Smart Shirt with Embedded Vital Sign and Moisture Sensing

João Lage, André Catarino, Hélder Carvalho, Ana Rocha
School of Engineering
University of Minho
Guimarães, Portugal
e-mail: helder@det.uminho.pt

***Abstract*—This paper presents the development of a smart shirt with embedded electrodes in two-lead configuration for heart rate measurement and a knitted moisture sensor for sweat detection. Signal conditioning for heart rate measurement is based on the Analog Devices AD8232 heart rate monitor front-end. The shirt is part of a fireman interactive Personal Protective Equipment (PPE), which monitors information on heart rate and sweat detection, among other variables. Sweat detection is used to avoid skin burns that may occur due to the combination of excessive moisture and heat. Tests have demonstrated that the measurement of heart rate using the shirt is as efficient as conventional solutions, such as heart-rate monitoring straps. Sweat detection through textile moisture sensors has also shown to be effective.**

Keywords-ECG; biosignal; moisture; e-textile; textile sensors.

I. INTRODUCTION

Textiles are excellent interfaces for bio-signal sensing, as they are flexible, stretchable and conform to the body. People use textiles daily and at all times, rendering them an interesting solution for ubiquitous, continuous health monitoring [1][2]. With the remarkable emergence of embedded textile sensors, the proposal of e-textile solutions has grown significantly, empowering the development of new designs to provide a better user-experience. This growing area values comfort and mobility of health monitoring devices. Nowadays, it is possible to seamlessly integrate sensors and electrodes into the fabric's structure of a clothing piece to monitor elderly people, sports or hazardous occupations. The complete integration of these sensing elements and connections into the garment structure represents a great advantage to the physical and psychological comfort of the user.

Several works proposed breathing rate and movement monitoring using extension sensors based on knitted fabrics produced with textile compatible conductive yarns [3]-[7], as well as, with specially made rubber coatings doped with carbon fibers and/or conductive polymers [8]-[11]. Electrodes for physiological signal sensing, such as Electrocardiography (ECG), Electromyography (EMG) or skin impedance have been developed and demonstrated [12]-[18]. Moisture sensing using textiles has been proposed in [19].

Textile-based sensors integrated into a shirt for PPE have been developed in the Proetex project [20] to measure heart and breathing rates in firefighting situations. Breathing rate was measured using two techniques: piezoresistive textile extension sensors and thoracic impedance measurement.

In this paper, the behavior of ECG electrodes and moisture sensors based on conductive yarn knitted in a shirt of an interactive PPE is evaluated and analyzed. The analysis focuses on two different components: the heart rate measurement with two leads and the moisture sensing with two conductive pads. The combination of temperature and moisture sensing is implemented for the detection of situations in which danger of skin burn exists. The shirt is one of the components of an integrated system in which temperature, movement, position and alarm signals are transmitted from/ to the firefighter interactive PPE.

After the introduction and review of the state-of-the art given in Section I, Section II focuses on the development of the shirt, describing materials used, the shirt's design and production. Section III gives an overview of the signal conditioning hardware developed for the measurement of the heart rate and moisture sensor. In Section IV, results of the measurements are presented and discussed, and some conclusions are drawn in Section V.

II. SHIRT DESIGN

A. Materials and Design

When considering wearable devices, strict requirements on volume, weight and energy use exist for optimal effectiveness. Therefore, the decision for a two-electrode configuration for the heart rate measurement was straightforward, considering that the goal was not the acquisition of the full ECG complex. In terms of shirt design, this also meant a reduction of the number of connection paths, and the possibility of placing the front-end hardware closer to the heart, making the system more robust and less vulnerable to common-mode interference.

The electrodes are knitted into the base-fabric using a silver coated textured polyamide elastic yarn from Elitex, produced by TITV, with low electrical resistance (in the order of tens of Ω/m).

The moisture sensor consists of two conductive parallel bars, knitted in the shirt using the Elitex yarn. The change of moisture absorbed/dispersed by the non-conductive textile substrate between the two bars produces a resistance change that is detected by appropriate hardware.

B. Production

The shirt is knitted in a seamless MERZ MBS knitting machine. This machine allows knitting patterned structures through local variations of the structure, which were used to knit the electrodes for heart rate measurement, the conductive bars, for moisture detection, as well as, conductive leads to connect these elements to the conditioning hardware. For the electrode area, a particularly voluminous structure was developed that makes the electrode area stand out of the rest of the fabric and thus improves skin to electrode contact [21].

To assure the correct positioning of sensors and signal acquisition hardware, the optimal electrode and sensor arrangements were studied.

Regarding the electrodes for the heart rate acquisition, measurements with the electrodes at different positions in the chest area were carried out and compared. The main goal of the tests was to obtain the clearest acquisition of the QRS complex present on the ECG wave with the purpose of amplifying and filtering the peak and more accurately calculate the user's heart rate. It was concluded that the best position was below the pectoral muscles, where the electrodes are closer to the ribs, avoiding electromyography interference (Figure 1a).

Regarding the moisture sensor, as shown in Figure 1b, the best solution for the placement of the conductive bars is on the lower back, near the lumbar curvature. This is the preferred location for human's eccrine sweat accumulation, making the design less vulnerable to false positives or negatives.

Conductive leads and conductive paths were also knitted in the shirt structure to avoid electrical wires. Snap fasteners, applied to the leads allow the easy attachment of the hardware, taking advantage of the electrical conductivity of the snaps and its mechanical stability.

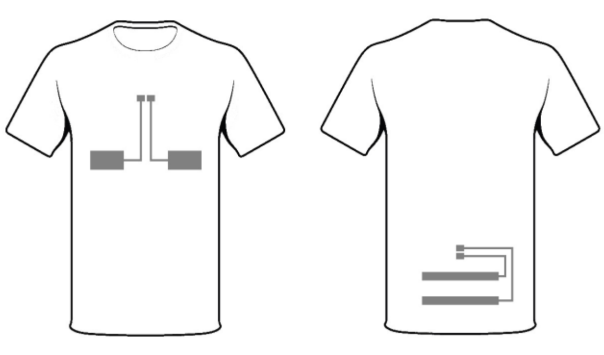

Figure 1. Smart Shirt Sensor Positioning: (a) front view (b) rear view.

III. SIGNAL CONDITIONING HARDWARE

A. Heart Rate Signal

To implement the heart rate measurement conditioning hardware, the AD8232 by Analog Devices was used. The AD8232, is a single-lead, heart rate monitor front end designed to measure small biopotencial signals in the presence of noisy conditions. This front-end can be used in several configurations, being the two-electrode measurement one of them. An evaluation board was used for the tests and set for two-electrode measurement combined with low and high-pass filtering, as shown in Figure 2.

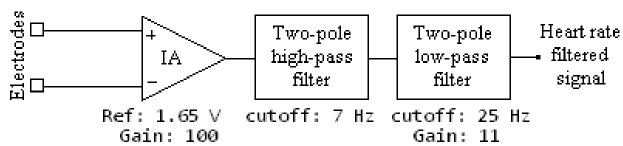

Figure 2. AD8232-EVALZ conditioning signal diagram.

In the tested configuration, the Instrumentation Amplifier has a fixed gain of 100 whilst the two-pole low pass filter adds another 11 of gain, resulting in an overall gain of 1100 V/V. Regarding the cutoff frequencies, Figure 3, the implemented block of the two-pole high-pass filter eliminates motion artifacts and drift caused by varying electrode-skin polarization and contact noise whilst the additional two-pole low-pass, using a Sallen-Key configuration, attenuates the line noise and other interference. Also, in this two-electrode configuration, the Right Led Drive (RLD) is used to drive the bias current resistors on the two electrode inputs, eliminating the third electrode needed.

In addition, the AD8232 also offers two outputs called Leads Off Detection (LOD) + and -, one for each electrode, detecting when an electrode is disconnected by sourcing a small 100 kHz current into them. When an electrode has lost its connection the accordingly LOD pin goes to a high state.

To compute the heart rate value, a CC2530 microcontroller, manufactured by Texas Instruments is used. This 2.4-Ghz IEEE 802.15.4 and ZigBee applications System-on-Chip solution is used in the project to implement the nodes of the Body Area Network in the firefighter PPE. The analysis and discussion of the wireless communication network structure will be presented elsewhere.

Using its ultralow-power internal analog comparator, with a supply current of 230 nA, it is possible to compare the filtered ECG wave with an external voltage level, as depicted in Figure 4, where the Input/Output (I/O) pins P0_5 and P0_4 correspond, accordingly, to the positive input and negative input of the comparator.

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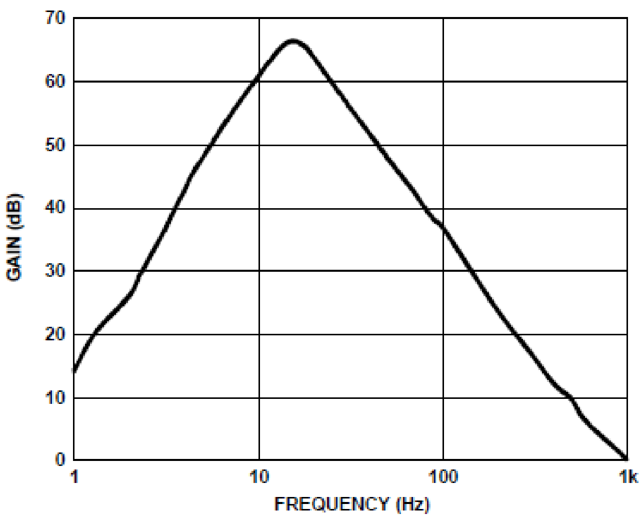

Figure 3. Overall frequency response of the heart rate signal measurement circuit.

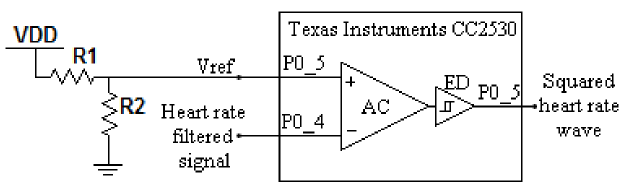

Figure 4. TI CC2530 – Analog Comparator block diagram and external components.

The voltage reference is set by a fixed voltage given by an external voltage divider and the output is internally connected to the I/O controller interrupt detector and can be treated by the Microcontroller Unit (MCU) as a regular I/O pin interrupt, being possible to configure the edge detection of the interrupt as rising or falling edge. This whole analog comparator solution compares the voltage reference with the ECG signal and when the ECG signal drops below the voltage divider value, set to 300 mV, the comparator output gives a logical one, triggering the masked Interrupt Service Routine (ISR) for port 0.

To calculate the user's heart rate value, a timer of the CC2530 is used to measure the time between two heart rate pulses. After fifteen triggers the average of these values is used to compute the heart rate.

B. Moisture Sensor

The physical principle of the textile moisture sensor is based on the variation of the electrical resistance of a non-conductive textile material when moisture, promoted by sweating, is absorbed or dispersed. The moisture sensor consists of two pads of conductive knitted fabric, which are used as terminals for measurement of the electrical resistance, separated by a non-conductive knit base-fabric.

For the signal conditioning of the moisture sensor, the approach represented in Figure 5 was adopted.

With this signal conditioning technique, it is possible to adjust the sensitivity of the moisture measurement by adjusting the input voltage E. Furthermore, a linear relationship between output voltage and sensor resistance is obtained [19].

Measurements are taken using the microcontroller's internal Analog-to-Digital Converter (ADC).

IV. Results and Discussion

A. Shirt prototype

Using the knitting machine's structure design software, the leads and the moisture sensing area pads were designed and integrated in the shirt as described above. Figures 6 and Figure 7 show the front and rear view of the finished prototype.

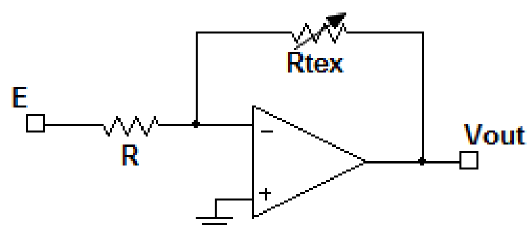

Figure 5. Inverting operational amplifier approach.

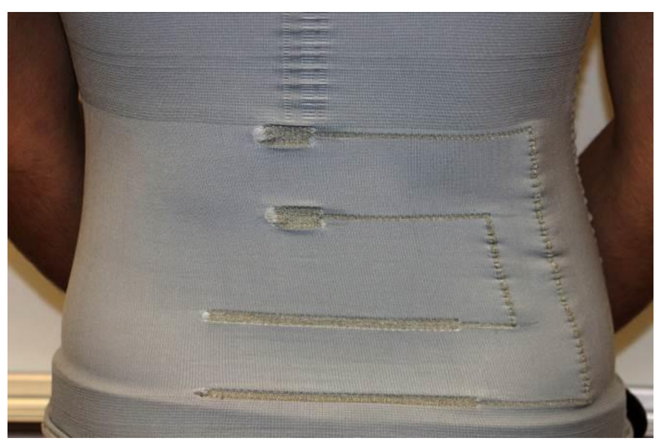

Figure 6. Shirt rear view with moisture sensor.

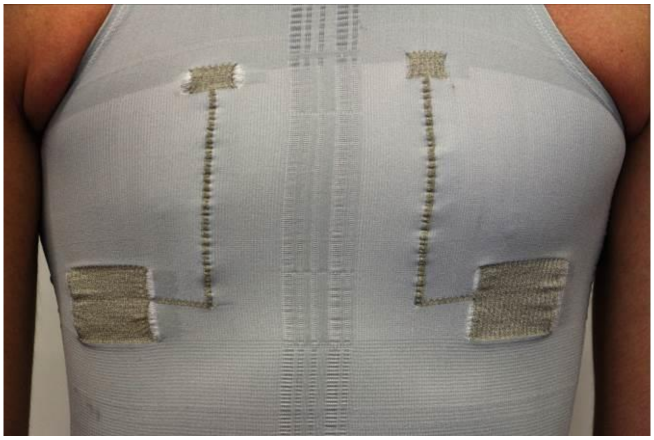

Figure 7. Shirt front view with ECG electrodes.

B. Heart Rate signals

Heart rate signals were acquired in different user's posture and movement conditions using a National Instruments (NI) NI-USB-6211 data acquisition device and NI Labview Signal Express software.

The signals depicted in Figure 8 were obtained with the user standing still. The waveforms represented are the output of the high-pass filtered AD8232's Instrumentation Amplifier (blue) and the amplified and low-pass filtered output signal. A clear and constant excursion of the signal from the 1.6 V dc level of the signal to nearly 0 V is observed. Analog comparison with the 300 mV threshold used at the microcontroller's analog comparator delivers the heart rate pulses very robustly. In the conditions and location of the experiment – the research lab in which the project is being developed – line and other noise are very small when compared to the relevant signal's amplitude. In future experiments, noise interference will be studied in more detail.

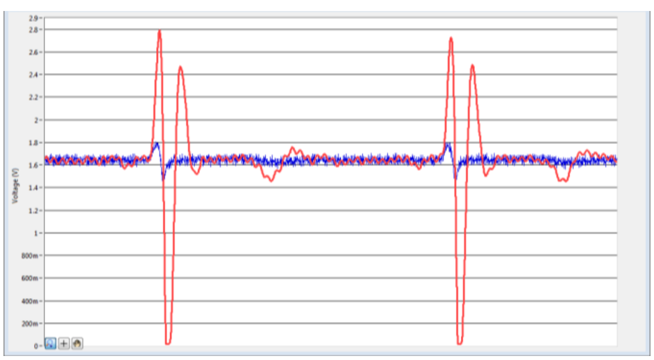

Figure 8. IA output (blue) and ECG filtered and amplified wave (red).

As soon as movement is added, the signal presents increasing motion artifacts, as well as missed heart beat pulses due to momentary loss of contact of the electrodes with the skin. The signal presented in Figure 9 was acquired with the user swinging and flexing the arms vigorously, whilst the signal depicted in Figure 10 results from an intense whole-body movement, with the user jumping and moving the arms. In both situations, some heart rate pulses are missing and in the second situation the motion artifacts produce the detection of false positives. It can also be observed that no problem due to dc level drift is present.

To compare these results with established, commercial products, a Polar model T-34 heart rate chest strap and receiver was also used in the experiments. Figure 11 shows the signal obtained with the user moving the arms vigorously.

As can be observed, the Polar heart rate monitor also misses heart beats. With intense full-body movement, false positives have also been observed. From the experiments it was clear that the two systems behave similarly in terms of heart rate measurement, failing information under extreme activity measurement conditions.

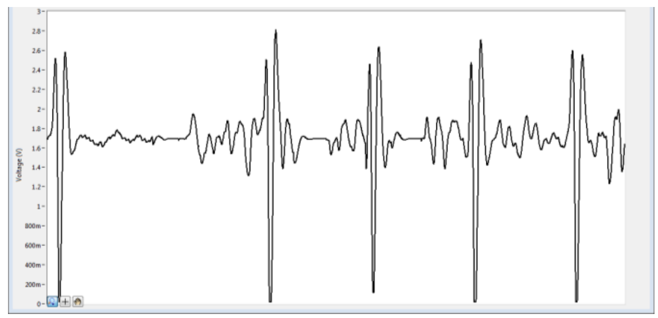

Figure 9. Arms moving vigorously while acquiring heart rate signal.

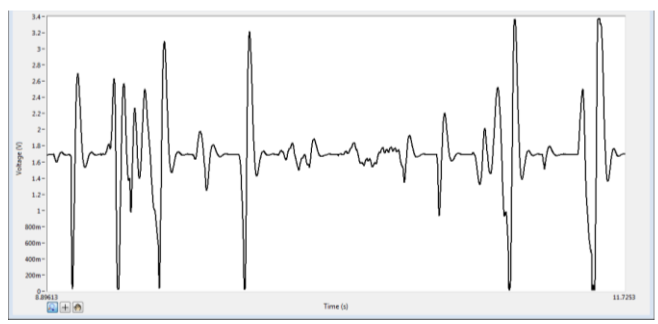

Figure 10. Intense movement of the body while acquiring heart rate signal.

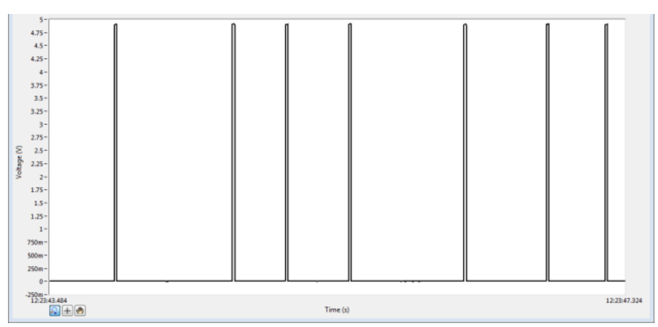

Figure 11. Polar T-34 heart rate response while vigorously moving the arms.

However, it has to be stressed that in normal running movement, measurement errors are insignificant with both systems.

C. *Moisture sensor*

The moisture sensor integrated in the shirt, shown in Figure 6, was previously studied using test samples such as the one represented in Figure 12. These preliminary tests were carried out to assess the behavior of knitted moisture sensors with moisture content and were performed in a chamber with controlled temperature. The samples were kept at a constant extension, to simulate wearing conditions, and a graduated syringe connected to a spray dispenser allowed to apply controlled quantities of artificial acid and basic sweat solutions. Resistance was logged with a precision multimeter throughout the experiment.

The sample represented in Figure 12 was produced with 100% cotton yarn, 30 Ne, in the non-conductive part of the knitted fabric, and Elitex multifilament polyamide silver coated yarn, 235 dtex, in the conductive part.

The results obtained in resistance change with the samples containing different amounts of acid and basic sweat solutions are represented in Figure 13 and Figure 14.

The graphs show that resistance is an order of magnitude higher with the acid sweat solution. On the other hand, with the basic sweat solution, resistance values tend to saturation with smaller quantities of sweat. In both cases the quick change of resistance makes it clear to distinguish between a dry and a wetted state of the sensor.

Figure 12. Sample for preliminary moisture sensor test.

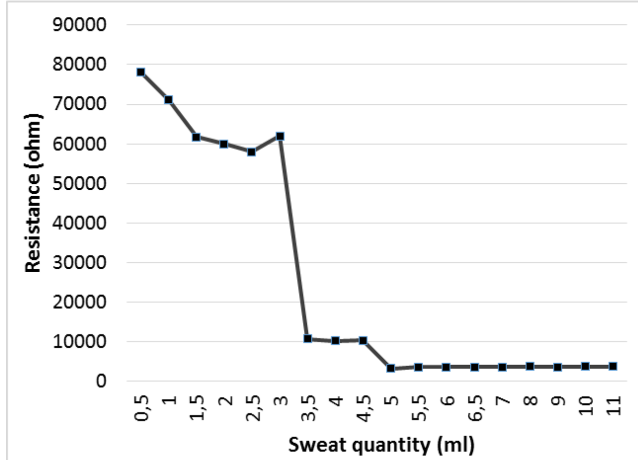

Figure 13. Resistance change with sweat quantity, acid sweat solution.

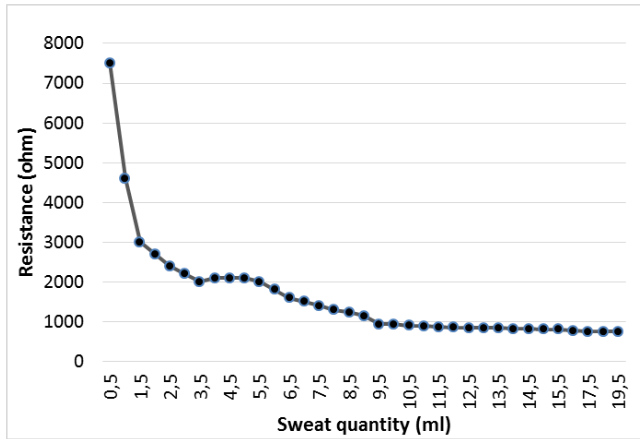

Figure 14. Resistance change with sweat quantity, basic sweat solution.

Based on these preliminary results, it is apparent that further testing is required. The influence of the sensor's geometrical parameters and non-conductive yarn material on the sensor's saturation behavior will be studied. A field trial will also be performed, to determine how the saturation point of the sensor matches the detection of the moisture content that may produce danger to the user if exposed to high temperatures.

V. CONCLUSIONS AND FUTURE WORK

This paper presents an overview of a smart shirt, where the dependence on non-textile materials to achieve interactivity is minimized. The performance of the textile sensors for heart rate measurement has been found to be comparable to the one of commercial products. Further experimentation is needed to define the final configuration of the moisture sensor.

The final design of the smart shirt will take into account other factors such as aesthetics, comfort, connection and support of hardware, electrical isolation in at some key points. Two battery-powered hardware modules, one for each sensor, inside a custom 3D-printed case will be attached to snap fasteners applied to the conductive leads. The snaps will assure both mechanical retention, as well as electrical connection. The modules will be integrated in a Body Area Network (BAN), to which other nodes will be connected to monitor other variables or provide information to the user of the firefighter PPE.

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REFERENCES

[1] S. Tang., “Recent developments in flexible wearable electronics for monitoring applications, Transactions of the Institute of Measurement and Control,” vol. 29 no. 3-4, pp. 288-300, 2007.

[2] S. Patel, H. Park, P. Bonato, L. Chan, and M. Rodgers, “A review of wearable sensors and systems with application in rehabilitation,” Journal of Neuro Engineering and Rehabilitation, 9:21, 2012.

[3] M. Catrysse, R. Puers, C. Hertleer, L. van Langenhove, H. van Egmond, and D .Matthys: “Towards the integration of textile sensors in a wireless monitoring suit,” Sensors and Actuators A 114, pp. 302–311, 2004.

[4] C. Cochrane, V. Koncar, M. Lewandowski, C. Dufour, “Design and Development of a Flexible Strain Sensor for Textile Structures Based on a Conductive Polymer Composite,” Sensors, No. 7, pp. 473-492, 2007.

[5] H. Zhang, “Electromechanical Properties of Intrinsically Conductive Fiber Assembles, Its Textile Structure and Applications as Strain and Pressure Sensors,” Dong Hua University, PhD thesis, 2006.

[6] M. J. Abreu, H. Carvalho, A. Catarino, and A. Rocha, “Integration And Embedding of Vital Signs Sensors and Other Devices into Textiles,” in Medical and Healthcare Textiles, J.F. Kennedy, S.C. Anand, M. Miraftab and S. Rajendran, Eds. Woodhead Publishing Textile Series Nr.75, ISBN 1-84569-224-1, pp. 381-389, 2010.

[7] M. Silva, A. Catarino, H. Carvalho, A. Rocha, J. Monteiro, and G. Montagna, “Textile Sensors for ECG and Respiratory Frequency on Swimsuits,” Proceedings of the Conference on Intelligent Textiles and Mass Customisation, Casablanca, Morocco, 12-14th November 2009, p.77, ISBN 978-9954-8878-1-4.

[8] H. Zhang, X. Tao, S. Wang, and T. Yu, “Electro-Mechanical Properties of Knitted Fabric Made From Conductive Multi-Filament Yarn Under Unidirectional Extension,” Textile Research Journal 75, pp. 598-606, 2005.

[9] Y. Li, X. Y. Cheng, M. Y. Leung, J. Tsang, X. M. Tao, and M. C. W. Yuen, “A flexible strain sensor from polypyrrole-coated fabrics,” Synthetic Metals, Vol. 155, Issue 1, pp. 89-94, 2005.

[10] A. Tjahyono, K. Aw, J. Travas-Sejdic, “A novel polypyrrole and natural rubber based flexible large strain sensor,” Sensors and Actuators B: Chemical, Vol 166–167, pp. 426-437, 2012.

[11] R. Zhang, H. Deng, R. Valenca, J. Jin, Q. Fu, E. Bilotti, and T. Peijs, “Carbon nanotube polymer coatings for textile yarns with good strain sensing capability,” Sensors and Actuators A: Physical, Vol. 179, pp. 83-91, 2012.

[12] P. J. Xu, H. Zhang, X. M. Tao, “Textile-structured electrodes for electrocardiogram,” Textile Progress, 40:4, pp. 183-213, 2008.

[13] A. Catarino, H. Carvalho, M. J. Dias, T. Pereira, O. Postolache, and P. S. Girão, “Continuous Health Monitoring Using E-Textile Integrated Biosensors,” 2012 International Conference and Exposition on Electrical and Power Engineering (EPE, IEEE), Iasi, Romania, pp. 25-27, 2012.

[14] T. Pereira, H. Carvalho, A. Catarino, M. J. Dias, O. Postolache, and P. S. Girão, “Wearable biopotential measurement using the TI ADS1198 analog front-end and textile electrodes,” 2013 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Ottawa, Canada, pp. 4-5, 2013.

[15] J. Mühlsteff, O. Such, “Dry electrodes for monitoring of vital signs in functional textiles,” Proceedings of the 26th Annual International Conference of the IEEE EMBS, San Francisco, USA, pp. 2212-2215, 2004.

[16] R. Paradiso, G. Loriga, and N. Taccini, “AWearable Health Care System Based on Knitted Integrated Sensors,” IEEE Transactions on Information Technology in Biomedicine, Vol. 9, No. 3, pp. 337-344, 2005.

[17] M. Silva, A. Catarino, H. Carvalho, A. Rocha, J. Monteiro, and G. Montagna, “Study Of Vital Sign Monitoring With Textile Sensors In Swimming Pool Environment,” Proceedings of the IECON 2009, The 35th Annual Conference of The IEEE Industrial Electronics Society, Porto, Portugal, pp. 4426-4431, 2009.

[18] O. Postolache, P.S. Girão, M. Ribeiro, H. Carvalho, A. Catarino, and G. Postolache, “Treat Me Well: Affective and Physiological Feedback for Wheelchair Users,” Proceedings of the 2012 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Budapest, Hungary, pp. 1-7, 2012.

[19] T. Pereira, P. Silva, H. Carvalho, and M. Carvalho, “Textile moisture sensor matrix for monitoring of disabled and bed-rest patients,” Proceedings of the IEEE Eurocon 2011 conference, Lisbon, Portugal, pp. 1-4, 2011.

[20] Project Proetex FP6-2004-IST-4-026987, Advanced e-textiles for firefighters and civilian victims, retrieved 23-02-2015 from http://www.proetex.org/p1_inner_garment.htm

[21] A. P. Catarino, A. M. Rocha, H. Carvalho, and M. J. Dias, “Electrodes based on textile substrates,” Portuguese Patent P105517, Europen Patent EP 2671506.