In order to extend the duration of the battery, so that it can be recharged once a day at most, the system is asleep most of the time, with the microcontroller awakening periodically (typically once every minute or so) to obtain environmental and posture data. Measurements may require different amounts of energy depending on the selected accuracy, averaging time and so on. The choice was made to have these parameters changeable on a per-measurement basis, depending on the decision of a Local System Manager (LSM) monitoring all the badges. Clearly, given the nature of the application, we need to include a mechanism to detect special events that may occur during the time in which the microcontroller is asleep and that may require immediate action by caregivers. To this purpose, we exploited the fact that the LSM6DS3 accelerometer is equipped with a low power autonomous system capable of detecting a few events including free fall, activity/inactivity, single and double tap, steps counting etc. The accelerometer is always connected to the battery, in such a way as to generate an interrupt that wakes up the microcontroller when one or more selected events are detected. As an example, in the tests system we have integrated the ability to detect a "tap" by the subject wearing the badge and this can be used to ask for help by simply "tapping" on the badge.

Depending on the particular context, and especially following the detection of a special event, the LSM can alter the measurement sequence by including more measurements or increasing the resolution/accuracy to obtain more accurate data on the status of the subject. To obtain this degree of

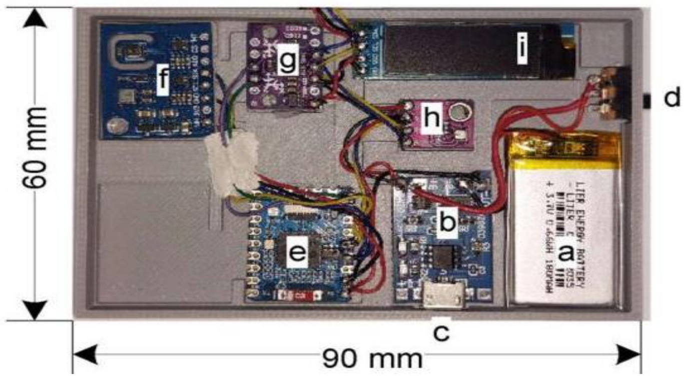

Fig. 1. Prototype of a Smart Badge. It includes a battery (a), a recharger board (b,c), a power switch (d), a microcontroller (e), a number of sensors (f,g,h) and a display for debugging.

functionality, the badges are part of a WLAN to which they connect any time they wake up. Communication between each badge and the LSM is obtained using the standard MQTT (Message Queuing Telemetry Transport) protocol. Both the badges and the LSM are nodes of a MQTT network.

C. Network architectures and protocols

The network architecture developed for the proposed monitoring system is shown in Fig. 2. The architecture exploits the MQTT protocol [21] to manage bi-directional, reliable, TCP-IP based communication channels between badges and control systems. The architecture consists of two levels of hierarchy. The Lowest Hierarchy Network (LHN) is made up of several clusters. Each cluster is named Badge Monitoring System (BMS) and contains a local MQTT broker (LB) and two kinds of MQTT peripheral nodes: one LSM and one or multiple ABs (Active Badges). Each LSM sends commands to, or receives data from, all the ABs of the BMS, using a mechanism based on MQTT topics. The Highest Hierarchy Network (HHN) is made up of a remote central server that integrates one HHN broker. The latter exchange MQTT messages with brokers in the LHN. In the system proposed in this paper, the several local brokers and a test HHN broker were implemented using Mosquito [22]. Integration of the data obtained from the BMS with the other sensors occurs at the HHN level. In the proposed system, a unique numeric identifier (id) nnn is assigned to each AB of each cluster. Within a BMS, the LSM subscribes to all the topics with name in the form RSP/R_nnn (where nnn is the id of each active badge authorized to join the cluster). In this way, the LSM receives notifications about the ABs that are currently joined and powered on.

The notifications on RSP/R_nnn topic are used by LSM to also receive the responses to commands which were previously sent to an active badge. After joining the local BMS using a wireless connection, each active badge connects to the LB and subscribes to a topic named CMD/C_nnn. Upon wake up, the AB publishes/updates a topic named RSP/R_nnn containing the string "s[ALVxxyy]", where the status character "s" can be "n" or "u", depending on the cause of the wake up, with "n" indicating normal wake up after predefined time and "u" standing for urgent wake up due to the detection of a special condition (i.e. the tapping on the badge as discussed before); xx indicates the specific wake up reason and yy is a session number. Once the status prefix has changed from "n" to "u", it will remain to "u" in the subsequent sessions, regardless of the reason for the wake up. This is done in order to maintain a steady indication that some anomalous conditions have occurred. Only the LSM can reset the status from "u" to "n" by issuing a proper message on a specific topic. The ALV message is the only case in which the AB publishes an unsolicited message to the broker. The LSM, upon receiving notification that the AB has subscribed to the MQTT network, can issue a sequence of commands in the form of messages on the topic CMD/C_nnn and the AB is expected to provide an answer, consisting in the status prefix letter, a copy of the command issued by the LSM and, possibly, a string of hexadecimal figures encoding the result of one or more measurements. For instance, the LSM can issue the command "[ACD]" (ACcelerometer Data) to ask for a reading of the accelerations sensed by the LSM6DS3. The response is in the form "s[ACDY $_{11}$ Y $_{10}$ ...Y $_{0}$]", where Y_{11} to Y_{0} are the raw data read from the sensor for the accelerations along the three axes. This choice is functional to the operation of the Local Relayers in Fig. 2. The LR can be regarded as a system that subscribes to both the LB of the BMS to which it belongs, and to the HHN Broker. Since the messages published by the badge to its (locally) unique topic RSP/R_nnn contains a copy of the command issued by the LSM, the LR, by subscribing to all RSP (local) topic and discarding the messages published by the LSM on the topic CMD/C_nnn, can easily generate messages contains all relevant data for each single transaction (involved AB, command, results) and relay it to the HHN broker for fusion with other data streams, elaboration and storage. Note that, in a way, after the ALV message is received by the LSM, the LSM acts as a client with respect to each connected AB, each one of which acts as an independent server. In our format, the entire client/server transaction is contained in the response by the AB, with the AB identified by the topic onto which the response is issued. The software running on the badge is structured in such a way that parsing of the messages exchanged with the LSM is managed in a standardized and structured way. This means that adding a new sensor to the badge, besides modifying the hardware, reduces to the development of an initiation routine (if required) and what is strictly required to send/extract data from the sensor. This can reduces to a few lines of code for each sensor, since the entire communication infrastructure is taken care of once and for all. At the end of data exchange between the LSC and a given AB, the LSC issues the command [ARMxx] (ARMing wake up) that instructs the AB to go to sleep for a time coded in the argument xx.

III. PRELIMINARY RESULTS AND DISCUSSION

For the active badge system to be effective, it should be lightweight and should not require more than one full recharge per day. In our prototype we employ a rechargeable 3.7V LiPo battery with a capacity of $180\mathrm{mA/h}$. The battery weighs $5\mathrm{g}$, with a size of $36 \times 200\mathrm{mm}$ and a thickness of just $3.5\mathrm{mm}$. While a larger battery can certainly be used without adding significant discomfort to the bearer of the badge, our choice appears to be more than adequate for a number of situations. As we have already discussed, in order not to waste battery life, the microcontroller is in a condition of deep sleep for most of the time. The results of typical measurements such as environmental parameters (temperature, humidity, quality of the air, posture and so on) are not expected to change significantly in a space of a few tens of seconds or even minutes. This means that a deep sleep time of 1 minute or even

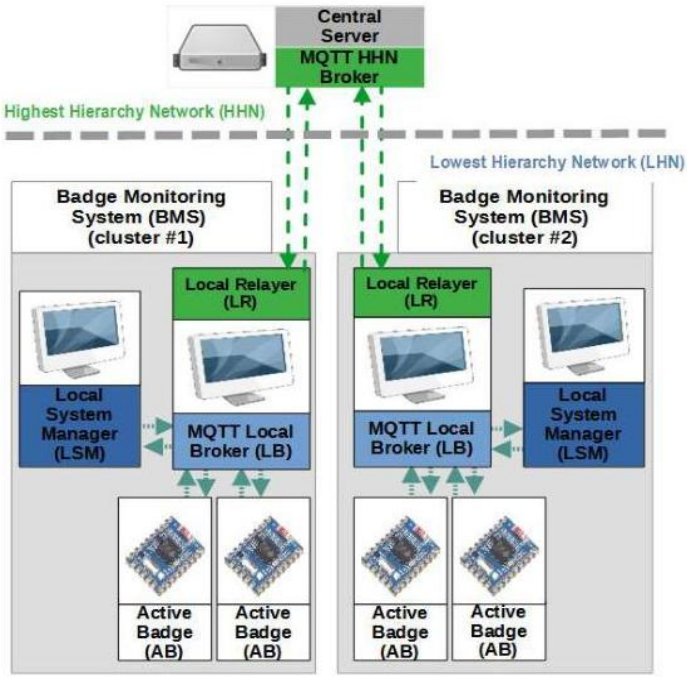

Fig. 2. Network architecture.

longer can be considered quite reasonable, if not too short. As we have noted before, the microcontroller can however be awakened under special conditions.

In order to test the average current consumed by each badge during standard operation we have resorted to a power profiler board for supplying the badge (Power Profiler Kit II by NORDIC Semiconductors) and we have measured the current while the microcontroller enters and exits the deep sleep state several times. When the badge wakes up, the following actions take place during our test:

- The reason for the wake up is retrieved and internally memorized by the microcontroller.
- The microcontroller asks and obtains an IP address from the router via DHCP.
- The microcontroller connects to the MQTT broker.
- The fact that the badge is now awake and ready is communicated to the broker by posting a the "ALV" message.
- Under the control of the LSM, the following actions take place
  1) the RGB led on the microcontroller board is lit with a predefined color.
  2) A temperature and relative humidity measurement is performed.
  3) An attitude measurement (acceleration along three axes) is performed.
  4) Thehe new duration of the deep sleep cycle is set.
  5) The microcontroller is instructed to enter a new deep sleep cycle.

In a first set of measurements the LCD on board was turned on and a log of all received and published MQTT messages was produced in real time. In the second set, the LCD was off all the time. During the experiments, the sleep time was set to only 30 seconds. This is really a worst-case scenario, since we do not expect to employ sleep times shorter than 1 minute in the field. As it can be noticed in the plots in Fig. 3, during sleep time the current consumption level is about $3\mathrm{mA}$. This current is the result of the current consumption by the sensors that remain active during the deep sleep phase (in particular the accelerometer and its internal event detection engine). During the "on" state, the current consumption is in the range of a few tens of mA for a short period of time. The "on" time duration mostly depends on the time needed for the badge to receive an IP address from the router via DHCP. This time can, in a few cases, become quite long (even tens of seconds). To prevent excessive power consumption, a timeout is present, whose length can be configured, so that the badge is sent back to sleep in the case in which the DHCP configuration becomes too long. Note that, thanks to the status character inserted as part of the messages published by the DB, even in the case of a failure to connect to the WiFi, the information about the occurrence of a special situation possibly requiring action from caregivers is not lost, since it is latched internally by the microcontroller and will be issued in any following communication cycle until it is explicitly cleared by the LSC by issuing the proper command.

In both the cases reported in Fig. 3, the results of the measurements demonstrate that the average current consumption remains below $10\mathrm{mA}$, with $8.3\mathrm{mA}$ being the relevant parameter for actual applications (the LCD, that is only present in the development phase, is not expected to be used, if even present on board, during normal operation). If the sleep time is increased to more reasonable durations (1 minute or more) the current consumption can become close to $5\mathrm{mA}$ that, with a $180\mathrm{mA/h}$ battery, results in a potential duration in excess of 24 hours and in any case sufficient to ensure that the badge needs to be recharged only once a day. More aggressive power reduction strategies have not been experimented so far. For instance, a few sensors could be turned on and off by letting the GPIO pins of the microcontroller provide for their power supply. However, this would require modification of the sensor breakout boards (for removing or disabling the on-board power regulators) which would make the replication of the badges more difficult. Fig. 4 shows an example of data monitoring. During the measurement, in a house setting, the following events took place. The badge is worn at the beginning of the test with the test subject in a bedroom. The heat pump in the bedroom is turned on after a few minutes, and this leads to the steady increase in the temperature recorded from $400\mathrm{s}$ to $2500\mathrm{s}$. Note that the temperature detected by the badge is the one close to the body of the subject, hence it is higher

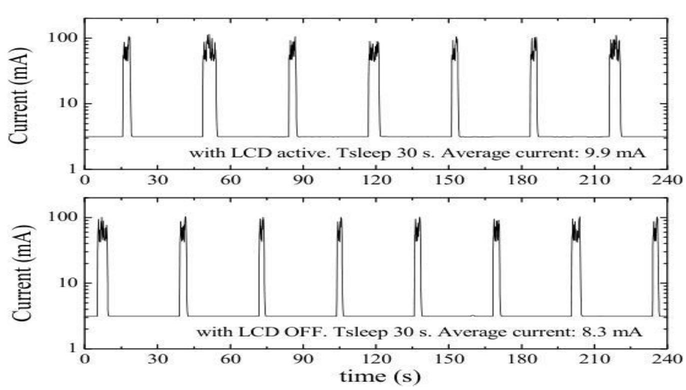

Fig. 3. Current consumption of the active badge.

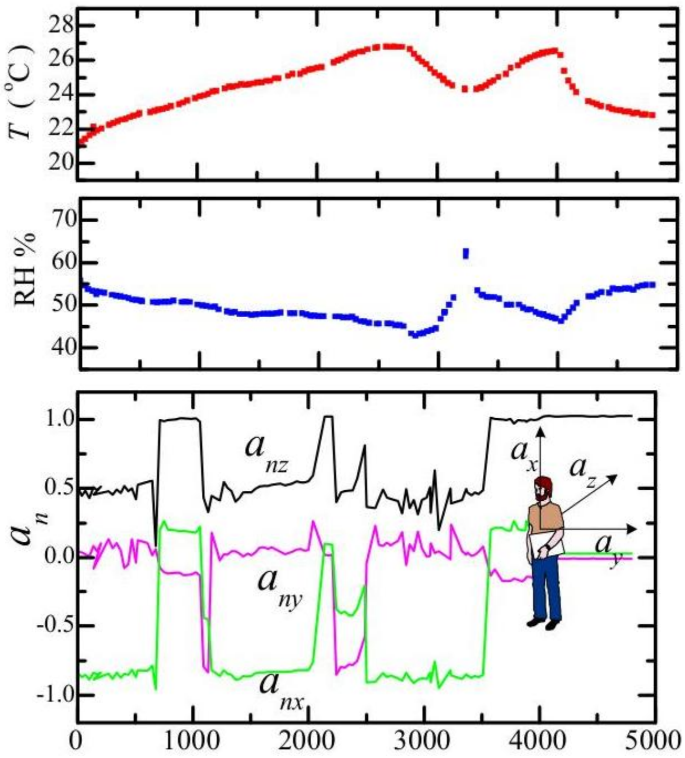

Fig. 4. Preliminary test measurement. From the top Temperature, Relative Humidity and acceleration (normalized to gravitational acceleration) components plots.

(more on this at the end of the test). During this first phase the subject is standing up or sitting (negative and large value for a_s); after a while the subject goes to bed and stays in the supine position for a while (600-1000 s), and then on a side. Posture changes several times during the test. The decrease in temperature at 3500 s with a significant increase in the relative humidity coincides with the subject going to the bathroom that is not heated. Finally, the subject goes back into the bedroom and lays down supine on the bed (from 3500 to 4000 s). At 4000s the badge is removed from the subject (without turning it) and placed flat on the bed stand. As it is apparent, the detected temperature, now that the sensor is far from the body, is significantly lower.

IV. CONCLUSION

This paper presented a wearable system that was part of the hardware setup of a project aimed at monitoring the activities and wellness of elderly people in a multi-resident scenario. The wearable system is part of a larger set-up with fixed environmental sensors and sensors mounted on a robot. The developed active badges are equipped with a microcontroller that manages all the sensors, while dedicated software was developed for data communication and storage. Some preliminary results have been reported, showing the effectiveness of the implemented badge. In particular, the badge has been successful in monitoring the posture changes of a test subject both during bed rest and when moving around in environments, providing the correct information on his posture and on the environmental conditions. Future developments will include integrating the badge with the rest of the system and verifying performance in the presence of multiple subjects.

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