# Smart Sensory Furniture Based on WSN for Ambient Assisted Living

Andres L. Bleda, Francisco J. Fernández-Luque, Antonio Rosa, Juan Zapata, and Rafael Maestre

***Abstract*— Ubiquitous computing has been defined as "machines that fit the human environment instead of forcing humans to enter theirs." An example of this type of approach is "Smart Sensory Furniture" (SSF) Project. SSF is an ambient assisted living system that allows inferring a potential dangerous action of an elderly person living alone at home. This inference is obtained by a specific sensory layer with sensor nodes fixed into furniture and a reasoning layer embedded in a PC that learns from the users' behavioral patterns and advices when the system detects unusual patterns. This paper aims to explain the SSF sensory layer, which is a distributed signal processing system in a network of sensing objects massively distributed, physically coupled, wirelessly networked, and energy limited. A complete set of experimental test has been carried out. The results show the level of accuracy for each type of sensors and potential use. Finally, the power consumption was experimentally measured and the results show the low maintenance requirements of this solution. The complete system design is described and discussed, including the node mesh details, as well as the type of sensors and actuators and other aspects, such as integration issues and solutions.**

***Index Terms*— Wireless sensor networks, embedded sensors, ambient assisted living, embedded systems.**

## I. Introduction

RECENT advances in computation, low power and high integration of electronics have greatly increased the power and possibilities of autonomous semi-intelligent devices, which in turn has made ambient intelligence [1], [2] a reality. Personal computers are rapidly becoming obsolete as opposed to mobile computing that can be anywhere everywhere in the user surroundings, or even on the human body [3]. This paradigm is also referred to as pervasive computing [4] or, more recently, everyware [5].

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As computing becomes more ubiquitous and distributed, healthcare systems, in particular for the elderly, have attracted enormous attention worldwide [6]–[8]. Elderly care (above 65 years old) drains much of the social resources of the national health care systems. For example, the estimated expenditure on medical care due to falls and related injuries of older people will reach 32 billion Euros in 2020 [9], therefore it is a must for social security and healthcare systems to make the best use of emerging assistant technologies [10], such as embedded devices (EDs), wireless sensor networks (WSNs), human-computer interaction (HCI), artificial intelligence (AI) and ubiquitous computing (UC).

Elderly population would like to maintain their independence, and live at their own homes for as long as possible. According to the European Commission Report [11], the percentage of elderly people living alone will rise in future years in the entire world, and the number of older people receiving care in institutions would almost triple. Those receiving formal care at home would more than double, and those receiving informal or no care would almost double by 2060. Either at homes or in any kind of caregiving institution furniture is always present and used. That is the main reason why our proposed system relies on furniture as a key integration element to achieve a really pervasive presence of devices in typical older people's environments.

By embedding sensors, ubiquitous computation, and wireless communication into everyday objects, future computing applications will be able to anticipate human needs. However, it is currently difficult to develop this type of ubiquitous computing in these everyday objects, because of the lack of devices that integrate both the required hardware and software. In that regard, we propose a type of small computers with wireless communication, sensors and actuators as the basis for low power smart objects.

The SSF (Smart Sensory Furniture) project aims to advance towards the support of people with special needs, with a strong focus on the elderly. The basic idea behind the SSF project is that by integrating networked sensors and actuators in objects like furniture, a system can be built providing supervision similar to a caregiver. The sensors can monitor the users and their environment, then the intelligent system can identify the main features of the context (i.e., what is actually happening), and finally can decide on the actions to take that will benefit the users in this context. In summary, the SSF project aims to achieve the following objectives:

(1) To make the concept of smart sensing furniture a reality. This concept intends to provide furniture of augmented functions within the scope of safety, prevention and eldercare.

As a starting point, the concept of smart sensory furniture takes into account the needs of geriatric homes.

(2) To develop a hardware infrastructure, consisting of sensors and actuators integrated into furniture. Sensors capture the information of interaction between people and furniture, and between people and the environment.

(3) To create a communication structure that allows sending the information wirelessly between sensors. Sensor can be arranged in different parts of furniture or located in different pieces of furniture. Furniture can be fixed or mobile.

(4) To build middleware for communications infrastructure [12]. This infrastructure must create a set of services for the proper management of the furniture, monitoring and control, providing smart and autonomous capabilities.

This article is mainly focused in hardware aspects (previous items 1, 2 and 3), and consequently point 4 (developed by our research partners at the University of Murcia) falls beyond the scope of this paper. Section 2 presents existing innovative devices based for ubiquitous computing and related research. Then, section 3 describes the system design and the developments of the above mentioned points 1, 2 and 3. Section 4 is devoted to the experimental results. Finally, the conclusions are presented in section 5.

## II. Related Work

In recent years different smart home systems with wireless sensors have been developed and reported for elderly people that live alone [6], [7], [13]–[17]. These sensors are part of a wireless network with a base station for data collection and processing. The base station diagnoses the ongoing situation and initiates assistance procedures if any strange behaviour is detected [18], [19].

Ubiquitous (or smart) healthcare applications envision sensor-rich computing and networking environments that can capture various types of contexts of patients (or inhabitants of the environment), such as their location, activities and vital signs. Such context information is useful in providing health related and wellness management services in an intelligent way so as to promote independent living [13], [20]–[24].

Tan *et al.* [25] developed a sensor system for integration in a common office chair that was capable of identifying its occupant's actions and needs. Surface-mounted pressure distribution sensors were placed over the seat and backrest of the chair for real-time acquisition of contact information between the chair and its occupant. Given the similarity between a pressure distribution map and a gray-scale image, pattern recognition techniques from computer vision were successfully applied to sitting posture classification.

Baek *et al.* [26] developed non-intrusive methods for simultaneous electrocardiogram, photoplethysmogram, and ballistocardiogram measurements that do not require direct contact between instruments and bare skin. These methods were applied to the design of a diagnostic chair for unconstrained heart rate and blood pressure monitoring purposes. Junnila *et al.* [27] and Koivistoinen *et al.* [28] developed a wireless ballistocardiographic chair for the Proactive Health Monitoring project. EMFi sensors are used for BCG measurement and IEEE 802.15.4 RF link for radio communication between the chair and a PC. The chair measures two BCG signals from the seat and the backrest and a rough ECG signal from the armrests of the chair. The R-spike of the ECG signal can be used as a synchronisation point to extract individual BCG cardiac cycles.

Sukeda *et al.* [29] present a concept for information equipment called information-accessing furniture, and developed an embedded module to be assembled into tables, mirrors, walls, etc. It enables building information equipment that is designed to match the surrounding environment, and it offers an intuitive interface to users, thus helping them to obtain information easily while doing routine activities. Tokuda [30] developed Smart Furniture which instantaneously converts the legacy non-smart space into a smart space where location-based context-aware services, service roaming, personalized services and the connectivity to the Internet are provided. Iwaya *et al.* [31] present the physical structure and middleware for the Smart Furniture. Since the Smart Furniture is equipped with networked computers, sensors and various I/O devices, it can provide various services by alone or by coordinating with other devices.

In this paper, we show that sensors in upholstered furniture can measure certain variables beyond the reach of remote sensing, or at least they can provide better accuracy, since they can get in direct contact with or very close to the user. Compared to the use of a large number of wireless sensors, the strategy of deploying a few but accurate enough, inexpensive, smart and intelligent sensors has significant advantages in case of home monitoring by furniture pieces. The advantages include uniform coverage, small obtrusiveness, ease of deployment, reduced energy consumption, low on maintenance and consequently more acceptance by the elderly community.

## III. System Design

Our system has been designed considering the presence of a local AmI (Ambient Intelligent) station used to process event patterns 'in situ' and take decisions. This home station is provided with a Java-based intelligent software which is able to take decisions about different events. In short, it has Java application for monitoring the elderly [12] and IEEE-802.15.4 wireless connectivity provided by a USB base station for our prototype. The application can monitor the events to determine if an unusual situation has occurred. If normal behaviour is detected by the latter devices, then the event might just be recorded as an incident of interest, or the user might be prompted to ask if they are all right. On the other hand, if a non common behaviour is detected, then the AmI station will immediately query the user and send an emergency signal if there is no response within a certain (short) period of time. This layer stack form a global software architecture (see Fig.1). For a more detailed description of the complete AmI system see [12].

The lowest layer is a hardware layer. In the context awareness layer, the software obtains contextual information provided by sensors. The middle level software layer, model of user behavior, obtains the actual state of the attendee, detecting if the resident is in an emergency situation which must be solved. The deep reasoning layer is being developed to solve

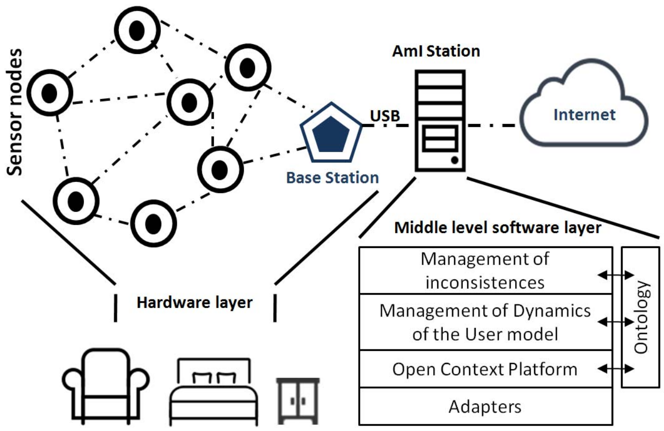


Fig. 1. Schematic block diagram.

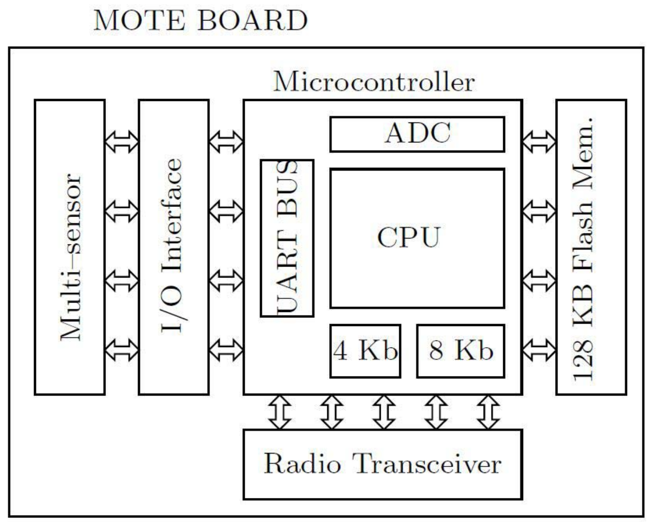


Fig. 2. Sensor node block diagram.

inconsistencies reached in the middle layer. The Open Context Platform layer captures raw data from sensorized furniture through sensor driver adapters, and transforms the data in an ontology-based format to represent context information. The dynamics of user model layer infers the users state (Semantic Web technologies are used to reason about the user's context and detection of anomalous situations). The management of inconsistencies layer is responsible of discarding false alarms or information related to noise and spurious cases. The AmI station is a small PC-based Linux machine and draws only 3-5 watts, consuming as little power as a standard PC does in stand-by mode. Ultra-small and ultra-quiet, the AmI station is about the size of a paperback book, is noiseless thanks to a fan-less design and gets barely warm. It includes a x86 architecture processor and integrated hard disk and its motherboard is a rugged embedded board having all components - including memory and CPU - soldered on-board.

An essential element of the system is furniture. These items allow a really pervasive integration of the system in environments, like homes or nursing homes, where furniture is a common object. The selected furniture pieces that comprise the system integration are a bed, an armchair and a bedside table. Elderly people spend most of their time in their bedrooms or living-rooms using these furniture types, so the system will monitor them for most of the time.

### A. Node Mesh

Activity monitoring is achieved by means of sensor devices embedded in furniture, developed by us for this purpose, which are based on the Iris device from Crossbow [32]. The node board we developed incorporates a single channel 2.4 GHz radio to provide bi-directional communications at 250 KByte/s; and an Atmel ATmega 1281V microcontroller running at 8 MHz which controls signal sampling and data transmission through an Atmel transceiver module (AT86RF230). The wireless sensor node is powered by a pair conventional LR6 (AA) batteries and optionally by an external power supply. Fig. 2 shows a schematic overview of sensor node architecture. This node board provides basic environmental sensing and an expansion slot for other sensing functionality. A PCB (Printed Circuit Board) antenna has been integrated on the board, as well as signal conditioning electronics for sensors, and an embedded firmware application has been programmed.

The TinyOS environment has been used for the firmware development. TinyOS-2.1.1 improves the robustness and efficiency of low-power asynchronous communication by sharing information on the physical layer (detection power in the channel), and link layer (short preambles header IEEE 802.15.4) in radio duty cycle. Therefore, TinyOS-2.1.1 implements a new MAC protocol type that uses information from both layers (cross-layer). The protocol is called BoX-MAC [33] and provides two versions: BoX-MAC-1 (improvement of B-MAC protocol) and BoX-MAC-2 (improvement of X-MAC protocol) [34].

The network routing feature has been enabled by means of DYMO. The DYMO (Dynamic MANET On-Demand, where MANET means Mobile Ad-hoc Network) [35], [36] routing protocol was developed as a simple implementation, substantially extensible. It results from the combination of the most important components of the AODV (Ad hoc On Demand Distance Vector) algorithm and other reactive protocols. DYMO performs similar to AODV search mechanisms while keeping a route that uses control messages. TYMO (DYMO for TinyOS) [37] is the implementation of the DYMO network protocol in the TinyOS environment. It has been adapted to the characteristics of wireless sensor networks; it is available for all hardware platforms; it has no restrictions in the context of communications (as opposed to the diffusion or collection protocols); it is stable, allows the inclusion of mobile nodes and is compatible with low power communications policies. TYMO is based on a reactive approach, meaning that it establishes a route to a destination only on demand. Therefore, if the network is static and the links are stable, it does not run any procedure for network control. This control and routing procedures generate high energy consumption in the network because all network nodes are involved in it [38].

The distributed sensor nodes are connected as a mesh network, which is a generic name for a class of networked embedded systems that share several characteristics, including: Multi-Hop (sending messages peer-to-peer to a base station) and Dynamic Routing (adaptively route based on dynamic network conditions). Typically, the nodes run in a low power mode, spending most of the time in a sleep state, in order to achieve multi-year battery life. The node is woken up when an event happens, by means of an interruption which is activated by the sensor board when the event is detected.

Event notifications are sent from the sensors to the base station. Also commands are sent from the AmI station to the sensors. In short, the base station gathers the information and acts as a central and special node in the network. The USB-based central node, also developed by us, provides different services to the wireless network. This base station is connected via USB to an AmI station (a Linux machine) which decides on an appropriate response by means of an intelligent software.

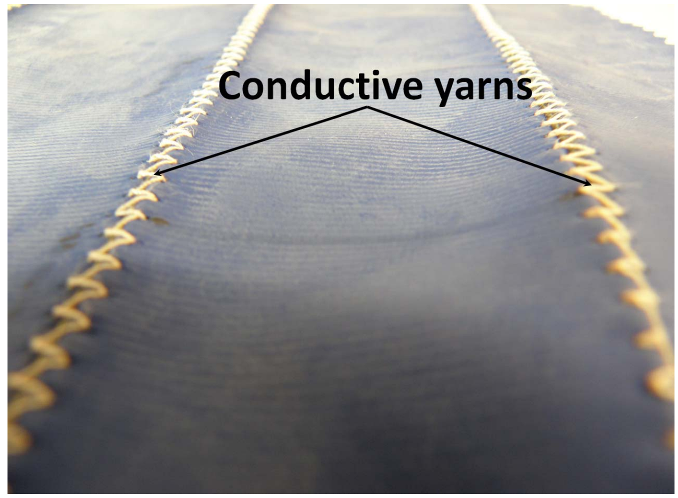


Fig. 3. Moisture sensor image.

### B. Sensors and Actuators

Sensor/actuator networks (SANETs) consist of sensor and actuator nodes that perform distributed sensing and actuation tasks. This section presents a study about relevant sensors for furniture-integrated nodes. Finally, a specific sensor for each magnitude has been selected. The justification for choice was dictated by technical or commercial reasons. As to the actuator, there are some actuator nodes distributed throughout the furniture, which we refer to at the end of this section. These wireless actuator nodes have a dual function, the first being to support and help the user in daily life activities, whereas the second is to provide assistance to elderly caregivers.

One magnitude of interest to measure is the user temperature. Using user temperature readings, the AAL system can detect anomalous temperature patterns and generate specific alarms if necessary. In this study, two different commercial sensors have been analysed. Each of them has singular features that make them suitable for furniture integration. (1) Thermistor: due to its small size, it can be integrated in furniture structure easily very close to the user and placed under the upholstery. These sensor types are very cheap but finally the selected sensor was the NTCLE100E3103JB0, (2) Infrared temperature sensor: this device allows obtaining temperature measurements from some distance of the target. It is not necessary to place it in direct contact with the user, which makes it especially useful. There are some commercial infrared temperature sensors, and the selected one is the model MLX90614 from Melexis.

Moisture sensor integration allows to detect liquid leaks on bed or couch. Even though there are some commercial humidity sensors, there are some difficulties to integrate such kind of sensor in furniture structure. So a specific moisture sensor has been developed for furniture as shown in Fig. 3. This wet sensor is made with electrical conductive yarn; the yarn is knitted on a waterproof and breathable textile material. Two individual conductive yarns are upholstered fixed in parallel avoiding direct connection between them. When the liquid makes contact with these two yarns, a connection between them is made and liquid leaks can be easily detected.

Elderly people spend plenty of time sitting or lying in furniture, and many of them are overweight or, at least, need their weight to be monitored. The integration of weight sensors in furniture allows controlling the user weight without any hassle for the user. These kinds of sensors are integrated in armchair and bed. There are some weight sensors commercially available such as the Flexiforce sensor [39] or widespread load cells. There are different types of load cell depending on its structure, mainly: beam type, can type, S-type and washer type. Beam and washer types are better fit for integration into the furniture, as they can be placed between the mattress and its bed base. There is a wide range of load cells with different quality/price ratios. Precision is required to be around 100 g. The choice was to integrate beam type load cells (model LAA-W1 from LCT [40]) mainly due to its low price and enough precision. This load cell will be easily integrated into the furniture structure.

A verticality sensor based on accelerometer will be able to detect when a piece of furniture has overturned or has been impacted. The accelerometer can be used to determine the orientation of the cabinet in case of possible loss of verticality, but it may also detect an impact if some thresholds are exceeded. Any of these conditions may indicate that the user may have fallen, or could be in a dangerous situation. The detection can be accomplished using a 3-axis accelerometer. The device ADXL345BCCZ-RL from Analog Devices incorporates all needed features; The accelerometer communicates with microcontroller through I2C bus.

Security accessories can be integrated into furniture. Beds can include rails to prevent falls when resting. Our system can detect if the bed rails are properly closed, and otherwise, warn the caregiver. On the other hand, opening or closing of bedside table doors provides information about the activity of the user, which can be used by the AmI system to learn about behavioral patterns. The selected sensors to monitor these variables are magnetic contact sensors. These devices implement a normally-open (NO) contact, this contact is closed when a magnet gets closer than a given distance, generally around 1 cm.

It is very interesting to monitor the spatial and temporal user activity, and select sensors capable of monitoring the user activity near the furniture. Passive infra-red (PIR) sensors have been used to monitor activity in the room. The PIR sensor model AMN41121 from Panasonic is selected to monitor activity. On the other hand, information about the illumination level is very useful to monitor and support the activity in a room. Besides, this information can be used to determine when a functional light should be turned on to help the user when getting up at night. The chosen sensor is the light sensor model APDS-9007-020. This light sensor was selected mainly due its low cost and low power consumption.

Some actuators have also been integrated into furniture to assist the user or caregivers. A light source is placed under the bed, and it switches on automatically when the system detects that the user is getting up without enough ambient light. This light can also be used to highlight where a specific person is having some problem. A 3-Watt LED (MX6AWT-A1-R250-000C51) was used to implement this functional light.

A nursing home bed integrates different motors and position sensors. These motors change the resting surface inclination in the back and leg zones. It is also possible to detect the overall bed height and inclination by measuring the height at the head and foot ends. These movements can provide optimal positions for the user to rest and event to get up. Two motors and a dual actuator manufactured by LINAK are integrated into the prototype bed. Motor model is LA27 from Linak [41] which is a motor with linear movement.

Motor movements and bed position can be known in real time by measuring two variables. Firstly, the inclination angle of the back and leg zones, and secondly the bed heights at the foot and head ends. For that purpose, two different types of sensors were integrated: (1) Two encoders (aka angular sensors), which allow the system to know the inclination angle of the back and leg zones. The selected sensor is the model EAW0J-B24-AE0128L from BOURNS (working details included in Furniture integration section). (2) Two infrared distance sensors, which provide the bed height at its head and foot ends. The selected sensor is the model GP2Y0A21YK0F from SHARP.

### C. Furniture Integration

This section includes a detailed description of the integration of each device (sensors and actuators) in furniture, indicating the exact location of sensor placement and main problems that sensors have for their integration into furniture.

As explained in Section 3.2, two types of temperature sensors have been selected, though the integration for each of them is different. The first one, thermistor NTCLE100E3103JB0, is integrated both in the armchair and the bed. The armchair integrates three of these sensors between the foam and the upholstery in three different zones (left armrest, right armrest and backrest). The bed includes three of these sensors into the mattress, equally distributed. These sensors are integrated under the mattress upholstery and due to the small sensor size, the user does not notice their existence. Two infrared temperature sensors (MLX90614 from Melexis) are integrated into both the bed and the armchair. Note that to obtain valid temperature measurements from this sensor, it is necessary to place it so that it has direct line of sight with the user's skin. Specifically, the armchair has a top zone where the user can rest the head, so the sensors are placed in this area. In the bed case, the sensors are placed into the headboard, so that they are pointing to the user's head.

The contact moisture sensor is integrated into both armchair and bed, in such a non-intrusive way . The moisture sensor is hidden underneath the armchair upholstery, so the user will not even notice it is there. The upholstery is impermeable in order to protect the internal foam, which increases durability in nursing homes and similar environments. A small hole in the armchair seating allows the liquid to reach the moisture sensor integrated in it. For the bed, a bigger sensor is attached to the upper side of the upholstery on top of the mattress. Similarly, the upholstery is impermeable to prevent the mattress from getting wet.

The integration of weight sensors in armchair and bed allows to monitor the user weight. The integration of this sensors in both types of furniture is very similar. Four load cells are placed under the armchair seat, or under the bed mattress. The furniture internal structure was modified so that all the weight rests completely on these sensors.

The bed has one bed rail to each side in order to prevent the user from falling from the bed. One open/closed sensor is integrated into each bed rail, inside its wood. The bedside table has an upper drawer and a lower door. An open/closed sensor has been hidden into each of them and remain invisible to the user. The drawer sensor was integrated in one of its sides, between the drawer and the external bedside table structure. The sensor in the lower door was integrated out of the line sight of the user.

A presence sensor (PIR sensor) is integrated in the front of the bedside table, at the very bottom. The bedside table front was properly mechanized to hold the sensor and connect it to the main mote.

A sensor node is needed to gather the sensor measurements and transmit them wirelessly to the AmI station. The integration of this sensor node is very easy due to its size and weight. Taking advantage of the small size of the selected verticality sensor based on the 3-axis accelerometer, this accelerometer has been placed in the sensor node board for simplicity.

A functional light (LED) is integrated under the bed. The light is oriented so that it illuminates the surrounding floor when the user gets up at night. The LED is integrated in a printed circuit board (PCB) that also includes a light sensor.

A detailed description of the assembly of the motor actuators (Twindrive TD33 from Linak) in bed is in [42], their movement varies the angle of the backrest and feet zones. Two additional motors (model LA27 from Linak) were selected which are also compatible with the actuator TD33. These devices can raise and lower the foot and head ends of the bed. They can act simultaneously or separately, so the bed can be tilted. The encoder for monitoring bed position is integrated in two different bed zones (backrest and legs). It has been necessary to properly mechanize the bed structure to join the rotational part of the sensor with the transverse rotational axes of the bed structure. The bed height is monitored by two infrared distance sensors placed at both ends of the bed. The sensors are directly fixed to the bed structure which makes the movement up and down and points towards the floor.

### *D. Sensor Node Prototype*

A first prototype was implemented in the laboratory, using a micro milling machine. After debugging, a second prototype was built to validate the design. Once the functionality of every sensor and other features was validated, the PCB layout was fitted for industrial manufacturing. A pre-series of 20 units of the prototype was manufactured (see Fig. 4), assembled and installed into the furniture for the tests described in Section 4.

Final prototypes have been designed as a single board, which incorporates all the sensor circuitry, although some of the transducers are externally connected by wires. Power supply can be provided through three different options. The board incorporates a double LR6 battery holder, a linear regulator for 3.6-12 V DC power supply and a AC/DC converter which allows direct connection to power grid.

Integrated instrumentation amplifiers have been used for the load cell signals, specifically the model ISL28270IAZ, configured to work in the range [0 to 75] kg, getting a linear output of Vo=43.26 mV/kg which is sampled by the microcontroller ADC. An external connector is provided to directly connect 4 load cells, with 4 wires each. The accelerometer has been integrated in the PCB, and an I2C bus has been used to communicate with the microcontroller, as well as 2 GPIO (General Purpose Input/Output) lines acting as external interrupts. Five voltage divider circuits are used to generate digital signals from the NO contact sensors, which feed GPIO lines in the microcontroller. Body temperature is measured in two ways, by means of thermistors and by means of IR sensors. The I2C bus communicates IR sensors with the microcontroller. A small external PCB has been designed to install the IR sensors on it, which is connected to the main sensor board by means of flat cable. A voltage divider is used to generate an analog signal from 4 thermistors, which is sampled by the ADC. The thermistor is connected to Vcc while a 10 k$\Omega$ resistor is connected to ground. Those thermistors are externally connected by wires. The same scheme is used for the moisture sensor, which is modelled as a resistive transducer. The sensor is connected to Vcc while a 1 M$\Omega$ resistor is connected to ground so signal voltage usually keeps close to ground but rises close to Vcc when moisture is detected. The PIR sensor, the light sensor and the power LED are also installed in a small auxiliary board like the one described before. The PIR sensor generates a digital signal which can be directly connected to the microcontroller. The light sensor generates a current signal which is adapted by a 56\,k$\Omega$ resistor to a voltage signal to be sampled by the ADC. The power LED is powered by a solid-state relay which is controlled by the microcontroller through a GPIO signal.

Power consumption is a main constraint in most WSN designs, especially in battery-powered nodes. However, some of our nodes integrate sensors as well as actuators, which require an external power supply. This is the case of the nodes for the bed and the bedside table. However, the armchair node has no actuators, and it could be powered by batteries, avoiding the inconvenience of power wires.


Fig. 4. Sensor node prototype.

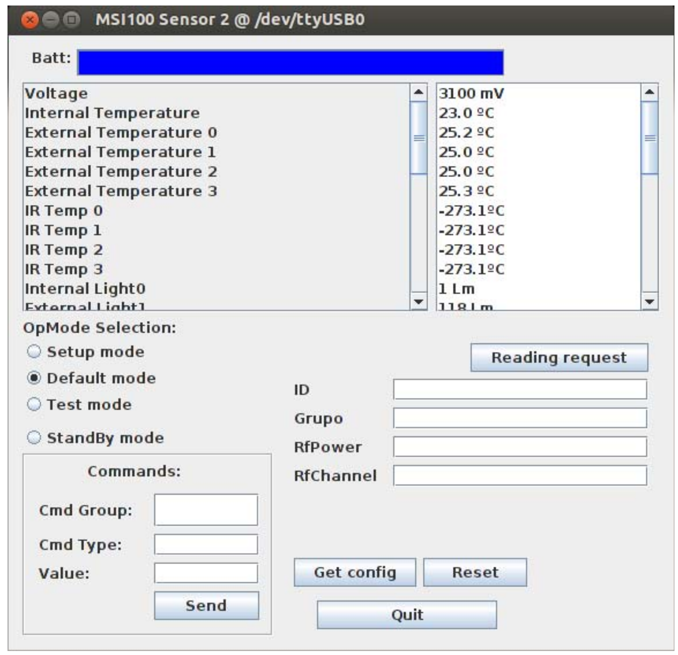


Fig. 5. Sensor node window from the GUI.

## IV. Results

The functionality of the designed system has been tested on prototypes. Specifically, 20 prototypes of the sensor node board have been manufactured, two AmI stations have been configured and four prototypes of bed, armchair and bed side table have been assembled with integrated sensors.

A Graphical User Interface (GUI) specifically developed for debugging has been used to monitor events generated by the sensor nodes. This JAVA application generates windows which are associated with each sensor node. The window shows the current status of the sensor readings, and updates the information when a data frame is received from the sensor node. Besides, buttons are available to generate the commands to make requests and reconfigure the sensor nodes. An example of these windows is shown in Fig. 5. In this way,

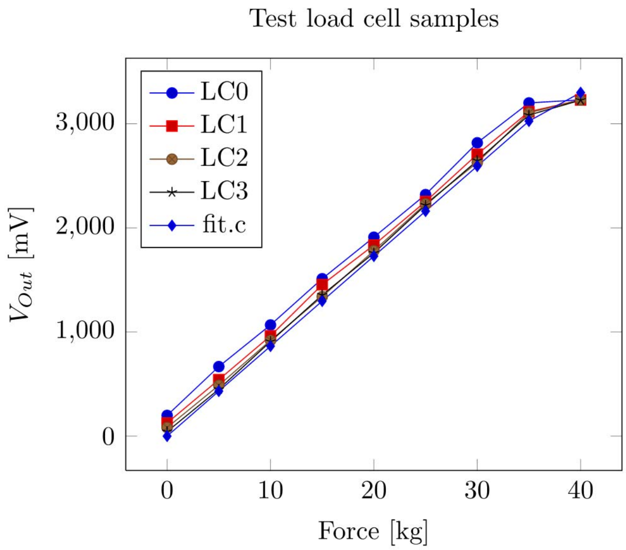


Fig. 6. Results of the test over the load cells (mV vs kg) and theoretical response.

TABLE I
MOISTURE SENSOR RESPONSE WITH DIFFERENT RESISTORS

| Rs | ∞ | 10MΩ | 1MΩ | 100KΩ | 38.9 KΩ | 10 KΩ |
|---|---|---|---|---|---|---|
| Reading | 0 | 293 | 1589 | 2959 | 3140 | 3230 |
| *Theoretical* | 0 | 294 | 1621 | 2948 | 3121 | 3260 |

each sensor has been tested off-furniture as a first stage, and once integrated into the furniture as a second stage.

### A. Off-Furniture Tests

A first set of results is obtained by testing the developed PCB prototype in the laboratory, prior to furniture integration. It allows validating the design and sensors performance in a first stage. Each of the available power supply sources have been tested: Vcc=3400 mV when the AC input is used, Vcc=3243 mV when a 12 V external AC/DC is used, and Vcc=3125 mV when LR6 batteries have been plugged. The accelerometer has two main features: impact detection and orientation at rest. The impact was signalled when the PCB was hit with a finger, and different positions for verticality were properly recognized. Short circuit at the inputs for normally-open contact sensors were properly detected by the sensor node. Temperature readings have been checked when the ambient temperature in the laboratory was between 26°C and 27°C. Readings for all the four thermistors were 26.1°C. IR thermometers indicated 26.5°C and 26.3°C when pointing to the table. The light sensor reading was 157 lumen under the laboratory illumination, 8 lumen when it was covered, and 2605 lumen when it was lighted by an LED. Load cells have been tested in the range [0,35] kg, in steps of 5 kg. Results are shown in Fig. 6 for each of the 4 load cells, and theoretical result is also plotted. The response of the input for the moisture sensor was tested for different resistance values and results are shown in Table I.

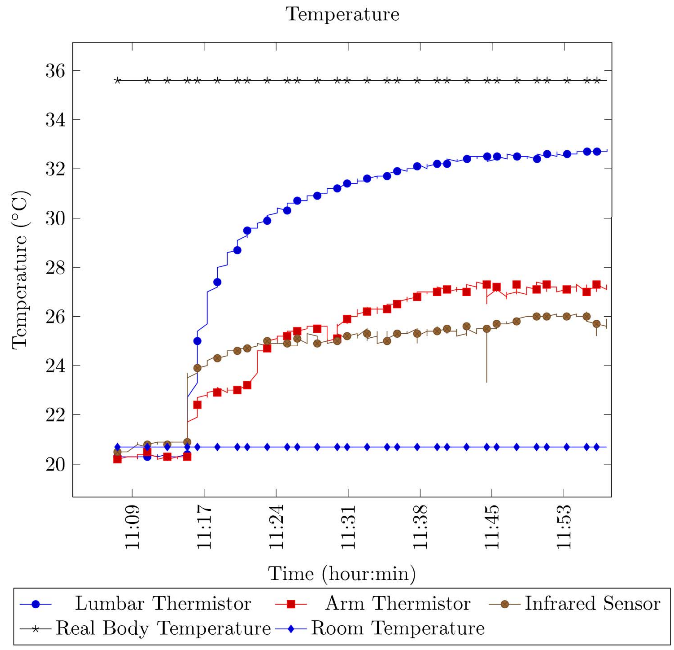


Fig. 7. Temperature values from integrated tests.

### B. In-Furniture Tests

In order to validate the full system, it is necessary to test all sensors in a complete furniture integration. This section describes these tests.

Temperature tests have been carried out in an armchair. The system monitors the temperature of a person seated on the furniture during one hour. Previously the user's body temperature has been recorded for comparison. The actual user body temperature during these tests was 35.6°C (value obtained with a commercial temperature contact sensor placed under the user's armpit), with 20.7°C room temperature. It should be noted that temperature sensing information comes from five different sensors: 3 NTC thermistor sensors and 2 infrared sensors. Due to symmetry, the response of the two arm thermistors is very similar, and so is the response of the two infrared sensors. Therefore, in order to clearly show the obtained data from the different sensors, Fig. 7 shows the response of just one infrared sensor, one arm thermistor and the lumbar thermistor.

The analysis of results provides us with some useful information. Firstly, there is a difference between lumbar and arm thermistors. Although both of them detect the user presence in the armchair (when the user sits down in the armchair, both sensor responses rise), the lumbar sensor response is closer to the real body temperature. Thus, the infrared sensor response is immediate, and the thermistor need some time to stabilize themselves. Finally, the lumbar thermistor provides the measurement closest to the real value, it is only 3 grades below the real body temperature.

Weight tests have been developed in both an armchair and a bed. Four armchair tests were carried out with motionless weights of 0, 20, 40 and 75 Kg placed on the armchair seat for 3 minutes each. Afterwards, the weights were replaced by a user of 75 Kg, who sat on it in three different

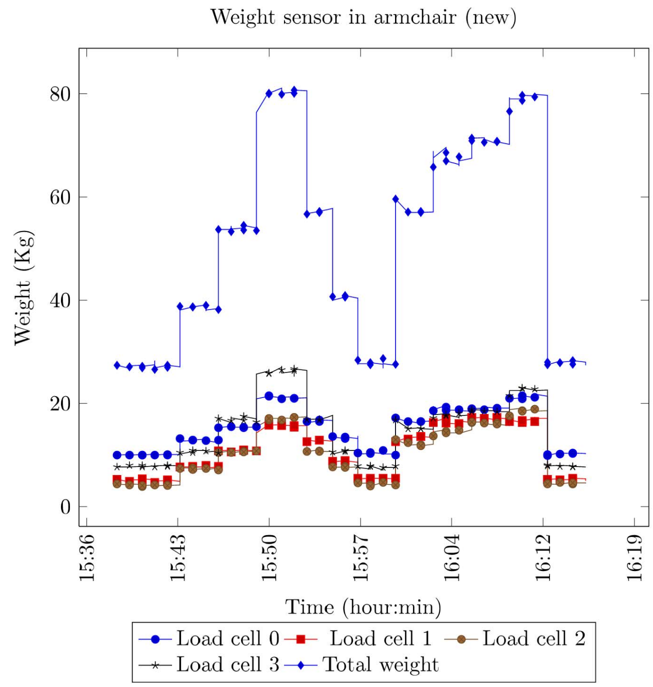


Fig. 8. Load cell responses in armchair.

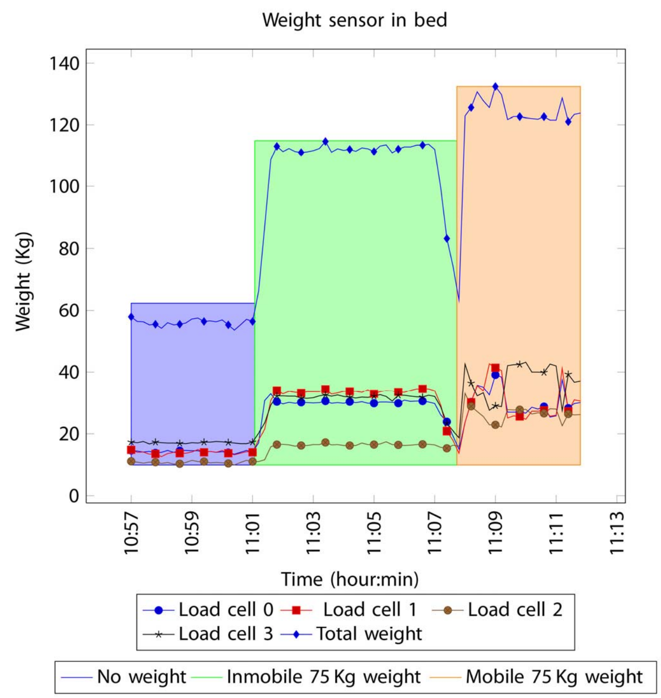


Fig. 9. Load cell responses in bed.

positions: (1) Normal position with the user's back on the backrest and feet on the ground. (2) The user's back on the backrest and feet up in the air. (3) The user's back and feet have no support, so that all the weight falls on the seat.

The bed tests were performed by first placing motionless weights of 75 Kg for 5 minutes, and replacing it by a real person of 75 Kg with some motion. Fig. 9 shows the results in both cases. The main objective of the armchair sensors was to measure the user weight, but after the test, there are some aspects to highlight. First, a measurement of 25 Kg is obtained with an empty armchair which accounts for the armchair weight. Secondly, it should be noted that for a 75 Kg person on the armchair, the sensors only measure an increment of around 45 Kg. The main reason is that not all the user weight rests directly on the seat and its load cells, since the user's feet and back rests on the ground and backrest. Obviously, the load cells can detect the presence of the user on it, and also distinguish if the armchair user is on movement or totally static, as shown in the bed weight graph. This kind of information is very important to find out how active the user is and learn about her behaviour. The bed weight sensor results are very similar to the armchair's (Fig. 8). A reading of nearly 60 Kg is obtained for an empty bed. When a 75 Kg weight is put on the bed, the total weight measured is around 120Kg, which means an increase of only 60 Kg. The difference between the real weight and the measured one is due to the bed frame and parts. Some horizontal forces and vertical friction are present in the bed in order to avoid tilting, and only part of the weight directly falls on the load cells. Even so it is possible to detect the user presence in the bed and her activity. In this case the response of an individual load cell indicates the movement with some oscillations.

The light sensor was integrate into a bedside table and was been tested during 24 hours in a standard room with natural lighting from a west-oriented window. The light sensor information obtained verifies the sensor is working correctly and as expected. According to the results in the graph, it is possible to distinguish three different main areas. Obviously, the lack of light coincides with night time. If the system finds out that the user is trying to get up from the bed or moving around the room and there is not enough light, the functional light would be switched on. The second area of the graph is related to the existence of sunlight during day time, but in this case, no direct rays of sunlight get in through the window, due to the room orientation. However, there is enough light for the user to move around. Finally, when the rays of sunlight go directly through the window, the light levels increase to a very high value, and consequently the user does not need any additional light. Fig. 10 shows light levels for one entire day.

Verticality, moisture, presence and open/closed sensors have been validated with the developed GUI in all furniture pieces (bed, armchair and bedside table). Tests of the verticality sensor have been performed specifically in the bedside table and armchair. When the table was turned to one side the sensor node sent an event message that was received by the base station. This test was also carried out in the armchair in the same way, and the base station received the event message properly. The moisture sensor was tested in the armchair by spilling 30 cl of water on the seat. A resistance of 32 k$\Omega$ is measured when 30 cl. of water is poured over the sensor. Please, note that due to its dissolved salts, the resistance value can decrease a little for urine. The water was easily detected by the moisture sensor, and an event message was sent to the base station.

Presence sensor tests were performed for the bedside table. A moving person in front of the furniture at different distances within a range of 5 meters triggered the detection. The system

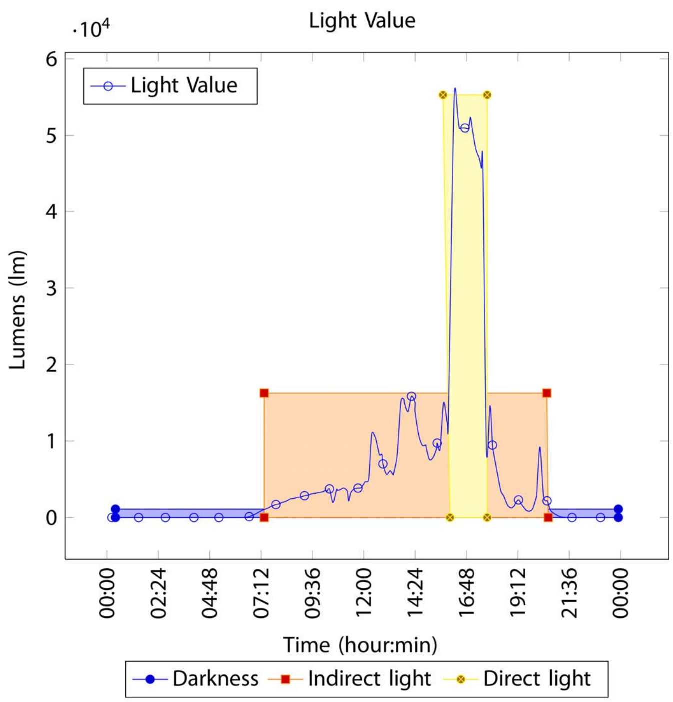


Fig. 10. Light sensor tests.

responded properly by sending a notification to the base station. When nobody was in front of the table there was no detection, avoiding the generation of false events. The open/close sensors were validated in the bedside table and bed. The bedside table drawer and door were closed and opened multiple times in order to verify that the sensor node sent the corresponding event (i.e. drawer or door properly closed). Different drawer positions were tested, and it was verified that it only detects the closed position of the drawer when it was completely closed, not in any intermediary positions. The tests for the bed were very similar to the previous ones. The bed rail was opened, closed and maintained in different positions to verify that the sensor only detects a closed rail when it is completely closed.

The bed position is determined by four sensors. Two of them are rotary encoders and measure the angles of the back and leg bed areas, whereas two infrared distance sensors measure the height of the bed head and feet ends. These sensors are connected to the Sirius D device, a radio frequency device which allows to deploy a IEEE 802.15.4 Zigbee-based wireless network in an easy and fast way. It is part of the n-Core platform developed by Nebusens [43], one of the partners in the SSF project. The different bed zones were moved and it was verified that these sensors were providing accurate readings.

### C. Power Consumption

As pointed out in Section 3.4, power consumption of the sensor node has been considered as a design constraint and has been quantified. Two different sets of conditions that represent typical scenarios have been defined in order to carry out some experiments and measure actual and representative values of power consumption. Table II summarizes the conditions for

TABLE II

SENSOR PARAMETERS FOR POWER CONSUMPTION TESTS ($T_s$: SAMPLING PERIOD)

| Sensor | $T_s$ | ‘In use’ conditions | ‘Unused’ conditions |
|---|---|---|---|
| *Load Cell* | 10s | 80 kg | 10 kg |
| *Thermistor* | 10s | 36 °C | 25 °C |
| *IR Temperature* | 10s | 36 °C | 25 °C |
| *Moisture* | 10s | Dry | Dry |
| *Verticality* | 3s | Irrelevant | Irrelevant |
| *Rail* | 3s | Closed | Open |
| *Belt* | 3s | Closed | Open |
| *Light* | 10s | High luminance | Low luminance |
| *PIR Motion* | 10s | Cont. detections | No detections |
| *Pressure Mat* | 3s | Detecting | Not detecting |

TABLE III

RESULTS OF POWER CONSUMPTION IN mA, (Vcc=3.2V). RESULTS FOR THE WORST CASE AND FOR A TYPICAL SITUATION FOR USE (50% DUTY CYCLE)

| | Worst case | Normal situation | |
|---|---|---|---|
| | In use | In use | Unused |
| P. Consumption | 6.5 mA | 5.95 mA | 5.72 mA |
| *Case average* | 6.5 mA | 5.83 mA | (DC 50%) |

these two scenarios: ‘in use’ and ‘unused’. The ‘in use’ case considers that a user is using a piece of furniture, whereas the ‘unused’ case assumes that the user is away from the furniture and undetected.

The average consumption has been measured for the worst case and for a typical situation. For the worst case, the time between event transmissions is the lowest allowed by the system, TTx=10s, and the sensors are always ‘in use’ as shown in Table II. The combination of both features maximizes power consumption, and this is why they define the worst case. For the normal situation case, a duty cycle of 50% has been considered between the ‘in use’ and ’unused’ conditions of the table. The time between event transmissions has been considered to be TTx = 60s for the ‘in use’ conditions and TTx=10min for the ’unused’ conditions. These tests have been performed during 2 hours for every situation. Power consumption has been estimated by measuring the voltage drop in a 10Ω resistor in series with the input fuse. This voltage drop has been sampled using a data acquisition board and collected values have been averaged. Results for the power consumption tests are shown in Table III. The average consumption under normal use conditions is 5.83mA, which leads to a battery life of 14.3 days for a typical 2.7A · hLR6 battery, or 57 days for an 8A · hLR14 battery, or even up to 85 days for a 12000mA · hLR20 battery. Any of the referred batteries could be easily integrated into furniture.

## V. CONCLUSIONS

AmI systems require the use of sensors that seamlessly monitor the users and their environment in order to anticipate their needs and provide the necessary support and assistance in a non-invasive way. Sensing accuracy is essential to develop reliable systems, whereas transparency and invisibility greatly contribute to the sense of comfort and lack of intrusiveness.

With the SSF project, we have taken the first steps toward the creation of smart environment platforms that deliver both, sensing accuracy and system transparency through the seamless integration of sensors in everyday objects like pieces of furniture.

In this paper we have shown that sensors in upholstered furniture can measure certain variables beyond the reach of remote sensing, or at least they can provide better accuracy, since they can get in direct contact with or very close to the user. Examples of these sensors are temperature, weight, level of activity/movement and moisture. At the same time, any kind of furniture can improve the information about the user context, and it is a great place to 'hide' the system hardware including sensors and communication nodes. The complete system design has been described including the node mesh details, as well as the type of sensors and actuators that have been used in SSF. Other aspects such as integration issues and solutions have been discussed.

A complete set of experimental test has been carried out in two stages: (1) non-integrated sensors and (2) furniture-integrated sensors. The results show the level of accuracy for each type of sensors and potential use. The thermistor integrated in the armchair backrest provides the closest reading to the actual user's temperature, which is only 3 °C below, but it requires a long stabilization time. Although this sensor cannot be used for accurate medical diagnostic, it may be used as a presence sensor, and it could provide an indication of high fever and may be used to shortly detect a decease. The response for the infrared temperature sensor is much faster, but its measurement is so low that it could only be used as a presence sensor. The load cells provide very good signs of user's activity on the furniture. Movements or stillness can be easily and accurately detected, however there are still some problems related to the mechanical integration of load cells that need to be resolved in order to provide accurate weight measures. The rests of the sensors (light, verticality, presence, open/closed, moisture and bed position) showed very good behaviour at all times. Finally, the power consumption was experimentally measured and the results show the low maintenance requirements of this solution with up to 3 months of battery life when using LR20 type batteries.

As discussed in the paper, smart sensing furniture could become a key component of AAL systems that support the elderly and significantly improve their care quality. Enabling platforms such as SSF allows us to investigate and address important practical issues such as integration, sensing problems, size, cost and power consumption. Our future work will focus on integration improvements for better non-invasive sensor accuracy, mainly for weight and temperature.

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