Unobtrusive Monitoring of Physical Activity in AAL
A Simple Wearable Device Designed for Older Adults

Adelmo De Santis, Antonio Del Campo, Ennio Gambi, Laura Montanini, Giovanni Pelliccioni,
Davide Perla and Susanna Spinsante
Dipartimento di Ingegneria dell'Informazione, Universita' Politecnica delle Marche, Via Brecce Bianche 12, 60131
Ancona, Italy

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Abstract: Many solutions and projects proposed within the Ambient Assisted Living research area, aim at monitoring the degree of vitality of elderly users in their daily activities, and in their home environment, to possibly avoid or strongly limit the need for clinical evaluations. In fact, the information on the subject's vitality, manifested through his/her activity profile, may be used to evaluate possible anomalous trends, related to cognitive or physical decay. For such a kind of analysis to be realistically affordable, the monitoring device shall be unobtrusive, and transparent to the user. With the aim of striving for the simplest and most reliable design compatible with the aforementioned requirements, this paper presents a wearable device equipped with a sensing insole hosting force sensors, and the related electronics for signal processing and data transmission. The device locally classifies different dynamic states (sitting, walking, standing) and transmits the corresponding information to a supervising system. Preliminary experimental results confirm the effectiveness of the approach, in correctly detecting and classifying the user's activities.

1 INTRODUCTION

The monitoring of physical activity has a very important role in Ambient Assisted Living (AAL) related scenarios, systems, and applications. In fact, one of the aims of AAL is to reduce risk factors for chronic disease and improve quality of life for older adults. This can be obtained by building awareness about the importance of physical activity and by assisting with the development and implementation of appropriate and effective interventions that reduce risk factors and improve quality of life (Wojtek, 2014). Behavioral analysis, to provide feedback for correcting erroneous habits, relies on the availability of data about the subject's physical activity. They have to be collected in unobtrusive way, without affecting the daily life activities performed by the subject, possibly within his/her usual home environment, and for a sufficiently long time (Sazonov et al., 2011). A shoe-mounted wearable device can be used to generate the requested data, and to comply with the aforementioned requirements. The device is composed by a sensing element, the so-called smart insole (DeSantis et al., 2014), and the associated electronics, in charge of collecting the sensor-generated data, performing a preliminary processing of them, and transmitting them to a receiving node, on a wireless channel. With respect to a solution providing the electronics fully embedded into a generic insole (Nagaraj and Sazonov, 2014), the proposed approach requires the modification of the shoe, which may be potentially seen as an obstacle to its effective adoption by an older user. Preliminary investigations were performed to clarify this issue, with the help of a shoe manufacturer specialized in the production of instrumented shoes for elderly, people with diabetes, or affected by stroke and motor impairments. The outcomes of such an analysis suggested that it is possible to limit the impact of the modification, both on the shoe manufacturing process and on the final product, so that the sensor and its electronics may be safely hosted in the shoe, and even easily moved from one shoe to another, if both of them were designed to be equipped by the wearable device. Based on the above premises, this paper presents a simple wearable device designed to keep complexity as low as possible, in any aspect, ranging from the manufacturing-related issues, to the data processing and transmission, to the usability constraints, in a real life scenario. Many proposals of smart insoles or wearable sensors for physical activity monitoring have been

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presented in the literature (Liu et al., 2009; Bamberg et al., 2008; Sazonov et al., 2011; Jarchi et al., 2014). Most of them aim at providing a gait analysis tool, or a tool that can make it possible to move a typical diagnostic process out to a home environment. For example, a sophisticated solution allowing to monitor the position of the foot in order to detect incorrect positions and send vibration feedback has been extensively tested, demonstrating a reduction from 30% to 50% of the over-pronation of the foot (Berengueres et al., 2014). Another solution exploits eight pressure sensors to assess the body balance in order to identify the pathomechanical dysfunction and evaluate an appropriate medical treatment (Manupibul et al., 2014). The device here presented, on the contrary, is conceived to ensure a reliable classification of the physical activity performed by the subject, striving for a simple design and use. Activity classification provides a basic information on the health status of the monitored subject, and its evolution along time may be observed to detect possible anomalies or alarming trends (Lester et al., 2006). The paper is organized as follows: Section 2 presents the main components of the system, from the design requirements to the hardware elements; Section 3 discusses the operations performed to process the signals generated by the sensing elements of the wearable device. In Section 4, the experimental activities performed to test the wearable device are discussed, and the results obtained are analyzed. Finally, Section 5 draws the main conclusion of the work.

2 SYSTEM

2.1 Design Requirements

The main requirements to account for in designing the wearable device for physical activity monitoring, deal with reduced obtrusiveness, limited power consumption (to avoid the need of frequently replacing the battery), and adequate precision and reliability in classifying the detected activity. The aim of the project is to get a device that can effectively discriminate among three main activity-related states: sitting (sedentary behaviours), standing, and walking. Further, it is expected to be able to detect the condition ”the subject is not wearing the shoe”, and to get information about the step cycle, for example to evaluate the step frequency and understand how fast the subject can move.

2.2 Sensing Component

The wearable device includes a sensing component, given by a smart insole equipped with Force Sensing Resistors (FSRs), and its electronic board. FSRs provide an output resistance that varies according to the pressure applied on the active area of the transducer. The output voltage generated by the transducer and depending on the applied force may be expressed as:

$$V_{out} = \frac{R_M \cdot V^+}{R_M + R_{FSR}} \qquad (1)$$

The value of R_M is chosen to maximize the desired force sensitivity range, and to limit the electric current, V^+ is the polarization voltage, and R_{FSR} is the electric resistance of the transducer that varies with the applied force. A family of V_{out} vs. *force* curves for the specific transducer used in the design of the wearable device, and for different values of the R_M resistor, is shown in Figure 1. According to the value of R_M, the sensor may get more or less sensitive to the applied force.

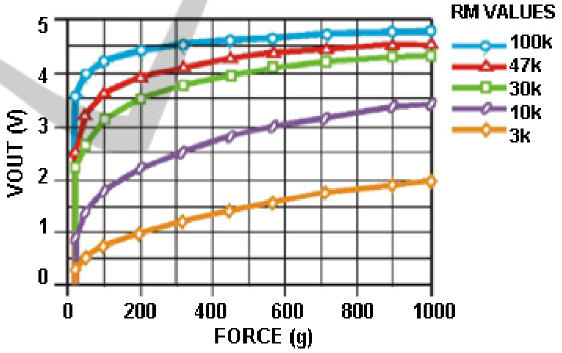


Figure 1: FSR sensor V_{out} vs. *force* curves.

The specific transducer model employed is the FSR 402 Short, manufactured by Interlink Electronics (InterlinkElectronics, 2014), and shown in Figure 2. It is a two-wire device, a robust polymer thick film (PTF) sensor that exhibits a decrease in resistance for an increase in the force applied to its surface.

Figure 2: FSR@ 402 Short sensor.

The selected transducer is 25 mm long, and the diameter of the active area is 13 mm: the reduced physical dimensions make the transducer suitable for application to a shoe insole, and the very limited thickness makes it not detectable by the subject, when he/she wears the shoe. These are important features in the perspective of a unobtrusive design.

The optimal positioning of the transducers on the insole is a crucial aspect to consider, because it affects the clear and reliable detection of the subject's physical activity or gait analysis, traded off by the limited acceptable complexity, set as a design requirement. For this reason, several tests have been conducted, considering different amounts of sensors and locating them in different positions on the insole. The outcome of this preliminary investigation suggested the possibility to employ only three FSR sensors, placed in two different configuration sets. In the first one the FSRs are placed in correspondence to the heel, the 1st metatarsal head and the toe, as shown in Figure 3(a), while in the second configuration the FSRs are placed in correspondence to the heel, the 1st and the 5th metatarsal heads, as shown in Figure 3(b).

(a) (b)

Figure 3: a) 1st configuration: FSR1 - heel, FSR2 1st metatarsal head, FSR3 - toe; b) 2nd configuration: FSR1 - heel, FSR2 - 1st metatarsal head, FSR3 - 5th metatarsal head.

The location chosen for the three sensors in the 1st configuration provides a high level of availability and allows to recognize the activity performed by the user. However, when dealing with the "walking" activity the choice of the second configuration allows to better analyse each step, identifying the different gait phases. Such an identification allows to isolate the individual steps, count them and, in the future, to extract information for gait analysis.

2.3 Electronics and Data Transmission

The signal acquisition and processing, and the data transmission procedures, are implemented by an electronic board developed ad hoc, and shown in Figure 4. Power is supplied by a Lithium battery, featuring a nominal capacity of 0.95 Ah @0.5 mA to 2V.

The following operations are performed by the microcontroller on the board:

- reading signals generated by the FSRs;
- processing the acquired signals and generating the corresponding data;
- transmitting the data to a control station.

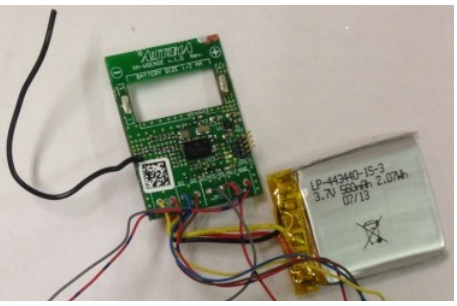


Figure 4: Electronic board for acquisition and processing of the signals generated by the FSRs, and wireless transmission of the data.

In the first version of the prototype device, a serial data transmission via USB cable was adopted, to rapidly check the feasibility of the design and the correct data transfer (DeSantis et al., 2014). In order to attain a really usable device, a wireless communication interface has finally been implemented, operating at a frequency of 868 MHz (ISM band). The use of such a frequency band is not licensed, however it is necessary to limit the occupancy of the channel to 1%-10% of the time. This constraint motivates the need for an onboard processing of the signals collected from the FSRs, aimed at generating a minimum amount of data to transmit. The choice of the 868 MHz operating frequency allows to use an antenna of reduced dimensions, that is compatible with the need of limiting as much as possible the impact of the wearable device on the shoe structure. Figure 5 shows the slot that has been manufactured within the shoe to host the wearable electronics, in the least obtrusive way possible.

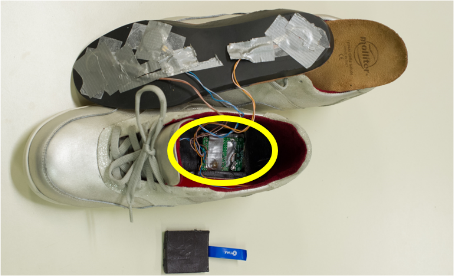


Figure 5: The shoe modified to host the wearable device: in evidence, the slot to accommodate the electronic board.

3 DATA PROCESSING

As previously stated the FSRs sensors have been applied to the insole in two different ways, aimed respectively at activity recognition and steps detection. During the step movement, the increase of the force applied on each individual transducer produces a decrease of the resistance at each sensor connector, and, consequently, an increase in the measured voltage. For every configuration, the analog voltage signals measured at each resistance divider are processed by a different algorithm running on the electronic board. The first one allows to identify the activity performed by the user. Figure 6 shows the binary tree allowing to identify all possible $3! = 6$ permutations of the subject weight distribution associated to each sensor. The value m_i, with i from 1 to 3, is the average of ten consecutive samples associated with the i-th FSR. From the six possible branches (through appropriate thresholds) a decision on the user's physical activity (sitting, standing, walking or not wearing the shoes) is made.

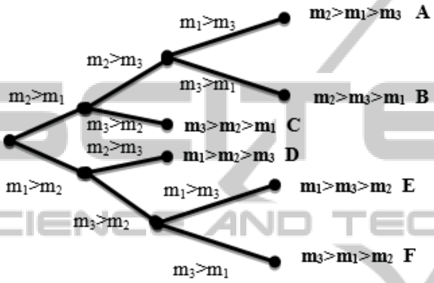


Figure 6: The binary tree allowing to identify all possible $3! = 6$ permutations of the subject weight distribution.

As previously stated, the second configuration allows to recognize the various phases of the step during walking , i.e. *heel contact (H)*, *flat foot contact (F)*, *push off (or heel off) (P)* and *limb swing (S)*. In this case, by combining the binary information on the state of each transducer (active = 1, non active = 0), it is possible to encode up to $2^3 = 8$ different foot-support conditions (eight step phases). Actually, not all the possible combinations correspond to a different state; some of them are related to the same state, as detailed in Table 1. The binarization of the information generated by each transducer is performed through the definition of a proper threshold, against which each output voltage level is compared, to discriminate between *activation* and *non activation* of the transducer. Using such a sensor configuration, the time variation of the analog voltage signal measured at each resistance divider is shown in Figure 7, where three step cycles are considered in time, along the horizontal axis. According to the association between the combinations of active and non active transducers, and the step phases detailed in Table 1, the sequence of step phases corresponding to these voltage outputs is provided in Figure 8.

Table 1: Step phases identification by transducer activation.

FSR1	FSR2	FSR3	Step Phase
1	0	0	Heel Contact (H)
1	0	1	Foot Contact (F)
1	1	0	
1	1	1	
0	0	1	Push Off (P)
0	1	0	
0	1	1	
0	0	0	Limb Swing (S)

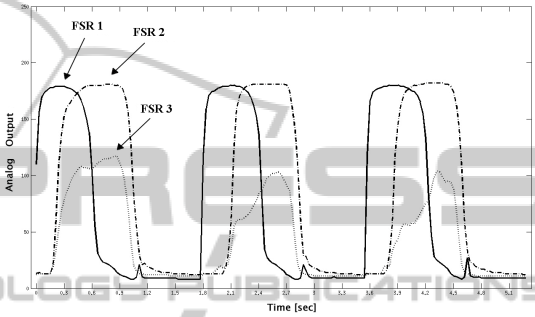


Figure 7: Time variation of the analog voltage signal measured at each transducer during the step movement.

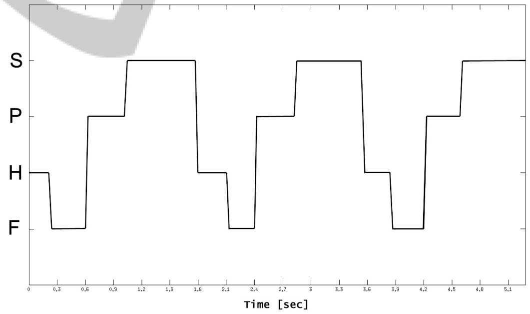


Figure 8: Time sequence of the step phases (*heel contact (H)*, *flat foot contact (F)*, *push off (or heel off) (P)* and *limb swing (S)*) corresponding to the time variation of the analog voltage signal measured at each transducer, according to Table 1.

4 EXPERIMENTAL RESULTS

The hardware and software components of the wearable device have been designed to address the aforementioned aims of the project, namely to discriminate among three main activities, i.e. sitting (sedentary behaviour), standing, and walking, and to be able to detect the condition of the subject not wearing the shoe. Both the two algorithms described in the previous section run on the electronic board of the wearable device. The first one is able to identify the weight distribution, and to exploit this information in order to determine the type of activity performed by the subject. The second one allows to perform a more accurate analysis of the step, distinguishing the various phases that characterize it and counting the walking steps. This way, the two software output a numerical value that identifies respectively the type of activity and the step frequency, which is wireless transmitted to a central unit.

This choice complies with the requirements on the use of the 868 MHz ISM bandwidth, and also allows saving on energy consumption, because the device transmits a small amount of data, less frequently than what required by a continuous transmission of each sensor signal.

Static activities concern whether the user stands still, either sitting or standing. In this case, the analysis is based on the fact that, when the user is in the upright position, the weight is almost uniformly distributed on the foot sole, while, when sitting, the weight is more distributed on the chair. So, in the former case, the average pressure on the sensors will be close to the maximum value they are able to pick up, while in the latter case, the average pressure will be much lower. Analyzing the duty cycle of the step waveforms allows to differentiate static and dynamic activities, and to discriminate the dynamic ones, according to the step frequency. The information transmitted by the board on the wireless link is collected from a software application running on a desktop system, that is used to visualize the activity performed by the subject through an avatar. The avatar may be standing, sitting, walking, or may be not wearing the shoes, as graphically shown in Figure 9. The desktop application (the interface of which is presented in Figure 10) could be running on a machine remotely connected to the wearable device, by means of an internet connection, thus enabling an unobtrusive and remote monitoring of the subject. The same information pictorially represented by the application graphic interface is also collected and stored in a database, to populate a suitable dataset for further analyses of the subject's health status and its time evolution.

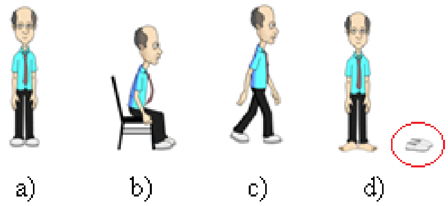


Figure 9: Physical activities visualized through the avatar: a) standing, b) sitting, c) walking, d) not wearing the shoes.

The saved data are used to derive user's daily activity reports, for example in Figures 11(a) and 11(b) the daily reports of the activities performed in a laboratory environment are shown. The upper one shows the daily percentage for each activity, instead the lower one shows the number of steps recorded at each hour of the day.


La pantofola intelligente 02/10/2014 15:08

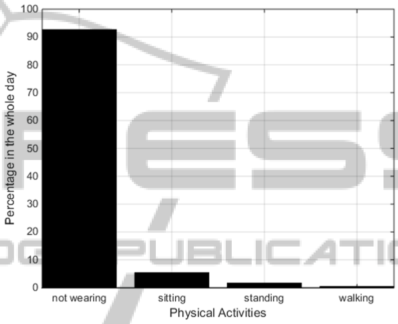
Rilevamento dello stato dell'utente

Rapidità di camminata:

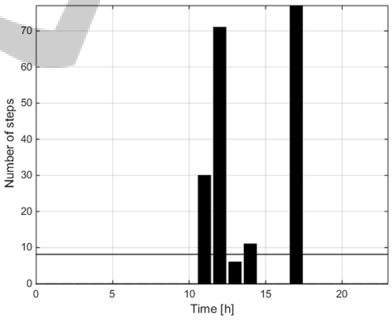
150 passi al minuto

Sta camminando

Figure 10: Desktop application interface.



(a) ADL Daily Monitoring



(b) Daily step frequency per hour

Figure 11: a) Daily percentage of each physical activity obtained using the configuration depicted in Figure 3(a); b) Daily step frequency per hour obtained using the configuration depicted in Figure 3(b). The horizontal black line represents the average of number steps on 24 hours.

5 CONCLUSIONS

This paper presented a simple wearable device designed to enable unobtrusive physical activity monitoring of ageing people. Despite the availability of more sophisticated solutions proposed in the literature, the proposed device can attain the expected outcomes, without affecting the user's daily life habits. The development activities performed up to this point are being completed and validated through an adequate test campaign involving users, possibly the older adults addressed by the proposed technology. Future work include implementation of a more widespread and energy-attentive communication technology (BLE). Furthermore, the configurations used in the prototyping stage could be combined in a single solution that allows, through a suitable decision algorithm, to recognize both activities and step phases. This solution, in addition to evaluating the vitality level of the user, should also contribute to perform a gait analysis, in order to diagnose possible pathologies or recognize incorrect postures.

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