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iSenior—A Support System for Elderly Citizens

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ABSTRACT Health and safety monitoring of elderly citizens are key to the improvement of their quality of life, by enabling them to be more independent. This was the general motivation for developing the iSenior system presented in this paper. iSenior is a wireless embedded system solution for people living in rest homes that retain their mobility and, thus, move around the facilities and can even go outside. iSenior is a cyber-physical system solution that currently supports a set of functions like monitoring, alerting, and requesting assistance. The system has been implemented and is under field evaluation in a real world deployment. The aim of this paper is to provide information on the main features of the system, including architecture, implementation details, and performance evaluation.

INDEX TERMS Network embedded systems, sensor-based applications, independent aging, healthcare.

I. INTRODUCTION

Healthcare systems and resources are under the pressure of high-quality services associated with fast ageing population [1]. In this context, wireless sensor networks (WSNs) technology is being used in order to reduce the strain on the healthcare sector and at the same time improve the quality of life of elderly citizens.

In this respect, there are several scenarios in which WSN-based solutions can help. Some examples are the detection of daily activity patterns, the identification of anomalous behaviours, the monitoring of physical condition on a long-term basis or after treatment or surgery, the location of people with orientation disorders, the detection of accidents such as falls, or even the reduction of people's isolation.

This paper describes iSenior, a WSN-based cyber-physical system intended for elderly citizen's support that enables continuous monitoring, alerting, and assistance. It allows caregivers to access and evaluate vital signs, answer emergency calls, localize persons, and detect conditions where a person needs assistance. The system is accessible anytime and from anywhere, just requiring an Internet or cellular connection.

The development of iSenior benefitted from the team's experience in the development of several other WSN-based monitoring systems, for a variety of scenarios. One of them is described in [2]. More recently, a request for the development of a system to help localize hospitalized patients was the trigger for the development of a modular hardware platform [3], which has been used as the basis of iSenior. It should be noted that the system presented in this paper is novel and has not been presented elsewhere. Nevertheless, some details on the used hardware platform [3] are included in this paper in order to allow the understanding of the architecture and implementation of the iSenior system.

The aim of this paper is thus to provide an insight on the various issues involved in the development of the iSenior WSN-based solution such as requirements, functionality, hardware architecture, software architecture, implementation options and performance. Consequently, the main contribution of the paper is the development, presentation and discussion of a completely new, operational cyber-physical system/application for healthcare support, comprising scalable monitoring, sensors, smart phones, and/or other wireless mobile devices, and its field trial evaluation.

In order to achieve the stated goal, the paper is organized as follows. Section II addresses related work and identifies the differences between the proposed system and existing ones. Section III provides a functional overview of the system, focusing on its main, distinguishing features. Section IV describes the system architecture from the hardware and software perspectives. The most relevant implementation details are presented in Section V. Section VI provides performance evaluation. Section VII provides the conclusions and guidelines for further work.

II. RELATED WORK

There have been several research initiatives to study the applicability of WSNs to the healthcare application domain. In addition industry-led initiatives exist. Both types of initiatives are briefly described in this section.

The AlarmNet [4] project built an assisted-living and residential monitoring network for smart healthcare research. Several monitoring platforms were developed to acquire patient physiological parameters (e.g. heart-rate, ECG, temperature, oximeter), enable activity recognition, provide identification and localization, and collect environmental parameters. These platforms are based on Telos / MicaZ [5] motes with specific add-on boards to support the sensing of the various parameters. The communication between body-worn nodes and the Internet is made via a base device (e.g. PDA, PC).

The Code Blue project [6] explored the application of WSNs to pre-hospital and in-hospital emergency care, disaster response, and stroke patient rehabilitation. The project developed several add-on boards to the Telos platform, enabling pulse oximetry, two-lead ECG, activity recording, and EMG. The project also developed a wearable platform in a compact form factor optimized for medical deployments. This platform (Pluto) is based on a redesigned Telos with an accelerometer, a charging circuit, and a LiPoly battery. The device is used at the wrist and can sense movement and support patient localization using beacon nodes.

Mercury's [7] goal is to enable high-resolution motion studies of patients being treated for neuromotor conditions at their homes (e.g. Parkinson's disease, stroke, and epilepsy). The project requires several Shimmer nodes [8] attached to the patient's body, each one sampling its sensors (accelerometer, gyroscope, and/or physiological data), saving raw data to flash, and doing feature extraction. The nodes decide when to transmit data to the base station considering the link quality, energy level, and experiment duration.

The Medical Emergency Detection in Sensor Networks (MEDiSN) [9] project uses WSN technology together with a specially developed physiological monitor device (a compact mote based on the TelosB architecture) to provide a solution that enables to continuously monitor patients' health conditions. This device collects parameters such as pulse, blood oxygen level, and ECG, and forwards them via a WSN to a backend infrastructure that makes this information available in real-time to the patients' supervisors, and also saves it for later analysis. The system can be used in several scenarios, including emergency rooms, by enabling the medical staff to monitor patients' vital signs and quickly respond to signs of health condition deterioration.

Medical Ad hoc Sensor Network (MASN) [10] is a platform, including hardware (based on an enhanced version of the TelosB mote) and software components, to perform real-time collection of healthcare data. The system has the capability of monitoring patients with cardiac disease and makes use of wavelet theory to extract ECG features in order to help the diagnosis process. The platform also supports patients' localization by using radio signal strength signatures from a set of beacon nodes deployed in the deployment scenario. The implemented communication protocol is based on a cluster organization, where patients carrying ECG sensors are grouped in clusters, and the information from cluster nodes is aggregated and relayed to the ECG server. To cope with the security risk of the infrastructure being attacked and to achieve confidentiality of ECG data, the system supports communications data encryption.

Industry-led initiatives are also noteworthy. The Continua Health Care alliance [11] is one of the driving forces, by coordinating the efforts in the area of *connected health*. Their currently proposed standard recommends Bluetooth Low Energy and ZigBee as the core technologies to support wireless communications. Nowadays there are several Continua certified products, which can provide blood pressure, weight, blood glucose, body temperature, and pulse oximetery data, among other.

There are several commercially available solutions specifically developed for assisting elderly citizens. True-Kare [12] is an example. It is based on a configuration portal and on an enhanced mobile phone platform that connects to the Internet and to a set of special devices used for requesting assistance and helping localizing lost objects such as keys or wallets. The system allows the definition of alarms on medication time, user leaving predefined areas (or being lost), and personal agenda-related events (such as visits to friends, doctors, relatives).

The previous paragraphs identified the most relevant research and industry work using WSN technology in the healthcare domain. For an in-depth discussion of the applicability and challenges of using WSNs in the healthcare domain, a good starting point is the Wireless Sensor Networks for Healthcare review [13]. Additionally, [14] provides a discussion of the WSNs technologies that are used in healthcare-related projects such as CodeBlue, MEDiSN, and MASN, with the goal of identifying the gaps between their capabilities and the requirements of the healthcare domain.

When comparing iSenior with the previously described projects/initiatives in the health care domain, several distinguishing aspects arise. iSenior was not developed to be a medical tool, but rather to provide useful information in detecting potential problems with elderly people at rest homes. Although it enables to collect variables such as heartbeat, activity level, and localization, the main idea is to enable alerting in case some unexpected event happens, and not to help diagnose health problems. In this way it can

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be seen more as a tool to help elderly people being more independent and to assist caregivers in doing their job. The system can be used indoor and outdoor, which is another aspect that differentiates iSenior from the mentioned projects. This enables elderly people to go outside (e.g. for leisure in parks) and have the means to alert caregivers in case something wrong happens. Another distinguishing aspect lies in the localization functionality. iSenior supports both outdoor and indoor localization. This allows, for instance, detecting when a person enters zones that can compromise their own safety. Finally the system provides mechanisms that allow the detection of potentially dangerous situations, such as falls, and enables its users to request assistance.

The True-Kare system [12], mentioned above, is also directed to support elderly citizens, although several important differences exist in relation to iSenior. The system seems to be very simple to configure and use, having an ergonomic interface. Nevertheless, it does not support monitoring of health parameters, nor does it detect falls. Moreover, it is not clear if the system can use local Internet access points. It seems to be more a system to help the elderly to be more independent and less a system to help the caregivers in doing their job, as is the case of iSenior.

III. iSENIOR OVERVIEW

The iSenior system presented in this paper was a direct request from a large institution that provides rest home services for elderly people. The system should support the following requirements:

- monitor and alert on parameters like heartbeat or activity level;
- detect and alert on user potential danger situations, such as falls or when the user enters or leaves a reserved area;
- support an easy-to-use request for assistance mechanism;
- support user localization when outside the rest home;
- operate continuously for 7 days without the need for recharging/replacing batteries;
- compact and light monitoring device, in order to be comfortable when used during long periods of time; preferably, the device should be carried at the waist.

The iSenior system is either applicable to foster homes for the elderly or to elderly citizens living on their own. In this regard, it provides better quality of life and improves autonomy. Elderly citizens can move freely, either indoor or outdoor, carrying a personal monitoring device called Elderly Monitoring Device (EMD) with them. Caregivers can provide assistance and monitor elderly citizens' condition in real-time, analyse historic data, localize persons in case they need assistance, and be alerted if something requiring their attention occurs. The system provides functions to monitor health conditions, encompassing data collection and storage, alarm management, localization, remote access, several user profiles, and auto-configuration. These are briefly presented below.

A. DATA COLLECTION AND STORAGE

All the information gathered by iSenior can be visualized in real-time or saved for later analysis.

Using the EMD unit, the system can collect information regarding heartbeat, movement, room temperature, and person location. All the information is made available to system users through a user-friendly interface. The EMD unit also sends internal state information, allowing the monitoring of the system operation.

In addition to real-time monitoring, the system has the ability to store the gathered data in the system database (specific details concerning the data format are provided in the implementation section). This feature allows future analysis of monitored data, either for medical assistance purposes, or to aid in the system's improvement.

B. ALARM MANAGEMENT

Alarm management enables one or more variables to be under observation. An alarm can be configured by defining a set of rules or, for some variables, by just selecting a checkbox.

If an alarm condition occurs, caregivers are alerted via an SMS message sent to a pre-defined set of mobile phones, by email, and/or by signalling the condition in the system web interface.

The system allows the user to concurrently set up alarms for all of the deployed sensors at an EMD. In most cases, alarms are configured by specifying a set of rules for each parameter under observation. Each *rule* has the following syntax:

$$< rule >::$$
$$= < parameter >< op >< value >< duration >< schedule >$$

where *parameter* designates the name of the parameter the alarm rule applies, *operator* can be ">" or "<", *value* defines the threshold, *duration* is the time the condition should last (to filter out noise or sporadic signals), and *schedule* defines when the rule is active. Other important types of alert relate to falls, entering reserved areas, and requiring assistance.

Alarms on parameters such as movement index and heartbeat require the definition of personalized thresholds. Despite the existence of sophisticated techniques that dynamically adjust those thresholds according to each person's historic data, in our case the thresholds are defined with the help of the patient's doctor. The system enables to define rules according to the period of the day to cope with the diversity of daily activity levels. This approach was, in fact, a request from the institution that commissioned iSenior, and has the advantages of simplicity and, at the same time, of flexibility, as each rule is under the complete control of the person's doctor.

To maintain the proper operation of the system, it is important to alert on EMD low battery condition and when the central management cannot communicate with an EMD for a predefined amount of time. Alarms can be activated for all these conditions by selecting the respective checkboxes.

All the details concerning triggered alarms are saved in a database in case they are needed for future analysis.

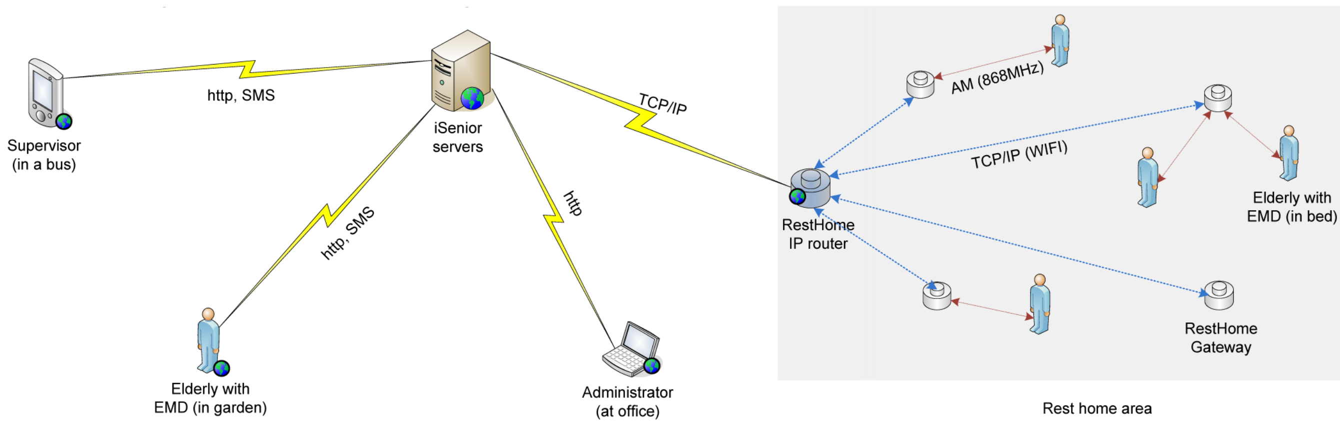

FIGURE 1. **iSenior hardware architecture.**

C. LOCALIZATION

The outdoor localization functionality is a main component of the system as it is essential to provide assistance in case any user requires it. The system displays the user location and information on its trajectory in real-time, using Google Maps.

D. REMOTE ACCESS

iSenior is accessible through a portal that performs user authentication and provides access to system functionality according to the user profile. The system can be accessed any time, from any location where an Internet connection is available, and using a variety of platforms, such as a computer or a smartphone. The user interface adapts itself to the capacities of the device being used for accessing the system.

E. USER PROFILES

The system supports three user profiles: caregivers, system administrator and end-users. A caregiver uses the system to check and analyse the monitoring data of one or more elderly persons and to provide the needed support. He/she can also analyse historic data, define alarms, and be notified if something abnormal happens. The system administrator has access to all the information and is responsible for system configuration. End-users are the monitored persons.

F. AUTO-CONFIGURATION

In order to make the system easy to operate, auto-configuration capabilities are supported, allowing the automatic addition of a new EMD device to the system. The basic idea is that when an EMD is turned on it informs the system of its presence and characteristics. As a result, the system registers the device in the configuration database. Naturally, the system also provides an interface for easily assigning EMDs to end-users.

IV. ARCHITECTURE

The iSenior architecture is both modular and scalable and takes into account the EMD's hardware capabilities (i.e. processing, memory, communication, and energy budget). The main hardware and software architectural aspects are presented below.

A. HARDWARE ARCHITECTURE

Fig. 1 presents a high-level view of the iSenior hardware architecture. EMDs communicate with a central unit (iSenior servers, in the figure) via GSM/GPRS or via a rest home WSN. The basic idea is that, when an end-user is outside the rest home, communication is based on GSM/GRPS, whereas when the end-user is at home the home network supports the communication.

Considering that rest homes can range from small to large buildings, the existence of several Internet providers with high service quality, the availability of inexpensive and robust routing equipment supporting WiFi-based communications, and the 7-days continuous operation requirement, a decision was made to have a network architecture based on a set of static nodes called Rest Home Gateways (RHGs), adequately deployed inside the building, that communicate with the iSenior servers via the Rest Home IP Router. When inside the rest home, an EMD node will communicate via an RHG in its communication range.

EMD devices are built on a modular platform called Hermes (Fig. 2) [3] that is based on two interconnected modules (named Pegasus and Fenix) supporting GSM/GPRS, 868 MHz radio communication, GPS and RFID localization techniques, and sensing modalities (namely, accelerometer, gyroscope, thermometer, and heart beat).

The RHG is a device based on the Pegasus hardware platform connected to a WiFly GSX 802.11b/g module that offers a TCP/IP sockets interface via a WiFi link. When communicating with the EMD, the 868 MHz radio supporting TinyOS Active Messages link layer (AM) is used. Communication with iSenior servers uses TCP/IP. RHGs operate in a similar

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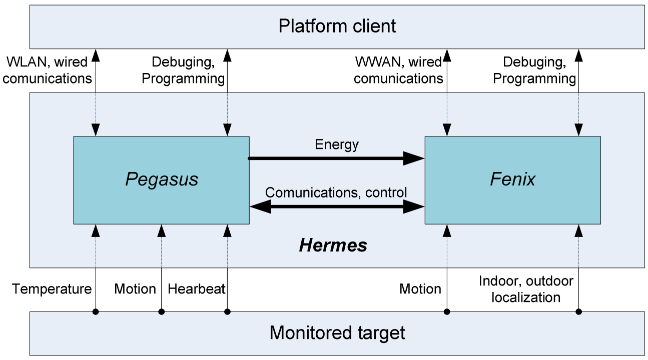

FIGURE 2. **Hermes simplified architecture.**

way to a TinyOS base station node connected to a computer running the serial forwarder software.

When an EMD device detects an RHG, it informs the iSenior servers and changes to inside rest home mode, turning off the GPS and the GSM/GPRS radios. In case the communication is lost, it returns to outside mode (and also informs the iSenior servers).

The Rest Home IP router is any access router that can be used to provide Internet access to a set of WiFi-based clients. It connects rest home WSN devices to the iSenior servers via an Internet access provider network.

iSenior servers (Fig. 3) run the portal, core application functionality, database, SMS gateway, and mechanisms used to communicate with EMDs (either directly or via the rest home gateway).

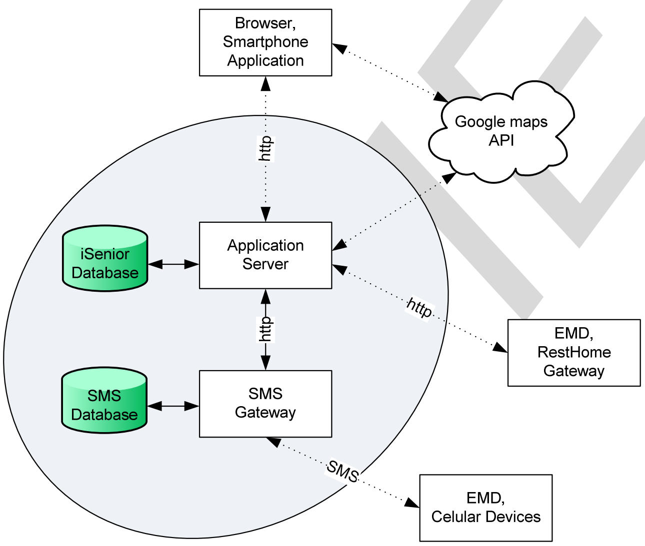

FIGURE 3. **iSenior servers functional view**

The iSenior portal can be accessed by caregivers and administrators using any of several types of equipment, including smartphones, tablets and notebooks. In case the equipment used by caregivers has GSM/GPRS capabilities, they will be notified of alarm conditions via an SMS message. If they are logged in the portal, they will also be notified via the web user interface.

The system supports an optional device called Reserved Area Alarm (not shown in Fig. 1) that can be deployed at the top of door cases to generate an RF signal in the 125 kHz band. When an end-user passes the door that connects an allowed space to a restricted one, his/her caregiver is alerted. This device can also be used in the main entrance door to detect when an end-user enters or leaves the rest home, because it also detects the movement's direction.

Although the system was designed to support a specific set of requirements, it can be easily expanded to support additional sensor devices, as is the case of an ambient station node based on the Pegasus platform that can measure various ambient parameters such as humidity, movement detection, and CO_2, using an add-on board.

B. SOFTWARE ARCHITECTURE

In what concerns software, iSenior functionality is supported on a set of modules executing at the iSenior servers, at EMD devices, and at the RHGs. This section starts by describing the functionality supported by the main iSenior modules—the portal, the kernel, and the alarm processing modules—that make up the application server. Subsequently, the EMD workflow is presented.

Portal—This module implements the user interface, providing authentication and access to iSenior. The user interface is dynamically generated, according to each user's settings and permissions. The adaptation of the user interface to the user's profile and device is extremely important in order to optimise readability for multiple screen resolutions, such as smartphones, tablets and PCs. This approach is based on the responsive design [15] technique. The portal is used for:

- displaying user state information in real time (e.g. heart beat, location, activity level) and accessing historical data;
- showing alerts (e.g. heart beat, changes in location, requested assistance, falls, enter/exit restricted zones);
- providing real-time user tracking and history analysis over Google Maps API;
- configuring alarms and monitoring functionality per end-user.

Kernel—This module is responsible for managing communications between the server software and EMDs:

- receives sensor queries from the portal module and forwards them to EMDs via RHGs or directly (in case end-users are outside the rest home) and processes the replies;
- supports the monitor scheduling functionality, by starting/stopping each monitor and storing the received sensor data in the system database;
- interfaces with the alarm processing module;
- implements the auto discovery/configuration protocols used to identify which EMDs are active and which sensors they currently support;
- implements an exponential back-off algorithm to avoid flooding an EMD with an excessive number of requests

and to cope with temporary unavailability of the cellular network, by dropping or queuing messages for sending at a later point in time, and by alerting the administrator in case of non-transient failures;

- provides asynchronous interfaces for system communication (e.g. between portal and EMDs).

Alarm processing—This module implements the algorithms that process the raw data received by the kernel from the EMDs, in order to detect conditions that trigger the alarms. It is also responsible for detecting abnormal conditions (such as long periods without any communication from an EMD). It triggers real-time alerts, displays them on the portal, and sends SMSs alerts.

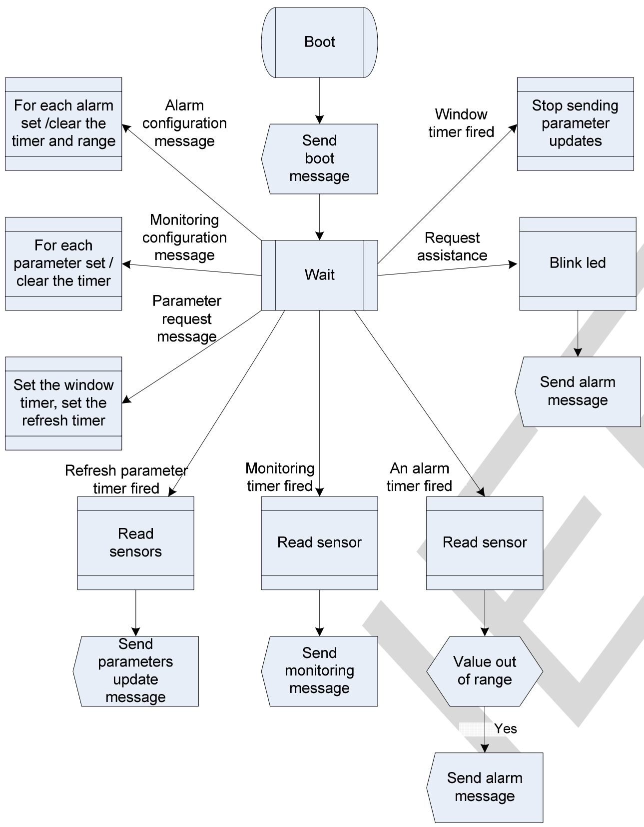

FIGURE 4. **Simplified EMD workflow**

A simplified workflow of the information processing inside an EMD is illustrated in Fig. 4. The alarm notification, real-time reporting, and monitoring functions are depicted. Special events (including reserved area access, and falls detection) are represented by the request assistance event.

V. IMPLEMENTATION

This section presents the major decisions concerning the platform and application implementation aspects, with the objective of detailing the system construction and justifying the main choices.

A. PLATFORM

The iSenior servers (see Fig. 1) are connected to the datacenter infrastructure that includes: two redundant connections to the Internet, a firewall cluster with two machines, a high-availability cluster with two machines (Quadcore 2.2GHz 8GB RAM) operating as proxy / load balancing for the web servers and connected to a RAID5 storage array via a fibre optic link.

There are two web servers (Dualcore 2.4GHz 4GB RAM, 140GB disk). The MySQL 5.5 database runs on an auto-replicated cluster with two machines (Dualcore 2.4GHz 4GB RAM, 140GB disk). The iSenior Application Server is a Quadcore 2.2GHz 8GB RAM machine.

The database server, the Application Server, and the SMS server run on Linux Ubuntu 11.10. The Application Server runs Apache 2.4 with Passenger 3.0.8 (in order to run Ruby applications on Apache).

The need for a reliable, fast, and cheap communication infrastructure supporting SMS messages implied the search for open source gateway solutions. Because the available solutions did not cope with a large number of SMSs per second, an in-house solution based on Gammu (a client application that can control most aspects of phones through AT commands) was developed. In this solution, Gammu is connected to the MySQL database to store all the communications, and there are PHP-based web services for sending SMS and for notifying the Rails web application when a new SMS has arrived. This allows having a distributed system that can linearly scale the SMS debit with each added GPRS/GSM USB pen.

The Hermes platform, detailed in [3], fulfils all the iSenior hardware requirements. In the following, a brief description of Hermes and its components will be presented in order to ease the understanding of the iSenior implementation description and evaluation.

A wearable device should be comfortable to use and, thus, it should be small sized and light. The usual approach, in mobile devices, is to design the hardware in order for it to fit in a single board. The decision not to go that way was due to the fact that this would restrict the platform's aimed flexibility. A two-board solution was an acceptable compromise between flexibility and size.

A picture of Hermes in its open casing is presented in Fig. 5 (the EMD, including Hermes, batteries, and the respective casing measures 9.5 × 4 × 2.5 centimeters and has a weight of 70 grams).

The used approach was to have the typical WSN node functionality, namely processing (MSP430F2618), storage (uSD), sensing (thermometer—DS7505, accelerometer—ADXL345, gyroscope ITG3200, heartbeat receiver, coulomb counter—DS2780), short range communication (CC1101), power management system based on LiPoly batteries (LTC3455), leds, buttons, debugging and programming hardware, and expansibility connectors, in a board called Pegasus.

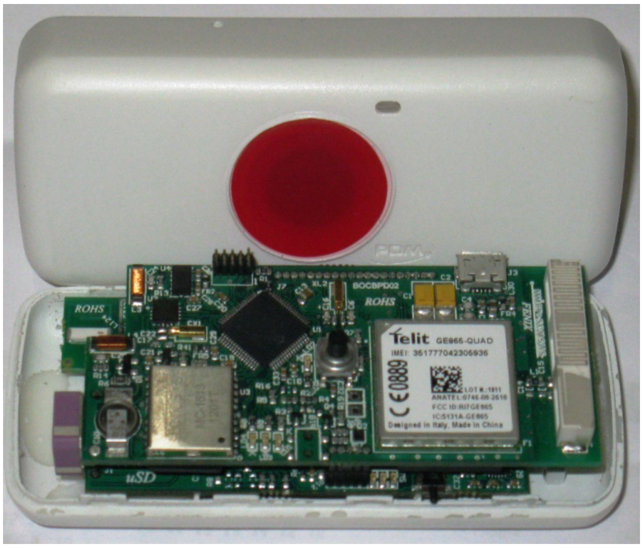

FIGURE 5. **Hermes in its open casing**

The second board, named Fenix, can be described as a localization system supporting indoor door crossing detection (AS3932) and outdoor localization (GPS_3M), WWAN communication (GE865), processing (PIC24FJ128), storage (uSD), movement sensing (ADXL345), leds, buttons, debugging and programming hardware, and expansibility connectors.

Depending on the application requirements, one can use each board separately or both boards. In [3], applications that benefit from this modular approach are presented.

The Hermes platform's firmware is based on TinyOS, in the case of Pegasus, and on a set of custom libraries, in the case of Fenix. Communication between both nodes at hardware level is based on a serial peripheral interface (SPI). On top of it, the Active Message communication primitives are supported.

Besides enabling each board to use the other's communication capabilities, a sensor abstraction mechanism was developed, which eases applications development. With this abstraction, using a local sensor or a sensor on the other board just requires selecting the adequate component in the application configuration. This approach is easily extensible, is symmetric (i.e., an application that executes in Pegasus can query a sensor in Fenix and vice-versa), and opens the way to more advanced sensing, as each board has a microcontroller unit (MCU) and it is thus possible to build a complex "sensor", such as a fall detector, in one board and provide it to the other.

B. iSENIOR APPLICATION

1) USED WEB TECHNOLOGIES

The iSenior Application Server executes a web application developed using Ruby on Rails 3.0 and supported by a MySQL database. The frontend side (browser side) relies on the jQuery framework to allow diversity of data views and asynchronous interaction mechanisms and/or real-time. It also uses the public Google Maps API to display end-user locations.

The Faye and DelayedJob gems (i.e. packaged Ruby libraries) play an important role in system operation. Faye provides abstraction mechanisms for implementing real-time message sending to browsers. This is done by supporting a publish/subscribe paradigm, according to which messages are placed in arbitrary channels that customers can subscribe to. These messages are encoded in JSON, which is interpreted at the frontend to determine which handler should be executed. This is used to support the display of alarm information when a user is logged in the system.

The iSenior application operation is supported on the cooperation of components that communicate using HTTP. To ensure that this communication is robust, HTTP calls are made asynchronously using the DelayedJob gem. This gem adds a Ruby daemon that will consume asynchronous calls in background, thus preventing a frontend user from being blocked by pending replies.

2) TRAFFIC OPTIMISATIONS

The system enables querying an EMD for individual parameters, either for real-time display or for storing them in the databases. Nevertheless, if the system requires several parameters it aggregates the queries in order to reduce the traffic to/from the EMDs. It also supports a query reduction mechanism, according to which a single query can specify the parameters to be monitored and the applicable rate and time interval, thus avoiding the need for repeatedly issuing the same query.

The alarm system enables defining several rules for each parameter, as discussed in Section III-B. The EMDs filter out the values that will not satisfy any rule (the system sends the value range of interest to the EMDs). All the remaining processing (e.g., time of day the alarm occurred, duration of a rule violation) is done centrally. This type of approach was already used in [2], and greatly simplifies processing at EMDs, without wasting too much energy in communications, since alarms represent low traffic.

3) COMMUNICATION ASPECTS

The communication between EMDs and RHGs is based on TinyOS communication capabilities for enabling high link reliability, via the software ACK mechanisms offered by the Packet Link Layer module, and energy saving through radio duty cycling, using Low Power Listening (note: RHGs can be mains powered).

To cope with indoor end-user mobility, EMDs send information to all RHGs, which will forward it to the Application Server (duplicates are discarded). If the Application Server wants to communicate with a specific EMD inside a rest home, it first sends the data to an RHG recently used by that EMD. In case of failure, it will re-sent it via the others. This is necessary because traffic in the RHG to EMD direction can easily increase because of the asynchronous low power mechanism operation. This was also part of the reasons behind the already mentioned traffic optimization mechanisms.

4) ENERGY MANAGEMENT

The main reasons for having a rest home WSN were to obtain energy savings, and to enable future support for indoor-only EMDs based on the Pegasus module.

When EMDs are used with GSM/GPRS and GPS radios turned on, transmitting a message every 5 min, the batteries last for around 3 days. As it is expected that most of the times the end-users stay indoors, the system will benefit from turning off the GSM/GPRS and GPS radios and communicating via the CC1101 radio. Moreover, the reason for not using a WiFi radio in EMDs was because of its high energy consumption. Also, because the main part of the EMD application runs in the Pegasus module, it is possible to keep the Fenix MCU in low-power mode most of the time. The Reserved Area Alarm uses the AS3932 radio that consumes 8.3uA and can wakeup Fenix.

On the Pegasus side, TinyOS does an excellent job in what concerns energy savings, by keeping the MCU in low-power mode when it is not required, supporting low-power listening, and enabling the sensors to go into a low-power sleep mode.

5) PARAMETERS CALCULATION AND SPECIAL EVENTS DETECTION

The movement index is calculated by sampling the Pegasus' 3-axis accelerometer at 100Hz and applying a band pass filter to remove the noise and to discount for the static acceleration components. Then, each sample's absolute value is summed in a non-overlapping 2 seconds window. The result is normalized to fit a 0 to 10 scale that is saved using a one byte unsigned integer.

The average heart beat calculation is based on a moving average of the n previous inter beat time intervals (e.g., $n = 8$). Individual beat signals are sent by the transmitter belt and are acquired by the Pegasus receiver. Filters are applied to cope with false beats, lost beats, and arrhythmia. The resulting heart beat average is saved using a one byte unsigned integer allowing a maximum of 255 bpm (a recent study [16] showed that even during exercise the maximum heart beat values for adults above 65 years did not exceed 163 bpm). This device is merely indicative and does not substitute a medical instrument in any way.

End-users entering indoor reserved areas are detected via the 125kHz receiver, as mentioned before. When outside, the GPS coordinates periodically sent by EMDs enable to locate end-users and display the information on Google Maps.

6) FAILURE MANAGEMENT

Monitoring iSenior's operation and alerting in case of malfunction is critical for assuring the system's continuous operation. iSenior is continuously monitored by Nagios at several levels (namely, Application Server, SMS Gateway, Rest Home IP, RHG, and EMD), and in case any anomalous condition is detected the systems managers receive an email and an SMS alert message.

To support further diagnosis in case an anomalous condition happens, several components generate logs during operation, namely the Application Server, the Kernel and the Alarm processing components, the Databases, the SMS Gateway, and the EMDs.

At EMD level, a logging component was developed in order to enable the support of failure diagnosis. This component can save execution traces, register variables' values, and save copies of sent and received messages. The component can be turned on/off during runtime to save node resources.

To cope with potential EMD critical software failures, a software watchdog mechanism was also implemented. The watchdog is cleared if EMD succeeds in accessing the provider network and sending a keepalive message. In case of failure, the log mechanism is used to save the system state, after which the EMD is rebooted. After reboot, the EMD sends a boot message with the information saved before the reboot, MCU reboot cause, sensor readings, and energy level. The keepalive message is also used to feed the Nagios server.

VI. EVALUATION

Designing wearable devices is a difficult task because the devices have to be comfortable. EMD is to be used by persons that typically avoid using this type of devices. In addition, some of them can have age-related limitations. All these requirements were considered in the system design and specifically in the way the enclosure was designed (Fig. 5). In order to assess in which way these requirements are being met, user experience evaluation is in progress. The initial tests are promising in what relates user acceptance. Clearly, users and caregivers perceive the advantage of a solution like iSenior in improving elderly safety. Nevertheless, as user experience results are still preliminary, their presentation is left for future work.

This section concentrates on the evaluation of iSenior's technical aspects, such as communications performance, energy consumption, and movement sensing capabilities.

A. COMUNICATIONS PERFORMANCE

EMD communication functionality is based on a Telit 865 GSM/GPRS radio and on a low-range TI CC1101 radio. The quality of service of the GSM/GPRS communication depends on the provider infrastructure. In this scenario, the percentage of success in accessing the service was higher than 99% (either for sending SMSs or for having Internet access), and the percentage of delivered SMS was higher than 98%, both over a 24 hours period during workdays.

A previous study [2] that measured the CC1101 radio communication range when the platform is used indoors enabled to conclude that it has a 55-meter communication range, with a delivery success rate of more than 95%. Because that range derived from the specific indoor scenario space limitations and not from the platform's hardware itself, a decision was made to repeat the study in a larger indoor space. As in the first study, one node (an EMD) was 0.25 meters above ground, and the other (the base station) was at a height of 2 meters.

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In this second study, a 77-meter communications range was achieved. The rest home scenario where the iSenior system is deployed covers a 100m by 70m area, and a decision was made to use a network with four RHGs for covering all the rest home area (Fig. 1) and to cope with unexpected problems (e.g. gateway failures, communication problems).

The communications latency is also an important parameter because the system provides alert functionality. The current iSenior version can use SMS or GPRS for outdoor scenarios, and WiFi for indoor scenarios. The measured latency over a 24-hour period with a rate of 4 messages per minute was less than 15 seconds for the SMS communication (standard deviation equal to 5 seconds) and less than 0.2 seconds in the other cases. Those results suggest GPRS should be used whenever possible when outdoor (note: to achieve this low latency, the GPRS connection had to be kept active).

B. ENERGY CONSUMPTION

As stated in Section III, the EMD battery should last for 7 days. To analyse the expected battery life when EMDs are used indoor and outdoor, the following should be considered:

- when used outdoor only, the battery (1000mA LiPoly) lasts for 3 days (∼70 hours) when transmitting a message every 5 min;
- in the case of indoor use only, measurements indicate an average battery life of 28 days.

Assuming mixed indoor and outdoor use, with outdoor periods of 4 hours, the estimated battery duration will average 11 days. This value was confirmed by our experiments, demonstrating that the 7-days battery duration requirement was met. Table 1 presents the current consumption measured when the EMD is indoor (Pegasus accelerometer and heartbeat receiver on, the other components turned off or in low power modes). We would like to emphasize that the measured durations took advantage of the mentioned traffic reduction techniques, which enable the sending of information in an aggregated way and avoid repeating the requests.

TABLE 1. EMD indoor current consumption.

Operation	Current
Mote Standby	340 uA
MCU idle, radio off	420 uA
MCU active	2.86 mA
MCU + Radio RX	19.4 mA
MCU + Radio TX (0/12dbm)	17.5 / 28.4 mA

In order to provide the reader a better understanding of the relative impact of individual EMD components on energy consumption, Tables 2 and 3 (from [3]) present each component's current consumption. Further data is available in the referenced paper. Table 3 clearly shows the impact of the GSM/GPRS and GPS modules on energy consumption. It is clear that maintaining active GPRS connections for achieving low latency comes with a high price in terms of energy consumption.

TABLE 2. Pegasus parts current consumption.

Part	Active (mA)	Sleep (uA)	Notes
MCU	0.5/MHz	1.1	
Radio	34.2 / 16.9	0.2	transmission at 12dbm / receiving
Temperature	<0.75	2	
Gyroscope	6.5	5	
Accelerometer	0.14	0.1	active value for max sampling
HeartBeat	0.06	-	can be turned off
Fuel Gauge	0.065	-	
SD card	20 to 100	~100	depend on model, can be off
PMS	-	90	SW1, burst mode, not switching

TABLE 3. Fenix parts current consumption.

Part	Active (mA)	Sleep (uA)	Notes
MCU	0.4/MHz	22	0.8mA/MIPS
Accelerometer	0.14	0.1	active value for max sampling
RFID	0.0083	0.8	active value for all antennas
GSM	16 / 420	62	registered / GPRS trans. (cl. 10)
	225		GPRS trans. (cl. 1)
GPS	28 / 32	1.5	active values track. / acquisition

The GPS device supports two low power modes (i.e. a fixed duty cycle mode and a dynamic one). In both modes, the GPS device alternates between active and standby periods, but in the dynamic mode it adjusts its active/standby periods to achieve a balance of positioning accuracy and power consumption, taking into consideration the environment and motion conditions.

C. MOVEMENT SENSING

Collecting movement-related information is required for supporting the calculation of the movement index and for detecting falls (the fall detector under evaluation is based on [17]). Available datasets that include falls, such as [18], have accelerometer and gyroscope data segmented by daily activities (including falls), sensor node body location, users' age, sex, weight, and height. Nevertheless, their data are not applicable to elderly people. This caused considerable difficulty in improving the algorithms with the objective of reducing false positives. Other constraints that applied in iSenior were related to the use of a single device located at end-user waist and to the need to keep the gyroscope turned off most of the time, as it consumes around 6.5mA

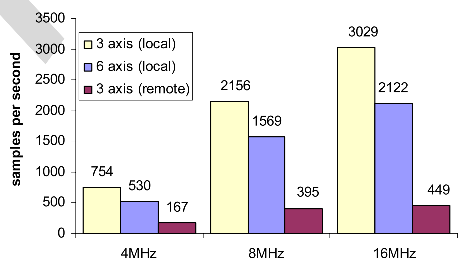

FIGURE 6. Pegasus sampling rates as a function of the MCU's clock.

To obtain elderly movement information data, Pegasus accelerometer and gyroscope are used. Fig. 6 shows the maximum sampling rate, measured at Pegasus, when sampling a 3-axis device (i.e. either the accelerometer or the gyroscope), a 6 axis device (a combined accelerometer and gyroscope unit that can also be deployed in Pegasus), and a remote accelerometer installed in the Fenix module. The implemented solution uses Pegasus' accelerometer and gyroscope, which, even in the most unfavourable conditions (lowest CPU frequency and assuming no overlapping in the sensor access), can achieve sampling rates much higher than the ones commonly used to characterize movement (according to [19], wearable motion detectors for monitoring human physical activity sample the accelerometers at ~30Hz, with an exception sampling at 128Hz). The figure also shows the suitability of Hermes' communications stack in supporting the use of a remote accelerometer, as, in the worst case, the sampling rate value is higher than 128Hz.

D. SYSTEM FIDELITY

In a system such as iSenior, fidelity is very important and, thus, the iSenior system was under evaluation in a rest home during several months in order to identify potential malfunctions and sources of erroneous alarms, either false positive or false negative. This provided important data that we are currently analysing and using for further work.

During the evaluation period we registered few situations where the alarm functionality generated false alarms (false positive) due to heartbeat spikes or activity level that were not properly filtered, and also to incorrectly defined alarm parameters. Nevertheless, those situations were easily detected and diagnosed by remotely accessing and analysing the sensors data. There were also some situations where an alarm was not generated (false negative) due to incorrect parameter settings. These were detected in routine analysis of stored data.

Communication problems can also compromise the alarm efficacy. This is why the system is always monitoring the nodes' connectivity, generating its own alarms in case of connectivity loss. In this respect, we did not encounter any problems during the evaluation.

Last but not least, we are also interested in having a fall detector, something that because of high false alarm rate could not be included in the system functionality and is still under development.

As a conclusion, the system proved to be very reliable, as most false alarms were due to improper system configuration or setting. Nevertheless, there is the need for collecting more data on the alarm system performance, in order to guarantee the statistical significance of the obtained values, this being the main reason why no concrete data is presented here and is left for further work.

VII. CONCLUSION

This paper presented iSenior, a WSN-based cyber-physical system and application for supporting elderly people, having the capacity to sense subject parameters (e.g.: heartbeat, activity level), process the respective information (e.g., for locally detecting alarm conditions), forward the processed information to a decision centre (e.g., for further processing, storage or personnel alerting), and supporting the mechanisms that enable specialized people to close the loop (e.g., interacting with the elderly in case of need). By providing monitoring, location, alerting and assistance request functionality, the system improves the autonomy and quality of life of elderly citizens.

Implementing and deploying such a system was a challenging, innovative, and complex task, not only from a technical point of view, but also from architectural, functional and performance points of view. Moreover, the size and difficulty of the challenges made it also a time-consuming task that spanned several years.

The aim of this paper was to provide details on the main features of the system, including its architecture, hardware and software platforms, and performance evaluation.

iSenior and its underlying concepts and solutions are constantly being assessed and refined. In addition to this continuing effort, further work will extend the system functionality, will optimise the system performance especially in what concerns energy efficiency and autonomy, and will further enhance reliability and security.

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REFERENCES

[1] World Health Organization, Geneva, Switzerland. (2012). *The World is Fast Ageing—Have We Noticed* [Online]. Available: http://www.who.int/ageing/en/

[2] A. Rodrigues, J. S. Silva, F. Boavida, and T. Camilo, "iHorse—A WSN-based equine monitoring system," in *Proc. IEEE 36th Conf. LCN*, Bonn, Germany, Oct. 2011, pp. 1036–1043.

[3] A. Rodrigues, M. Silva, T. Camilo, N. Blanco, J. Pedro, J. Martins, *et al.*, "Hermes: A versatile platform for wireless embedded systems," in *Proc. IEEE Int. Symp. World Wireless, Mobile Multimedia Netw.*, San Francisco, CA, USA, Jun. 2012, pp. 1–9.

[4] A. Wood, J. Stankovic, G. Virone, L. Selavo, Z. He, Q. Cao, *et al.*, "Context-aware wireless sensor networks for assisted-living and residential monitoring," *IEEE Netw.*, vol. 22, no. 4, pp. 26–33, Jul./Aug. 2008.

[5] Memsic, Andover, MA, USA. (2012). [Online]. Available: http://www.memsic.com/products/wireless-sensor-networks/wireless-modules.html

[6] V. Shnayder, B. Chen, K. Lorincz, T. Fulford-Jones, and M. Welsh, "Sensor networks for medical care," Division Eng. Appl. Sci., Harvard Univ., Cambridge, MA, USA, Tech. Rep. TR-08-05, 2005.

[7] K. Lorincz, B. Chen, G. W. Challen, A. R. Chowdhury, S. Patel, P. Bonato, *et al.*, "Mercury: A wearable sensor network platform for high-fidelity motion analysis," in *Proc. 7th ACM Conf. Embedded Netw. Sensor Syst.*, New York, NY, USA, 2009, pp. 183–196.

[8] M. McGrath and T. J. Dishongh, "A common personal health research platform—SHIMMER and BioMOBIUS," *Intel Technol. J.*, vol. 13, no. 3, pp. 122–147, 2009.

[9] J. Ko, J. H. Lim, Y. Chen, R. Musvaloiu-E, A. Terzis, G. M. Masson, *et al.*, "MEDiSN: Medical emergency detection in sensor networks," *ACM Trans. Embedded Comput. Syst.*, vol. 10, no. 1, pp. 1–29, Aug. 2010.

[10] F. Hu, M. Jiang, L. Celentano, and Y. Xiao, "Robust medical ad hoc sensor networks (MASN) with wavelet-based ECG data mining," *Ad Hoc Netw.*, vol. 6, no. 7, pp. 986–1012, Sep. 2008.

[11] Continua Health Alliance, Beaverton, OR, USA. (2012). [Online]. Available: http://www.continuaalliance.org/products/productshowcase.html

[12] (2012). *True-Kare* [Online]. Available: https://www.true-kare.com

[13] J. Ko, C. Lu, M. Srivastava, J. Stankovic, A. Terzis, and M. Welsh, "Wireless sensor networks for healthcare," *Proc. IEEE*, vol. 98, no. 11, pp. 1947–1960, Nov. 2010.

[14] E. E. Egbogah and A. O. Fapojuwo, "A survey of system architecture requirements for health care-based wireless sensor networks," *Sensors*, vol. 11, no. 5, pp. 4875–4898, 2011.

[15] E. Marcotte, *Responsive Web Design*. New York, NY, USA: A Book Apart LLC, 2011.

[16] R. L. Gellish, B. R. Goslin, R. E. Olson, A. McDonald, G. D. Russi, and V. K. Moudgil, "Longitudinal modeling of the relationship between age and maximal heart rate," *Med. Sci. Sports Exerc.*, vol. 39, no. 5, pp. 822–829, May 2007.

[17] J. Jacob, T. Nguyen, D. Y. C. Lie, S. Zupancic, J. Bishara, A. Dentino, *et al.*, "A fall detection study on the sensors placement location and a rule-based multi-thresholds algorithm using both accelerometer and gyroscopes," in *Proc. IEEE Int. Conf. Fuzzy Syst.*, Jun. 2011, pp. 666–671.

[18] University of Pisa, Pisa, Italy. (2012). *Fall Detection Database* [Online]. Available: http://wsn.iet.unipi.it/falldb/index.php

[19] C.-C. Yang and Y.-L. Hsu, "A review of accelerometry-based wearable motion detectors for physical activity monitoring," *Sensors*, vol. 10, no. 8, pp. 7772–7788, Aug. 2010.

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