Low Power Wearable System for Vital Signs Measurement in All Day Long Applications

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***Abstract*— In recent years, the demand for wearable devices has grown. This is due in large part to the ability to monitor in real time a critical state in the person's health in all daily activities. However, such devices have not yet had a significant development. This is because of some technological aspects not yet fully consolidated. One of these aspects is the battery power supply that due to the weight and overall dimensions can prevent the movement and / or increase the invasiveness of the system. The present work describes an instrumented autonomous T-shirt adopting a low power circuit board consuming only 8.15 mA in run mode. The proposed low power wearable system can permit smaller and lighter batteries and continuous monitoring in all day long applications. The instrumented T-shirt is capable of measuring the frequency of respiration, heart rate and movement of the body, transmitting data to a readout unit and sending alarms if necessary. The methodology adopted, the design choices and the experimental results are clearly reported and discussed. The proposed methodology can be an effective solution for all wearable devices.**

Keywords*— *wearable system; vital sign monitoring; autonomous system; hart rate monitoring; respiratory frequency monitoring; low power; instrumented T-shirt; vital sign measurement.

I. INTRODUCTION

A wearable device is in many cases a solution for the monitoring of vital parameters of a person during daily activities. These devices are used for a variety of applications in the medical, sports and fitness. In the medical field, one of the main problems, in which the wearable devices can provide an important solution, is the monitoring of the health status of the elderly population, which is expected to grow in the coming years, since it raises questions about the cost of the structures and assistance activities. The main advantages in the adoption of a wearable system are the decreasing health costs both for the patient and for the medical corps, the waiting time and the overcrowding in the medical structures; on the other hand, the increasing of the people independence and their autonomy improves their quality of life [1]. Other interesting application fields are sports and wellness, in fact, wearable systems can constantly monitor the performance of the athlete and provide information on its performance in real time so as to constantly improve his/her physical activity.

In the literature, some biomedical wearable systems equipped with sensors and suitable electronic to condition and store the vital signals are reported [2-6]. In these systems, the acquired data are sent to a remote processing unit as a medical center able to diagnose the situation and organize assistance if needed.

In most cases, the systems operate in continuous mode powered by rechargeable batteries and often the power consumption is not indicated. In [2], the MagIC is an interactive shirt used for the home monitoring of cardiac patients. This device allows more than sixty hours of continuous activity per charge but is not classifiable as low-power. Another system for long-term continuous monitoring of ECG signals is described in [3]. The adopted electrodes are not indicated and the system could not be classified as low-power because a Bluetooth transceiver module is implemented. In [9], a smart shirt, which measures the ECG signals and the acceleration for the continuous health monitoring was designed and developed. However, the possibility of measuring the respiratory activity is also crucial to check the patient health. Medical analysis showed that the most important parameters are those that specify the functionality of heart and respiratory system [1]. A particular technique to measure the respiratory activities is presented in [5]. This work exploits highly flexible polymeric optical fibers, which react to applied pressure due to chest movements. A wearable system that transmits data to the patient's PDA (Personal Digital Assistant), mobile phone via Bluetooth, and following the doctor's PDA via Global System for Mobile Communications (GSM), is shown in [6]. Probably, the solution of PDA phone is not the best option for elderly patients, for monitoring at home and it could not be classifies as low-power.

The previous devices, even if numerous, have not yet had a mature development, probably due to some technological aspects, such as power consumption, invasiveness, etc. The hardware for detection and data collection of the physiological data must be attached to the subject and thus it requires a wireless communication to transfer the raw data from the sensors to the receiver avoiding cabled solutions which can constrain the movements and low power electronic circuits.

These monitoring devices, aiming to guarantee the best solution in the person assessment, need to be integrated in garments, as clothes, belts, and cuffs or other. Therefore, they can be embedded on the wearable garments in different ways but have to be developed under terms of size, comfort, portability, durability and, more important, power dissipation. Electronic textiles (e-textiles) applied to wearable devices has recently done many advances in health monitoring field [7].

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In a previous paper [8], an instrumented wearable garment for wireless health monitoring was designed. A T-shirt were developed to monitor the principal subject's vital signs. The monitored physiological parameters are ECG, heart rate, respiratory rate, and subject's inclination through the use of three-axis accelerometer. This solution is not low-power; in particular the system implements a Bluetooth transmission sending the data to a remote central unit for the following processing. In [9], a study was developed to validate position and movement data obtained using the tilt and movement sensor system compared with an optical visual system. A 3D vision system commercialized by Codamotion was used to evaluate the accelerometer data. This paper describes a different device respect the previous works. In particular, a new low-power electronic board has been developed to improve the data acquisition, power consumption, comfort and portability. The methodology adopted, the design choices and the experimental results are clearly reported and discussed.

II. SYSTEM DESCRIPTION

The wearable system with details about the smart instrumented T-shirt is schematically shown in Figure 1; it can be divided in several blocks:

(i) electronic circuit board including conditioning sensor circuits, accelerometer to measure body motions, and wireless transfer module;

(ii) sensors measuring cardiac and respiratory activities (ECG electrodes and inductive plethysmographic sensor)

(iii) external reading unit which receives the data from the circuit board via wireless and can be connected to internet.

Table 1 shows the characteristics of all the physiological signals that can be measured and in the follow paragraphs, details about each blocks of the wearable monitoring system are reported.

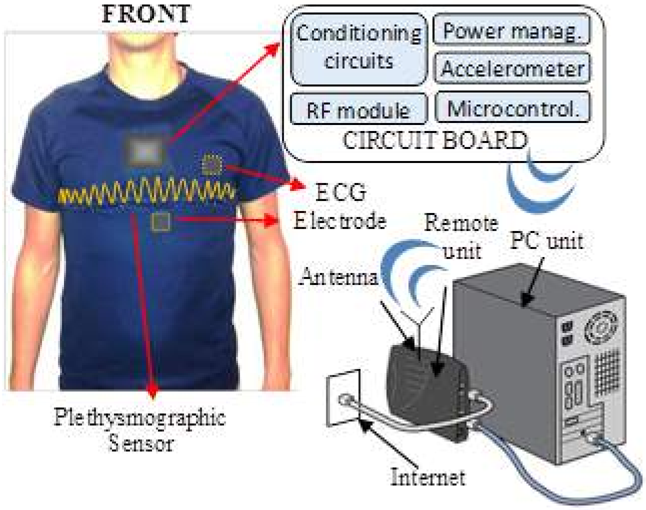

Fig. 1. Overall view of the wearable system with details about the smart instrumented T-shirt.

TABLE 1. SPECIFICATION OF VARIOUS PHYSIOLOGICAL PARAMETERS MONITORED.

Physiological Parameter	**Specifications**
Electrocardiogram (ECG)	Frequency: 0.5 Hz – 100 Hz
Heart Rate (HR)	40 – 220 beats/minute
Respiratory Rate (RR)	2 – 50 breaths/minute Frequency: 0.05 Hz – 10 Hz
Position	-90°, +90° 3-axis
Body acceleration	±2 g

2.1. Electronic board

In Figure 2, the block diagram of the electronic circuit board of the wearable system is shown. The electronic board has dimensions of 5.5 cm x 4.5 cm and weights 25 g.

The electronic circuits are supplied by 3.3 V using the power management circuit composed by a multimode low-power DC-DC regulator in step-down mode, the TPS62100. The adopted battery (GSP 063048) is a light rechargeable lithium battery of 3.7 V (850mAh). The variable energy from the battery is converted in 3.3 V fixed and sufficient current to supply the electronic board. Furthermore, on the electronic circuit board, a protection supply circuit and an integrated voltage reference of 1.8 V, which is exploited by the conditioning circuit of the ECG analog signal, are mounted.

The three sensor signals are acquired by the microcontroller, the low-power 10-bit MC9S08QE128 by Freescale. The ECG electrodes are connected to a front-end electronics and then the output signal is converted by the 12-bit Analog/Digital Converter (ADC) inboard to the microcontroller. The plethysmographic sensor generates a frequency signal acquired by the microcontroller trough the timer unit. Finally, the data generated from the digital accelerometer are acquired by the microcontroller using the SPI interface with four connection wires.

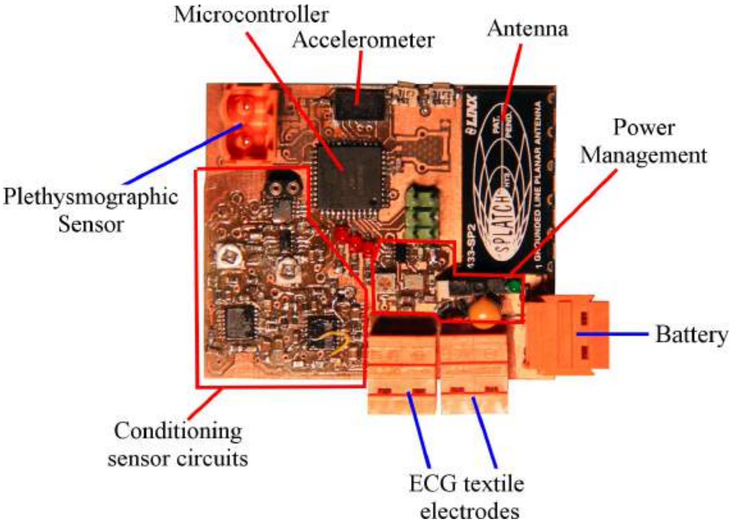

Fig. 2. Electronic board and its embedded circuits and connectors.

Figure 2 shows the electronic board that manages the operations of acquisition and transmission of the instrumented

T-shirt system. The electronic board has been designed and realized on a printed circuit board (PCB) in double sided (two copper layers). The good layout practices have been considered (short traces, ground plane, bypass capacitors) to improve performance and provide benefits such as reducing the electromagnetic-interference susceptibility. Figure 3 is the architecture of the electronic board and the external peripherals that compose the wearable system.

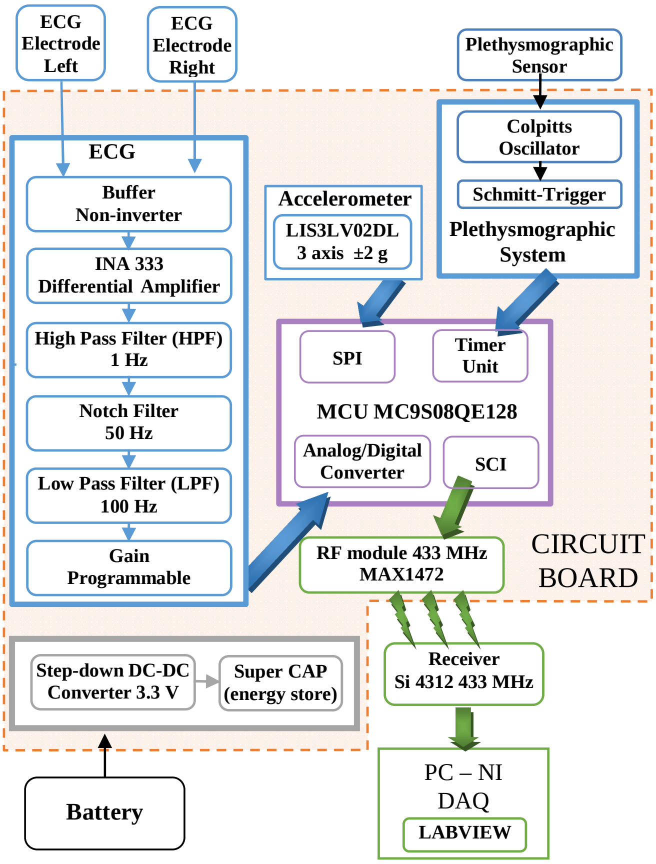

Fig. 3. Architecture of the wearable system.

The microcontroller is also responsible for sending the stored data to a readout unit using an RF module. The data transmission is made using a low-power RF transmitter (MAX1472, Texas Instruments) which is placed on the electronic circuit board. The frequency range for this type of transmitter is 433 MHz and the modulation mode is ASK with 90 dB of modulation depth that guarantee some meters of transmission distance. The antenna is ANT-433-SP (Linx Technologies) which has an ultra-compact package, good performance and very low cost.

The data are sent to the Silicon Labs 4312-DKEB1 receiver connected to the remote unit (PC) by means of National Instruments acquisition board. Therefore, a dedicated LabVIEW program processes the received signals that includes the useful physical information. The measurement algorithm of the microcontroller is programmed to sample, convert and send the data with frequency of 66.23 Hz. This frequency has been selected with the aim to obtain useful signals also when the heart rate and respiratory rate are very high. Furthermore, the stop mode is used in the algorithm to reduce the power consumption after the data send. The real-time interrupt wakes-up the microcontroller and starts another measurement.

The wearable T-shirt has been designed using low-power components to decrease as much as possible the current consumption. In Table 2 are shown the current consumptions of the each circuits that compose the electronic board. The current in sleep mode is relevant because not all the components can operate in sleep mode. The next step will be to change the components to decrease the power consumptions. However, using the light rechargeable lithium battery of 3.7 V at 850mAh, it is possible to supply the designed instrumented T-shirt up to 117 h.

TABLE 2: CURRENT CONSUMPTIONS OF THE COMPONENTS MOUNTED ON THE ELECTRONIC BOARD.

Circuit	**Run mode [mA]**	**Sleep mode** [mA]
Microcontroller	4	0.5
Power management	0.6	0.6
Accelerometer	0.5	0.05
ECG circuit	0.2	0.2
Respiratory circuit	0.8	0.8
RF module	4	0.2
Total	**10.1 mA**	**2.35 mA**

2.2. Heart rate measurement

The measurement of the cardiac activities is made using two textile electrodes woven directly on the T-shirt (Figure 1). The electrodes are located inside of the T-shirt on the right and left chest respectively, as shown in Figure 1, in “leads I” configuration. The electrodes are realized using a conductive metallized nylon fabric (Nora Dell) commercialized by Shieldex. This material is a lightweight, rip-stop fabric woven with nylon monofilament that has been plated first with silver, then with copper, and finally with nickel to provide weatherability and protect against galvanic corrosion. The textile is characterized of good conductivity and its main features are listed in Table 3. In order to improve signal quality, a conditioning circuit is implemented on the electronic circuit board to eliminate noises and impedance problems (Figure 3).

TABLE 3. MAIN PARAMETERS OF THE NORA DELL TEXTILE USING TO REALIZED THE ECG ELECTRODES.

Parameter	**Value**
Surface Resistance	< 0.009 Ω/□
Shielding Effectiveness	Average 95 db from 30 MHz to 10 GHz
Abrasion Resistance	1000000 cycles
Temperature Range	-30 °C to 90 °C
Total Thickness	0.13 mm
Weight	95 g/sq.M
Clean Room compatible	yes

2.3. Plethysmography

The respiratory rate measurement technique uses an inductive sensor to measure changes in a cross section of the rib cage during a respiratory cycle. The sensor consists of a wire of copper sewn to the smart-shirt with a sinusoidal form of height of 4 cm and step of 2 cm. The operating principle is the inductance variation due to dimension coil change when it is applied a stretch generated by the rib cage movements during inhaling and expiration.

The inductive sensor sewed to the T-shirt was characterized using an impedance analyzer (HP4194A). The impedance magnitude and phase diagrams are shown in Figure 4 and they show that for the operating frequency over about 200 kHz, the sensor is mainly inductive. The equivalent circuit can be represented by an inductance in series with a resistance. To perform the measure, the inductive sensor is used in a Colpitts oscillator circuit feedback (Figure 3). In this way, the oscillation frequency changes with the inductance variation due to the chest volume which increases or decreases during the respiratory activity. The oscillator output signal is squared through a low-power integrated Schmitt-trigger (SN74AUP1G17) in order to make readable the modulated signal to the timer unit of the microcontroller.

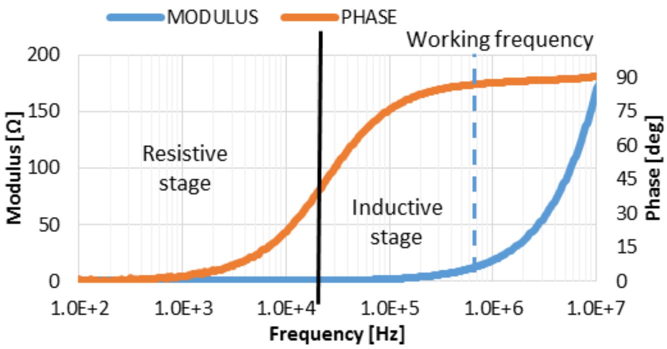

Fig. 4. Impedance analyzer (HP4194A) characterization of the inductive sensor sewed to the T-shirt.

2.4. Tilt sensors

The measurements of the position and the main tilts of the chest are made by an accelerometer of the STMicroelectronics, the low-power LIS3LV02DL. It is a three axes digital output linear accelerometer composed by an inertial system and an IC interface to provide the measured acceleration signals from the sensing element to the external world through a SPI interface. The human body motion frequency typically belongs to the range 0.5 – 10 Hz in accordance with the locomotion studies. For example, measured frequencies for chest, back and shoulder are included in a range of 1.7 – 2 Hz [10], whereas the walking gait cycle frequency is about 1.0 Hz [11].

The digital three axes accelerometer can be used to tilt-sensing applications due to its capacity to measure static accelerations assuming that the gravity acceleration is the only acceleration value acted on the human body. Other accelerations, such as the dynamic contribution and the artifact due to the fabric movements, where the electronic board is fixed, are filtered by a low-pass filter with a cut off frequency of 0.5 Hz, according to [12].

In our application, a measurement range full scale of ±2g and an output data rate of 160 Hz are used. With this configuration, the accelerometer resolution is 1.0 mg and the sensitivity is 1024 LSBs/g, about 1 mg.

Two rotation angles of the body are measured: the antro-posterior angle and the medio-lateral angle. Hence, the useful information from the accelerometer is the acceleration by the patient movements and the ahead/back (antro-posterior angle) or left/right (medio-lateral angle) imbalances of the person that uses the smart-shirt. The coordinate system used in this application is based on the accelerometer orientation:

- the accelerometer Z-axis points forward with respect to the human body and represents the antro-posterior axis of the patient. In the vertical rest position of the patient, the angle assumes the value of 0 deg and it can go from -90 deg, when the patient falls back, to +90 deg when the patient falls ahead.
- The accelerometer Y-axis is aligned at right angles to both the X-axis and Z-axis so that the three axes form a right handed coordinate system. The medio-lateral angle is defined as the angle between the Y-axis axis and the horizontal plane. As the antro-posterior angle, in vertical rest position the medio-lateral angle assumes the 0 deg value. The extreme value of the medio-lateral angle in this application is -90 deg when the patient is completely bending on the right side and +90 deg on the left side.

The angles are calculated using the three acceleration values by the following Equations (1) and (2), using the inertial measurement unit theory. The value a_x, a_y and a_z are the acceleration from the X-axis, Y-axis and Z-axis, respectively.

$$antro-posterior = \arctan \frac{a_z}{\sqrt{a_x^2 + a_y^2}} \tag{1}$$

$$medio-lateral = \arctan \frac{a_y}{\sqrt{a_x^2 + a_z^2}} \tag{2}$$

III. PRELIMINARY EXPERIMENTAL RESULTS

A consumption measurement was carried out to evaluate the power consumption during the different operations. The current consumption was obtained with an oscilloscope by measuring the voltage drop across a resistor of 10 Ω in series with the supply. The electronic board consumes on the average about 8.2 mA and 2.4 mA, in run-mode and in sleep-mode respectively. In particular, in run-mode in the initialization phase the current is about 7.5 mA for about 0.6 ms, in the reading phase the current is about 8.2 mA for about 4.4 ms and in the transmission stage the current is about 9 mA for about 0.6 ms). At the end of transmission, the microcontroller and all peripherals are put in sleep-mode up to the next real-time interrupt, generated each 15 ms.

Preliminary experimental results about the heart rate monitoring are shown in Figure 5. In particular, the ECG layout acquired shows the curve PQRST: according to the “lead I” mode, the P wave, during normal atrial depolarization, is not visible, whereas the T wave, representing the repolarization of the ventricles, is more accentuated. The information relating to the heart rate can be calculated measuring the time between consecutive picks due to the QRS complex that represents the rapid depolarization of the right and left ventricles. In addition, the QRS complex measured reflects the typical layout of the “lead II” configuration where the QRS has a large amplitude because the ventricles have a large muscle mass compared to the atria.

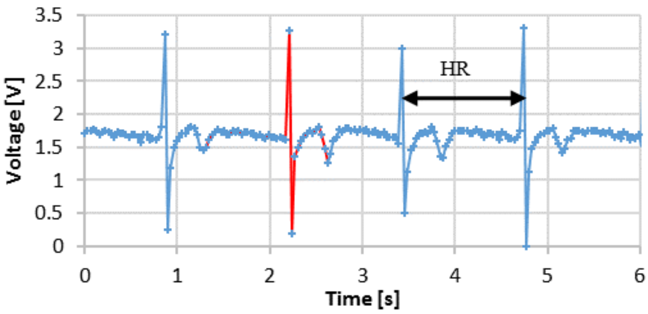

Fig. 5. ECG layout monitoring during resting activity. The red line highlights a PQRST complex. The subject monitored had a heart rate of about 42 bpm..

In Figure 6a, the ECG trace, when a person stand-up and sit-down from/on a chair continuously, is shown. The measured ECG is compared with the antro-posterior angle measured by the tri-axial accelerometer. Figure 6b compares the ECG layout with the medio-lateral angle when the patient oscillates to right and left. These graphs indicate that the ECG is less affected by the noise due to the movement of the person. The PQRST complex, typical trend of the “lead II” configuration, is visible.

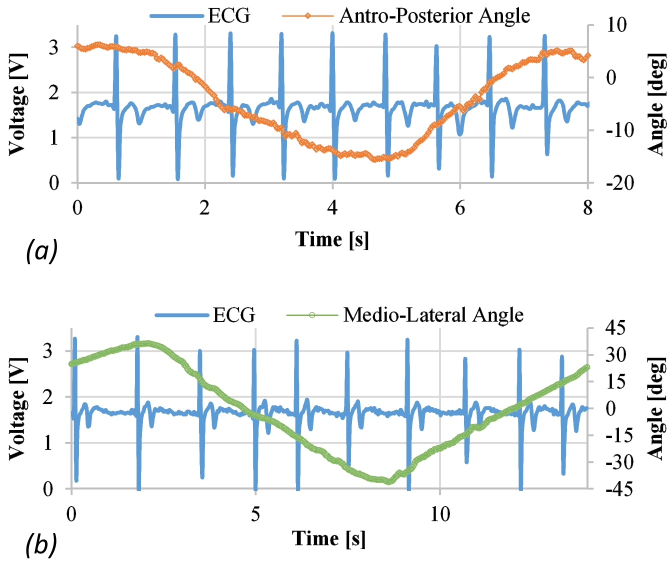

Fig. 6. Comparison between the ECG layouts with (a) the antro-posterior angle of the patient in stand-up or sit-down activities, and (b) the medio-lateral angle when the patient oscillates in right and left directions..

In Figure 7, the output signal of the respiratory circuit is shown. The signal represents the relative frequency change of the output signal produced by Colpitts oscillator. Using the timer unit of the microcontroller in input capture mode was measured the real-time frequency of the Colpitts oscillator and consequently the respiratory rate. The oscillator circuit generates an output signal with frequency of inhalation lesser than exhalation because the inductance increase in according to growth the chest volume. An about 5 kHz of change frequency was been measured between exhalation and inhalation phase.

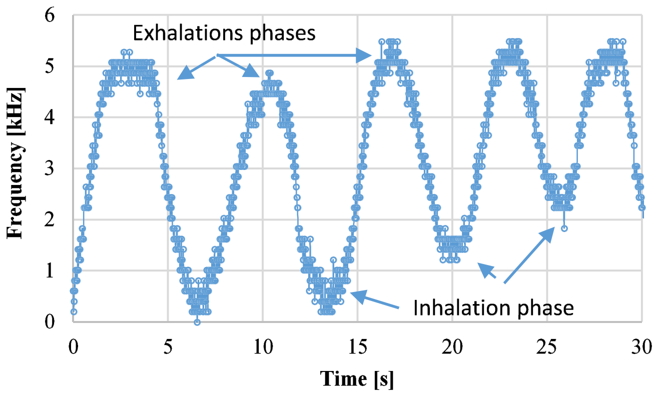

Fig. 7. Frequency change of the oscillator circuit produced by the respiration during resting activity. The subject monitored had a respiration rate of about 10 breaths/min.

Three different tests were executed aiming to evaluate the wearable system behavior during typical day-life activities and high-risk situations: fall-ahead, fallback and lateral imbalance. The movements, when a person fall ahead, are recognizable by the antro-posterior angle because the subject flexes his body in forward and arrives to the horizontal position in correspondence of the +90 deg, as it is show in Figure 8. The chest movement goes ahead so that the board weight pulls the shirt, thus some unwanted acceleration contributions are generated. As the results obtained in the fall-ahead exercise, the fallback of the person is recognizable by the antro-posterior angle. In particular, the trend is inverse with respect to the previously results, in fact when a person falls back the antro-posterior angle goes to -90 deg, as shown in Figure 9.

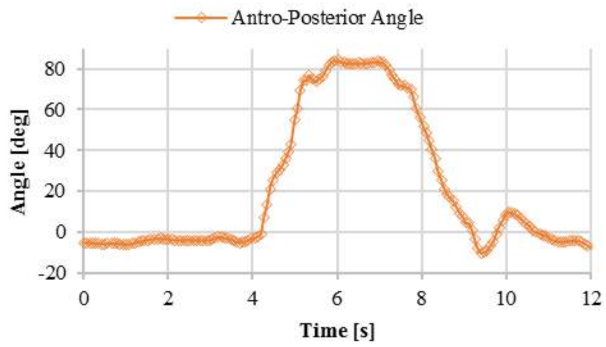

Fig. 8. The antro-posterior angle when the patient falls forward.

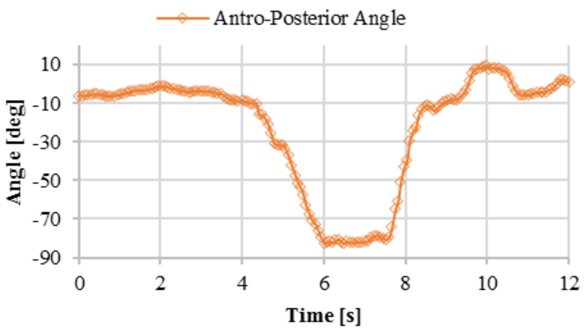

Fig. 9. The antro-posterior angle when the patient falls back starting from the vertical position.

The imbalances to right and left side of the body are visible due to the medio-lateral angle, as shown in Figure 10. When the person is right imbalanced the medio-lateral angle is positive, on the contrary the angle is negative. Using these results, to establish the position and the eventually falls in both side is possible. Therefore, from the experimental results, it is possible to observe that different situations of risk can be monitored and it is possible to associate alarms to the surpassing of predetermined thresholds. In this phase, only tests regarding risk events such as falls have been taken into consideration and reported. However, with the accelerometer mounted on the system, other activities as shown in [9] can also be monitored.

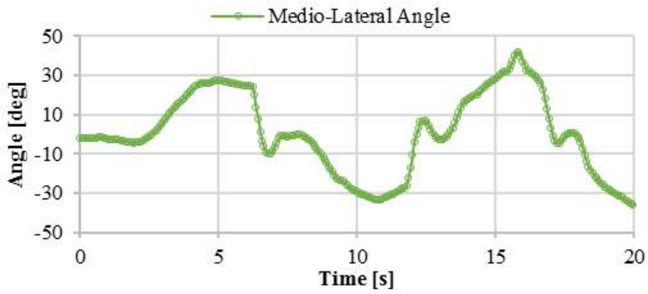

Fig. 10. The medio-lateral angle measured when the patient oscillates on the right and left side.

IV. CONCLUSIONS

In this paper, a new autonomous instrumented T-shirt is presented. The wearable system monitors the main vital physiological parameters (heart rate, respiratory rate and movements of the chest). The wearable system has been designed, built and tested, thus the description of each block of the wearable system and the adopted methodological choices have been reported. Furthermore, other aspects were considered; during the test, the subject did not sweat, however, even if this should happen, the sweat in normal condition is supposed to not interfere. In fact, the variations in the conductive paths of the currents caused by the sweat are avoided because the conduction wire is enameled, preserving from the possible environment influence and avoiding the contact with the human body. However, we will investigate the use of the proposed T-shirt in different context on different physical activities. Different tests will be executed to certify the conformity to the recommendations for a wearable device. The T-shirt with the conductive electrodes and wires is washable; the electronic circuit board can be separated from the T-shirt by means of snap buttons. Further research will investigate a clinical adoption with an evaluation of the uncertainty values for the tilt sensor, ECG and plethysmographic systems with different subjects; this activity requires to be done with a physician through the prototype and reference instrumentations.

REFERENCES

[1] Chana, M.; Estève, D.; Fourniols, J.; Escriba, C.; Campo, E. Smart wearable systems: Current status and future challenges. Artificial Intelligence in Medicine 2012, 56, 137-156.

[2] Di Rienzo, M.; Meriggi, P.; Rizzo, F.; Castiglioni, P.; Lombardi, C.; Ferratini, M.; Parati, G. Textile Technology for the Vital Signs Monitoring in Telemedicine and Extreme Environments. Information Technology in Biomedicine, IEEE Transactions on, 2010, 14, 711-717.

[3] Hu, S.; Wei, H.; Chen, Y.; Tan, J. A Real-Time Cardiac Arrhythmia Classification System with Wearable Sensor Networks. Sensors 2012, 12, 12844-12869.

[4] Dong, Y.L.; Chung, W.Y. Wireless sensor network based wearable smart shirt for ubiquitous health and activity monitoring. Sensors and Actuators B: Chemical, 2009, 140, 390-395.

[5] Krehel, M.; Schmid, M.; Rossi, R.M.; Boesel, L.F.; Bona, G.-L.; Scherer, L.J. An Optical Fibre-Based Sensor for Respiratory Monitoring. Sensors 2014, 14, 13088-13101.

[6] Tay, F.E.H.; Guo, D.G.; Xu, L.; Nyan, M.N.; Yap, K.L. MEMS Wear-biomonitoring system for remote vital signs monitoring. Journal of the Franklin Institute, 2009, 346, 531-542.

[7] Stoppa, M.; Chiolerio, A. Wearable Electronics and Smart Textiles: A Critical Review. Sensors 2014, 14, 11957-11992.

[8] Ometto, M.; Sardini, E.; Serpelloni, M. Multi-parameter wireless shirt for physiological monitoring. Medical Measurements and Applications Proceedings (MeMeA), 2011 IEEE International Workshop on, Bari, Italy, 30-31 May 2011 2011, 316-321.

[9] Dionisi, A.; Pasqui, V.; Sardini, E.; Serpelloni, M. Instrumented Shirt to Evaluate Classical Human Movements. Medical Measurements and Applications (MeMeA), 2014 IEEE International Symposium on, Lisbon, Portugal, 11-2 June 2014, 1-6.

[10] Romero, E.; Warrington, R.O.; Neuman, M.R. Body motion for powering biomedical devices. Conf. Proc. IEEE: Eng. Med. Biol. Soc., Minneapolis, USA, 3-6 September 2009, 2752–5.

[11] Tao, W.; Liu, T.; Zheng, R.; Feng, H. Gait Analysis Using Wearable Sensors. Sensors 2012, 12, 2255-2283.

[12] Mathie, M.J.; Coster, A.C.F.; Lovell N.H.; Celler, B.G. Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring human movement. Physiological Measurement, 2004, 25, R1-R20.