# Wearable Sensors for Foetal Movement Monitoring in Low Risk Pregnancies

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**Abstract.** In low risk pregnancies, the continuous monitoring of the foetal health is based on traditional protocols for counting the foetal movements felt by the mother. Although the maternal perception is a relevant characteristic for the evaluation of the foetal health, this kind of monitoring is hard to accomplish and being subjective can induce into errors due to mother's anxiety and lack of concentration. Furthermore, the majority of foetal fatalities occur during the last weeks of low risk pregnancies. Therefore, it is important to obtain a universal electronic obstetric tracing, allowing for the identification of sudden changes in the foetus health, by continuously monitoring the foetus movements. The Smart-Clothing project aim has been the development of easy-to-wear belts with a telemedicine system for this purpose. One of the tried solutions is the Flex sensor belt system, which guarantees real-time and continuous foetal monitoring while creating effective interfaces for querying sensor data and store all the medical record (which can later be accessed by health professionals). Another developed belt has piezoelectric sensors incorporated onto it. The piezoelectric sensor belt has shown a high capacity to detect foetal movements, isolating them from external interferences.

**Keywords:** smart textiles, hierarchical wireless communications, WSAN, telemedicine, foetal healthcare.

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## 1 Introduction

Technological innovation applied to healthcare is making the use of new materials and tiny communication systems embedded into textiles. The development of smart textile belts prototypes, such as those proposed by the Smart-Clothing project, combines investigation in functional textiles materials, data acquisition and processing, and wireless communication networks in the context of human body monitoring and statistical methods for the data analysis and treatment. The data extracted from the Wireless Body Area Network (WBAN) attached to pregnant women may be made available to the health professionals through a hierarchical communication system. Research on WBANs is already being conducted considering WBAN Medium Access Control (MAC) and routing schemes, as well as different remote monitoring architectures, namely "On-body" and "In-body" ones, as mentioned by the authors from [1].

The interest in the coexistence among several wireless communication systems is increasing because of the possibility of using unlicensed frequency bands. In Europe, there are two unlicensed frequency bands specifically available for wireless networks: i) The Industrial Scientific and Medical (ISM) band, which includes the 433 MHz, 900 MHz, 2.4 GHz and 5.8 GHz frequency bands; ii) the Unlicensed National Information Infrastructure (UNII) band, which includes the 5.2 GHz frequency band. It is nevertheless important to note that users of unlicensed bands can equally affect the quality and the use of the frequency spectrum. Hence, one of the principal disadvantages of unlicensed frequency bands is frequency sharing and resulting interference.

The remaining of the Chapter is organized as follows. Section 2 presents the overview of the Smart-Clothing project. Section 3 describes its main area in detail and presents the associated scenario. Section 4 describes the experimental layout for the project, presenting two versions of the Flex sensor belt, as well as the piezoelectric sensor belt and a belt with conductive fabrics. Section 5 presents the experimental results for the flex sensor belt and piezoelectric sensor belt. Finally, Section 6 presents the conclusions and suggestions for further work.

## 2 Smart-Clothing

The Smart-Clothing project is an iCentro project approved by CCDR-C with FEDER funding. The methodological specifications applied in this project enables to quantify the precision of the experimental measurement with a new device for signal acquisition, develop algorithms to extract the parameters that show clinical relevance and to establish strategies for efficient data mining in the context of medical diagnostic of foetal health in pregnant women. From the conventional sensor and data acquisition and storage circuit's point of view, the objective is to develop a set of electronic microcircuits associated with textile materials that enable to measure relevant biomedical and biomechanical parameters through an easy-to-use telemedicine gear, e.g., a belt. One example of how the theme of pregnancy monitoring is gaining importance in the research community is mentioned by the authors from [2], which describes an innovative, remote monitoring decision support system, employed in the early diagnosis of pregnancy complications, through the effective and non-invasive monitoring of maternal and foetal electrocardiograms.

A hierarchical communication system, Fig. 1, is needed to deliver the data from the WBAN that is attached to pregnant woman. Note that, although the main focus of the Smart-Clothing is to produce the sensors integrated into the clothes and to integrate them into the WBAN, the consideration of aspects of data aggregation, routing and MAC protocols were also important, as they facilitate the integration of wireless sensor networks (WSNs) into the hierarchical network.

New algorithms and protocols were developed to optimize the trade-off between energy consumption/processing and communication capabilities, namely in the MAC layer [3]. Hierarchical communications can be a solution to obtain a network of networks, e.g., by using internet protocol (IP). A bottom-up architecture formed by i) WSNs, ii) Wi-Fi, and iii) Ethernet (or WiMAX) was explored to facilitate healthcare monitoring anyway, anywhere and anytime.

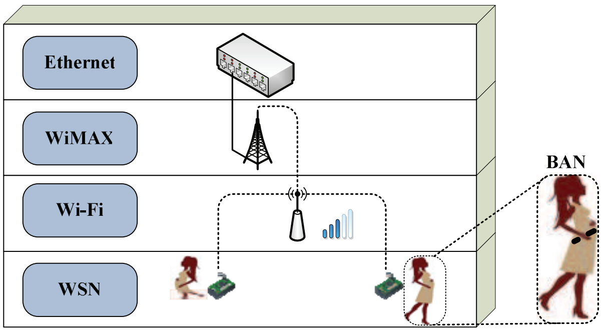


**Fig. 1.** Hierarchical network considering the WBAN and other communication networks

## 3 Field of Study

### *A. Main Area*

The majority of foetus fatalities in the end of pregnancy occur in the low risk pregnancies group. The main area addressed by the Smart-Clothing project is obstetric tracing, enabling to identify sudden changes in the foetus health, by monitoring its movements and the foetal heart rate (FHR). In low risk pregnancies, in the periods between medical sessions (that occur weekly during the last five weeks of pregnancy), the objectively monitoring of the foetal health based in traditional protocols for counting the foetal movements felt by the mother is very important [2, 4]. Although the maternal perception is a relevant characteristic for the evaluation of the foetal health, the monitoring is hard to accomplish and may induce into error, e.g., due to the mother's anxiety or lack of concentration.

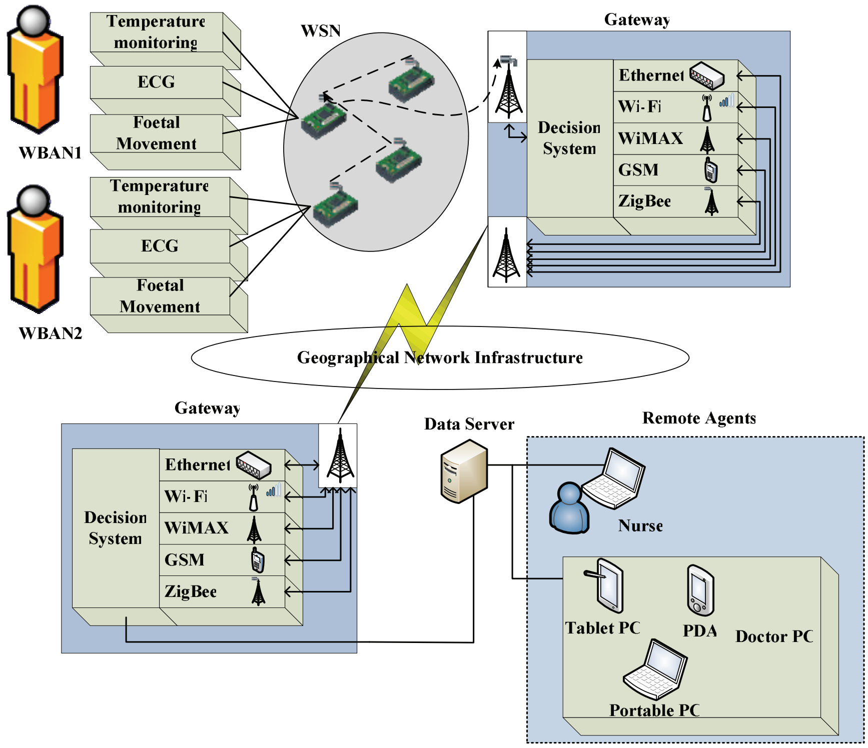


**Fig. 2.** Smart-Clothing main healthcare scenario

In the Hospital, the foetal monitoring is done by using a Cardiotocograph, which records the FHR and the uterine contractions. The FHR is determined by means of an ultra-sound Doppler sensor (operating at a frequency $f = 1$ to 3 MHz), while the uterine contractions are detected with a pressure sensor (dynamometer). The foetal monitoring can be done by the pregnant woman at home, counting the foetus movements (the pregnant woman feels 80% of them), which should be registered by herself in a form for posterior analysis of the physician. There is in the market low cost portable equipments based on the Doppler technology, which allow for foetal heart sounds hearing and the foetal movements detection, to be performed by a pregnant woman [6]. They can be used beyond the 12 weeks of pregnancy and allows for recording the cardiac sounds. The possible effects over the foetus due to the use of equipments based on the ultra-sound technique raise some concerns but their effects, although not well known, are probably unimportant when applied intermittently.

Frequently pregnant woman does not show the same accuracy in detecting the foetus movements as it is done by the health services. Smart-Clothing is motivated by the need to conceive an automatic harmless remote monitoring device to the purpose of foetal movement monitoring.

### *B. Project Scenario*

The main Smart-Clothing scenario is presented in Fig. 2. It consists of four main actors: the WBANs, WSN, gateway and remote agents. Each WBAN is attached to the pregnant woman and collects the data from the electrocardiographic (ECG) and the foetal movement sensors. The WSN is itself responsible by the aggregation of the data collected by the WBAN, and its accurate delivery to the gateway. The gateway has got a decision system that chooses the better way to deliver the data to the gateway located in the Hospital. The Hospital gathering system has the same decision system and is used for the interconnection of a WSN with remote agents through a geographical network, to collect, aggregate and eventually preprocess data received by the WSN.

Finally, the remote agents can be either a collector of information (through a server where the information is stored and could be accessed later on) or a nurse that monitors the foetus in the pregnant women as well as a doctor that closely monitors the foetus by using his/her personal digital assistant (PDA), or his/her laptop or even his/her tablet PC or Ultra-mobile PC (UMPC).

## 4 Experimental Apparatus

### *A. Belt with Flex Sensor*

After the application scenarios had been defined [6], the next step was to identify which types of sensors would be incorporated into the Smart-Clothing belt. To achieve this goal, several belts were made, tested and compared to see which sensors were capable of better detecting the foetal movements [6]. One of the Smart-Clothing belt prototypes is based on the Flex sensor, while another one incorporates a piezoelectric sensor.

The first version of the Flex sensor belt incorporates eight Flex sensors, as shown in Fig. 3. A simple voltage divider, associated to a temperature compensated voltage reference, generates the input signal. The manufacturer proposes a correspondence of standard values of the flexion angle to a certain value of resistance.

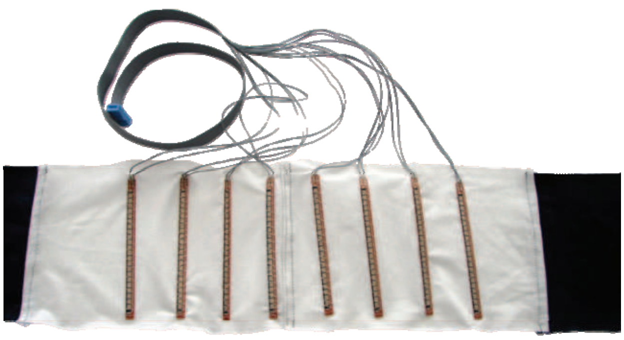

**Fig. 3.** Flex sensor belt

The acquisition system diagram is presented in Fig. 4. For the sake of simplicity just one Flex sensor is presented. Besides the Flex sensor a button was incorporated in the system to be pressed by the pregnant woman (when she feels or detects foetal movement). The recording of these events is very useful for comparison purposes, as they enable a comparison of personal detected movements with the movements automatically detected by the belt.

A microcontroller was used for data acquisition and communication. For practical reasons, in a preliminary experimental context, we supplied the $V_{cc}$ voltage to the voltage divider by using external pin from the MSP430 microcontroller (MSP430-F449STK2 module) and read the voltages from the voltage dividers using the Analog-to-Digital Converter (ADC) inputs from the microcontroller.

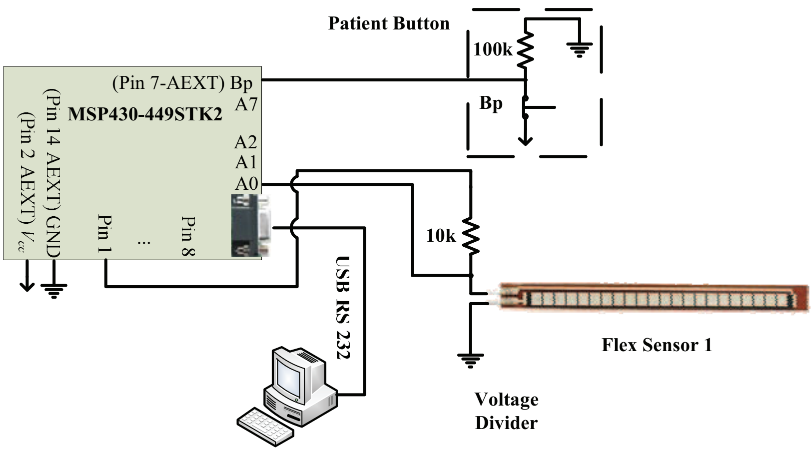


**Fig. 4.** Flex sensor belt acquisition system diagram

To compute the resistance value from the Flex sensor one uses the voltage divider formula as follows

$$R_{Flex1}=R_1\times V_{out}/(V_{in} - V_{out}) \quad (1)$$

where $R_{Flex1}$ is the resistance value, $R_1$ is equal to 10 kΩ, $V_{in}$ is the $V_{cc}$ value supplied to the voltage divider, and $V_{out}$ is the voltage value from the voltage divider. The $V_{cc}$ voltage supplied to the voltage divider is measured periodically by a routine that is located in the microcontroller, in order to compensate the battery losses during the system operation. This enables a better accuracy for the values extracted from the Flex sensors.

Two formulas were used for the conversion of the resistance value to the angle value, as follows

$$\theta_1[^\circ]=(R_{Flex1}-10\times 10^3)/44.44 \quad (2)$$

$$\theta_2[°]=(R_{Flex1}-6001)/88.88 \quad (3)$$

where $\theta_1$ and, $\theta_2$ are the angles for the corresponding Flex sensor resistance value. This enables to extrapolate the angle values.

Equation (2) is used when the resistance value is between 10 kΩ and 14 kΩ while equation (3) is used when the resistance value is between 14 kΩ and 22 kΩ. We have made a calibration curve to identify the broad range resistance characteristic for the sensor. The Flex sensor manufacturer states that a resistance value of 10 kΩ matches an angle of 0º while values of 14 kΩ and 22 kΩ match angles of 90º and 180º, respectively.

These formulas were based on the theoretical and calibration curves for the Flex sensor, as shown in Fig. 5. The theoretical line is based on the resistance values and corresponding deflection angle supplied by the flex sensor manufacturer. The calibration curve is results from an experiment where the flex sensor was bent from 0º to 90º and the resistance value measured with a protractor was registered at each 10º of bending increment.

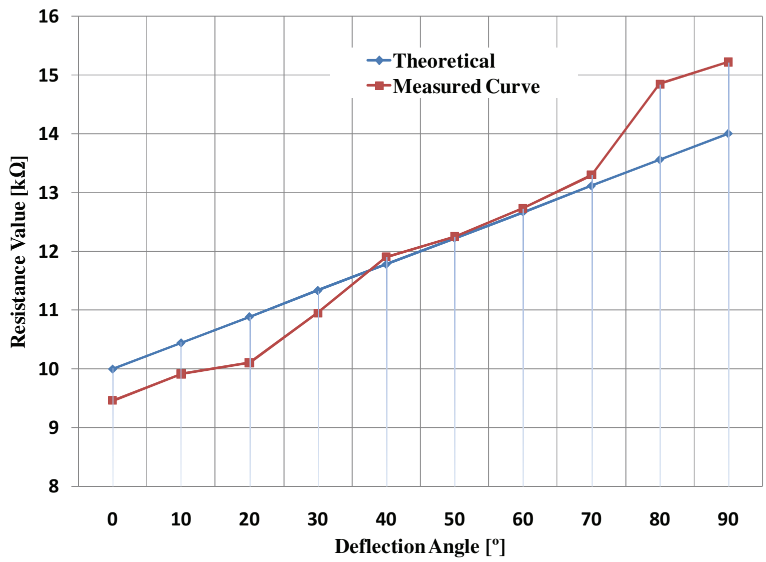


**Fig. 5.** Theoretical and calibration curves for the Flex sensor

The MSP430-F449STK2 module, after acquiring the values for each Flex sensor, sends all the data to the computer (where several values for the correspondence between resistance and angles are presented), and automatically counts the movements above a preset threshold.

The algorithm from Fig. 6, used in the acquisition module, begins with the reset option, (applied to all system). If the reset option is not chosen then the algorithm will measure the voltage from the power supply, in order to compute later the corresponding voltage to a flexion angle. Then if button B1 (located in the acquisition module) is pressed a timer (of 100 ms) is set. After 100 ms, the algorithm starts reading all Flex sensors. First, the Flex sensor 1 voltage divider is powered up. Then, the algorithm waits 10 ms so that the ADC can read properly the voltage value from the voltage divider. Then, it computes the flexion angle depending on the read voltage value and extracts the state of the patient button (if the patient pressed the button it records the time and add one unit to the counter). This procedure is repeated for the other seven Flex sensors. However, in the last one the data from all the Flex sensors and patient counter is aggregated enabling to build the data packet while sending it to the computer. The Flex Sensor View program running presents the values of the different angles for each Flex sensor.

The final version of the standalone Flex sensor belt uses only one data packet to transmit the deformation angles of the eight Flex sensors, according to the packet protocol established between the computer and the acquisition module. This data packet is sent at the end of the routine controlled by a timer in the microcontroller only, in order to maintain a constant data flow between the acquisition module and the computer. Besides, a calibration routine was implemented in the microcontroller. Each calibration packet is sent from the program running in the computer to the acquisition module and has the ability to calibrate all the (eight) Flex sensors (or only one).

Considering the preliminary work performed in the first version of the Flex sensor belt, a belt with only five Flex sensors was integrated with a WSN device. Each of the five Flex sensors is connected to an ADC channel, in order to convert the voltage (given by each Flex sensor voltage divider) to the corresponding deformation angle.

This device consists of an IRIS mote from Crossbow, a small battery and a set of Flex sensors. A hybrid communication system is employed in order to deliver the data through the WSN. The system detects the foetal movement based on the flexion angle of the sensors while the IEEE 802.15.4 network delivers all the data collected by the motes to our Centralised Management of Resources (CMR) identity.

An application that manages the WSN (and saves the information) was developed and is located at the CMR, by using a Structured Query Language (SQL) database. Fig. 7 shows a simplified block diagram for the monitoring system. The WSN management application is also responsible to present the data to the user (nurse/doctor). As an option, it is possible to transmit the data via Wi-Fi. The information can be shared or accessed by other authorized users. The foetal movements are monitored while data is being transmitted wirelessly to a Mote Interface Board (MIB) directly connected to our CMR, as shown in Fig. 7. The CMR is formed by a personal computer, an application which displays and saves the measured data into the database, and a Wi-Fi module to transmit data through the Wireless Local Area Network (WLAN) [7, 8].

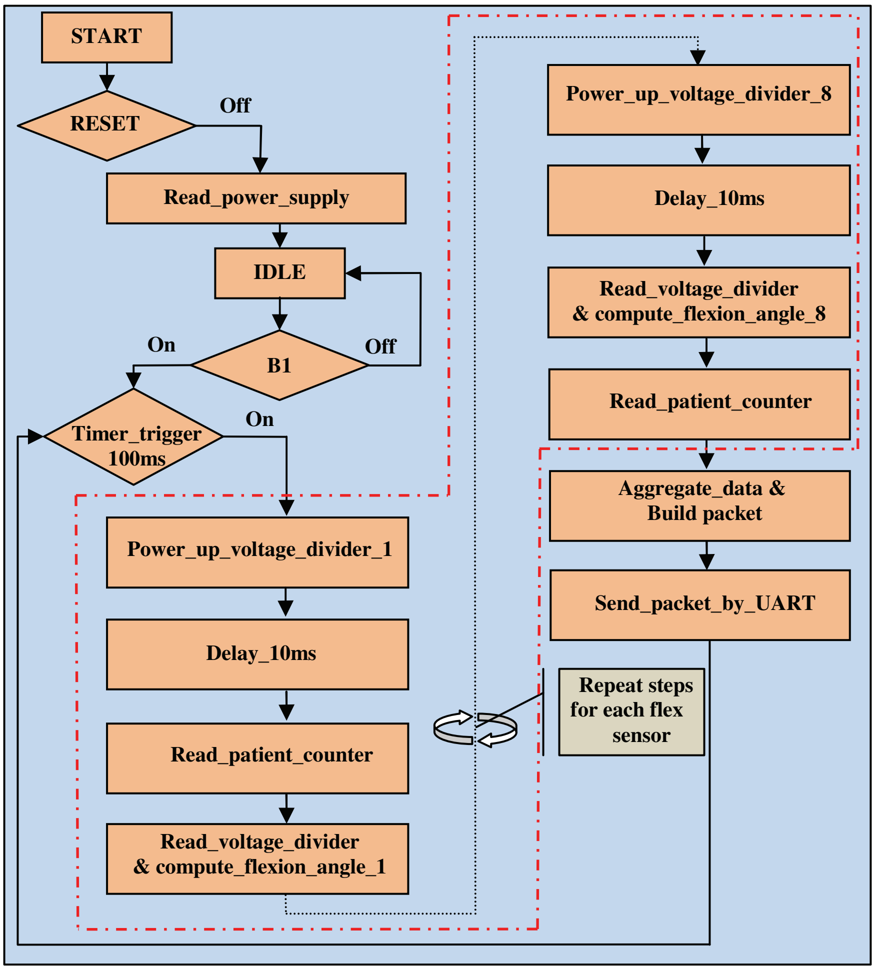


**Fig. 6.** Algorithm diagram for the flex sensor acquisition system

There are two different possibilities to receive and send information. One uses an IEEE 802.15.4 network, while the other one considers two protocol layers (IEEE 802.15.4 and 802.11 ones). If the priority is to collect as much data as possible from the patient, some questions like energy consumption arise. Trade-offs between energy consumption and processing and communication capabilities are relevant [3].

The IEEE 802.15.4 standard was chosen because of its unique characteristics that lead to energy-efficient MAC protocols. It also facilitates the development of our application according to the patient needs, while ensuring an integrated and complete solution for sensor networking based applications, including analog-to-digital conversion. One possible scenario for this small scale wireless flex sensor belt network is a waiting room of the health centre or clinic, where pregnant women wait to visit the obstetrician.

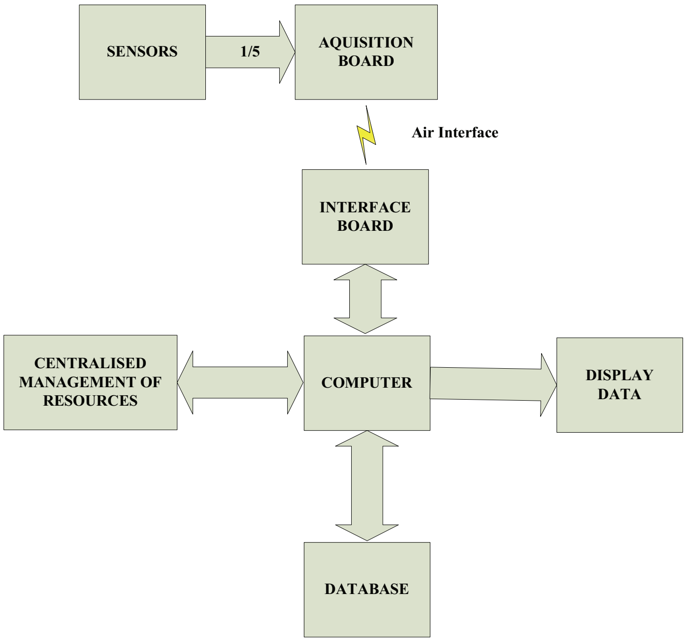


**Fig. 7.** Block Diagram for the acquisition system

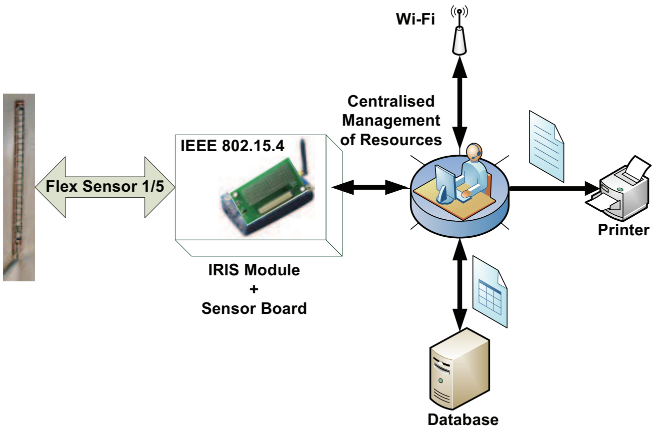


**Fig. 8.** Patient monitoring and IEEE 802.15.4 wireless networking

In the second solution for this belt, another communication layer was considered that allows for sending and receiving information that was collected from the IEEE 802.15.4 network through an IEEE 802.11 wireless network, as shown in Fig. 8. This solution was chosen because it constitutes a practical and interesting solution for network connectivity while offering some mobility, flexibility, and low cost of deployment. An example is transmitting the data from our CMR to any computer that is in its range and has an IEEE 802.11 (Wi-Fi) connection capability. In this scenario the CMR identity may be controlled and monitored by a nurse that looks up for anomalies in the Flex sensor belt data.

*B. Belt with Piezoelectric Sensors*

We developed a belt incorporating piezoelectric sensors. This type of sensor transduces the force to voltage (and vice-versa) and present high sensitivity. They proved to be an appropriate choice to detect mechanical movements such as those originated from foetus in a pregnant woman. Furthermore, the sensors could be very small, they respond to a broad frequency range, do not react to static forces and are cheap.

In this belt, we used plastic pre-encapsulated piezoelectric sensors with a BNC connector (to drive the electrical voltage signal to the signal processing circuit). This type of sensor, Fig. 9, is used by PowerLabs data acquisition system from ADInstruments [9], at Health Science Faculty from Universidade da Beira Interior.

**Fig. 9.** Piezoelectric sensor MLT1010 (ADI Instruments)

Other healthcare monitoring devices are based in piezoelectric film sensors, as the one shown in Fig. 10, commonly used for the detection of biological signals. This sensor is placed against the abdomen of the pregnant woman in order to detect slight surface deformations caused by the movements of the foetus. Compared with other sensors this one presents a high sensibility, reduced dimensions and does not need power supply to operate.

Fig. 11 shows the signals captured by the sensor above, during an experiment where the pregnant woman also holds a pressure switch that should be pressed when perceiving a foetal movement. In this experiment, only one sensor was used several times, placed in several positions in order to detect the foetal movements. Besides the detection of the foetal movement, the mother's breath movement is also as well as the movements due to the displacement of the sensor (motion artefacts). These movements represent an interference signal that should be eliminated [10], and are represented upon the curve in Fig. 11.

**Fig. 10.** A piezoelectric film sensor used in a preliminary Smart-Clothing belt

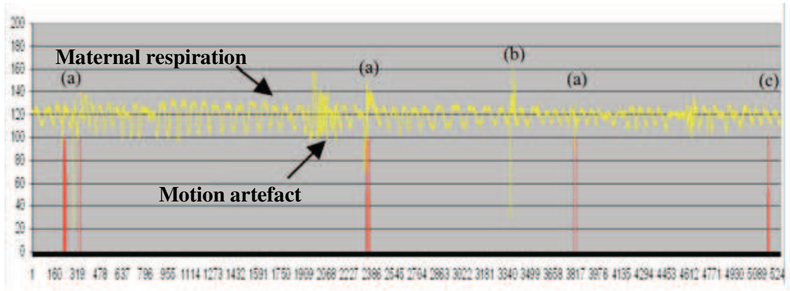


**Fig. 11.** Foetal movement curves (upper=belt, lower=mother): (a) detected by mother and belt, (b) detected by belt only, and (c) detected only by the mother

## *C. Other Techniques*

Another belt is based on pressure sensors. It was built up with conductive and semi-conductive fabrics. The pressure sensor belt shown in Fig. 12 is made with two different types of conductive fabrics: one is conductive in the entire surface while the other is conductive only in some zones.

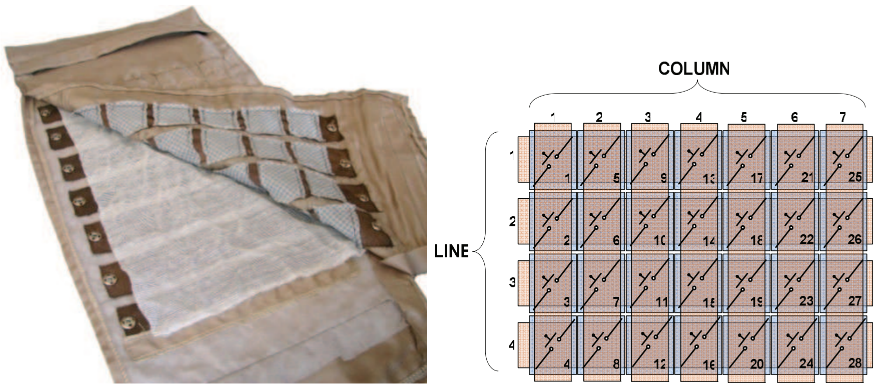


**Fig. 12.** Smart-Clothing On-Off belt with fabric pressure sensor

Fabrics are deployed in layers so that the fabric (with square shaped conductive areas) stays between the other layers. This will act as a switch when the outer fabric layers are pressed, letting the current traverse from one to the other, according to the value of its resistance. By observing Fig. 12, while the orange stripes are conductive fabric, the blue squares are the semi-conductive fabric which forms the switch.

The system diagram is presented in Fig. 13, where the lines and columns from the belt are connected to MSP430 based acquisition module.

As presented in Figs. 12 and 13, the Smart-Clothing On-Off sensor belt is based on a matrix of 28 fabric squares. Each of these fabric square acts like a switch that closes the circuit if it is pressed and leave the circuit open if it is not pressed.

Besides the On-Off belt, a button (or a patient counter) was incorporated into the system, to be pressed by the pregnant woman when she feels or detects the foetus moving. These events will be very useful for comparison purposes, as they enable a comparison with the movements detected automatically by the belt. One idea was to connect each individual fabric square (a switch) to the power supply and the other connector of the switch to a port in the acquisition module and detect if there was any signal entering in the port of the microcontroller. This possibility was abandoned due to hardware restrictions. To further develop this idea, twenty eight inputs of the acquisition module would be needed but the chosen microcontroller did not have so many inputs available. To overcome this difficulty, the final and definitive proposal to read the switches was to connect the seven columns and the four lines to input/output ports.

The algorithm to scan all the switches uses only eleven ports and has the following sequence:

- It places a signal at the first column and reads if there is any signal at the first line;
- It places a signal at the first line and reads the first column to detect any signal;
- It puts a signal at the first column and reads if there is any signal at the second line;
- It feeds a signal at the second line and reads if there is any signal at the first column;
- A signal is applied at the first column and the algorithm reads if there is any signal at the third line;
- It places a signal at the third line and reads if there is any signal at the first column;
- It places a signal at the first column and reads if there is any signal at the fourth line;
- It puts a signal at the fourth line and read if there is any signal at the first column.

When it reaches the last line verification for a column it checks if the patient pressed the button. The procedure for the other columns is the same. The data packet is built and sent to the computer when these iterations are finished for all the switches from the last column.

Some tests have been made with this belt in a pregnant woman and the results have shown that the belt was too sensitive to allow for a discrimination of movements. The belt detected some foetal movements but it was quite difficult to understand if the detection was due to a foetus movement or to the woman movement.

Note that the conductive fabrics from the On-Off belt may be washed after disconnecting all the electronics associated to the belt.

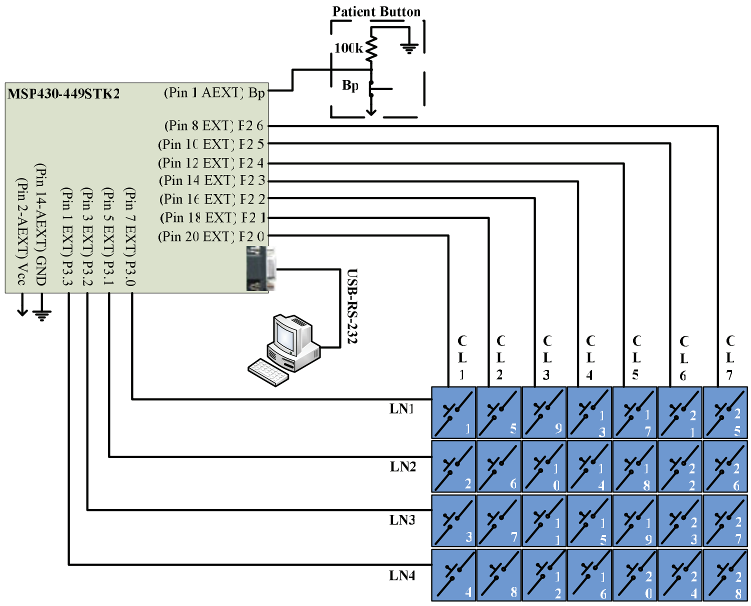


**Fig. 13.** System diagram for the On-Off belt

## 5 Experimental Results

### *A. Flex Sensor Belt*

Some initial results were extracted from the Flex sensor belt with a patient that was not a pregnant woman. The objective of this test was to verify if the respiratory movements or other type of motion artefact influence the angles of each Flex sensor in the belt. It was verified that the respiration movements were slightly felt. Besides, if the patient moves quickly the sensors may detect the deformation from the belt.

After these preliminary tests, the Flex sensor belt was tested in a pregnant woman, in order to detect foetal movements and compare these occurrences with those signalled when the pregnant woman presses the button. A good idea that can be extracted from these initial tests is to implement a routine which automatically defines the value for a detection threshold-trigger whose values will be tuned.

The Flex Sensor View software was incorporated and its final version is presented in Fig. 14. Examples are the capability to simultaneously show eight angles from the Flex sensor, the patient counter and the option to save the data in a log file (for later treatment). This version enables the communication between the computer and the acquisition module by using a single interface a packet for all Flex sensors.


**Fig. 14.** Main window for Flex Sensor View application

Fig. 15 presents the real-time view chart plot for the Flex sensor, extracted from the application to display the deformation angles. For each sensor, an independent threshold trigger can be defined individually or a unique threshold value can be defined (as a whole) for all the sensors.

When considering this threshold-trigger, even if the sensor detects some motion artefact, a boundary can be established in order to tune when the application should count the deformation angle as a foetal movement.

In Fig. 15, the value used for the global threshold is equal to 15º (angle deformation). This threshold was established by analysing the experimental data. This means that the automatic counter from each Flex sensor counts a flexion as a movement when the instant value of the Flex sensor angle is larger than the threshold value at one time instant and smaller at the next time instant. As an example of how the automatic counter works, considering Flex sensor 8 in the view chart at time instant $t_1$ the angle value is equal to 28º. Hence, the counter will count a foetal movement if this value decreases at the next time instant. In time instant $t_2$ the angle value is equal to 8º; so, the automatic counter will add one unit to the counter of the Flex sensor 8.

Some tests were made in a pregnant woman. During the test, the patient was sitting in a chair most of the time. A calibration of the flex sensors is made in the belt circuit before any test. A test was also made on how curves vary if a sudden change of the pregnant woman position happens, as shown in Fig. 16.

One may verify that the change of position occurred approximately at the time instant 190 s. There was a lot of artefact movement detected during the change of position, which causes the loss of the initial calibration.

Another test was made while the patient was sitting in a chair. Two different foetal movement occurrences were detected. In this case, instead of presenting all the flex sensors in the same window we enabled the software option to show separate windows for each flex sensor. The movements were detected in the flex sensor 1, at time instants ≈420 s and ≈460 s, as shown in Fig. 17. A motion artefact was detected after the time instant 500 s, probably due to the mother respiration movements.

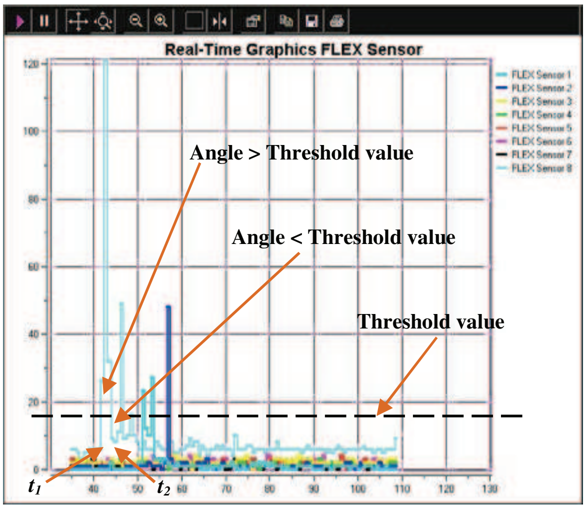


**Fig. 15.** Real-time view chart plot for the Flex Sensor

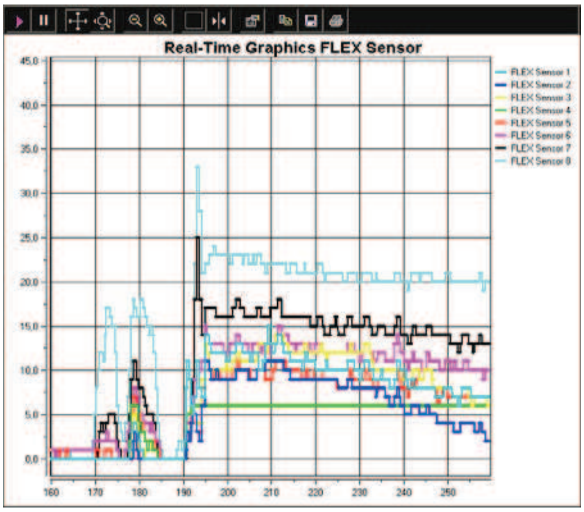


**Fig. 16.** Results when patient stands up at time $t$= 190 s

Simultaneously, the window that monitors the Flex sensor 2 shows two peaks, whose amplitude is larger than the other peaks in the chart, one at the time instants ≈420 s and another at time instant ≈460 s, as shown in Fig. 18. The movements detected by Flex sensor 1 caused a deformation angle larger than the one from flex sensor 2. Hence, because the Flex sensors are placed side by side (and separated by 8 cm) we may conclude that the movements detected were nearer Flex sensor 1.

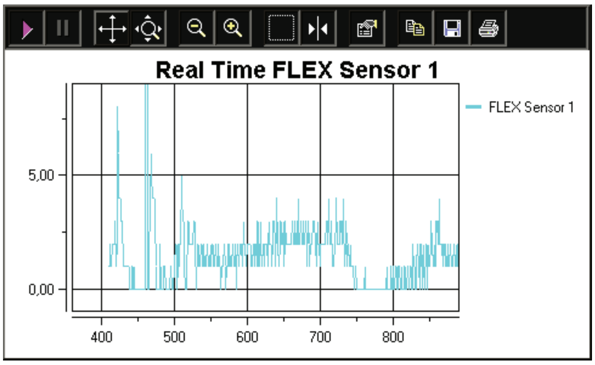


**Fig. 17.** Results from Flex sensor 1 when patient is sited

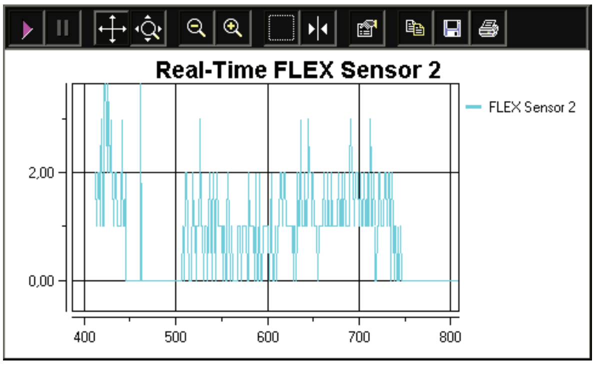


**Fig. 18.** Results from Flex sensor 2 (Patient sited)

Another test was made when the patient was sitting in a chair, as presented in Fig. 19. A movement was detected by the system, while the patient claims to have detected two foetal movement occurrences. The time instant when the system and the patient detected the foetus movement simultaneously was ≈910 s. The system detected the movement at the Flex sensors 1, 2, 3, 4, 5 and 6, with a stronger intensity in the Flex sensor 3. The other movements the pregnant woman claimed to have felt a foetus movement was at time instant ≈895 s. However, the system did not detect any foetal movement. At the instant ≈925 s the system detected a foetus movement but it was considered a false positive, as the patient did not feel it.

### *B. Piezoelectric Sensor Belt*

All the tests of the piezoelectric sensor belt were performed in Centro Hospitalar da Cova da Beira. A woman in her 38th week of pregnancy wore a belt that incorporates three piezoelectric sensors (one central sensor and two on both sides), adjusted to the abdomen by an elastic belt. The signals obtained from the sensors were combined into only one signal, amplified, filtered and applied to an ADC

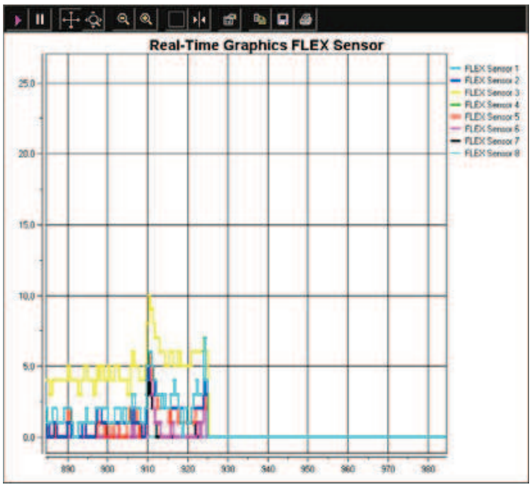


**Fig. 19.** Results when patient is sited

converter, and then sent to the computer via USB. At the computer, the signals were processed and graphically presented to the medical team. The pregnant woman had a manual event marker (patient button) to mark the foetal movements when she felt it, for redundancy purposes. Another device was also used, called Respisense [11] and usually applied to detect the baby breathing. The signals of the event marker and Respisense were compared with those extracted from piezo-electric sensors. Fig. 20 shows a block diagram of the circuit to acquire the signals from the sensors.

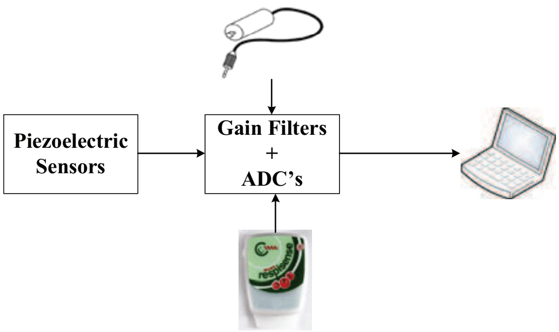


**Fig. 20.** Diagram for the circuit to acquire the signals from the sensors

Fig. 21 shows the Hospital environment in which the tests were performed, as well as the pregnant woman. The belt covers only a small part of the pregnant patient belly, contributing for non-ideal results. We plan to use more piezoelectric sensors in a future version of the belt.

**Fig. 21.** Field tests for foetal movements' detection

Fig. 22 shows the experimental results. Different signals can be observed, distinguished by different colours:

- Red – original signal (piezoelectric sensors);
- Blue – filtered signal (finite impulse high-pass response filter);
- Brown – event marker;
- Green – detected foetal movements.

Fig. 22 presents a screenshot from the program developed to display the signals from the sensors. It shows the a) multiple foetal movements simultaneously detected by the mother and sensors, as well as b) some discrepancies caused by

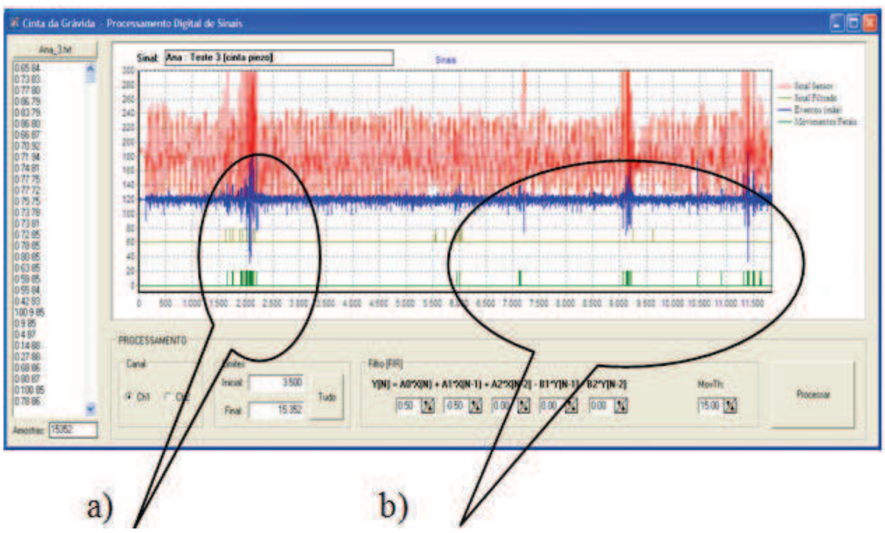


**Fig. 22.** Test results for foetal movements' detection

patient movements (like speaking, tossing), by the event marker detection forgotten by the patient, and due to the reduced number of piezoelectric sensors included.

From the experimental results, we can conclude that the system has a high potential to detect foetal movements, isolating them from external interferences. However, weak foetal movements are easily hidden by signals with larger amplitude, such as maternal walking, speaking and even breathing.

Filtering and interference reduction will be important topics that need further research. Also, using more piezoelectric sensors inside of the belt, to cover a broader area of the pregnant woman abdomen, is one suggestion for future developments. As a suggestion, it may be possible to use sensors built with polymer films (Polyvinylidene Fluoride) [12] in the future.

## 6 Conclusions

This paper presents two main versions of prototype sensor belts produced within the Smart-Clothing Project, which aim at counting the movements of the foetus in a pregnant woman. Besides the standalone solution for the Flex Sensor belt, where data can be saved into a memory card, we developed a wireless Flex sensor belt network based on the IEEE 802.15.4 standard. A hierarchical wireless network with a Wi-Fi layer on top of the sensor network will allow for extra flexibility in data communication. The system guarantees real-time and continuous foetal monitoring while creating effective interfaces for querying sensor data and store all the medical record (which can later be accessed by health professionals). Another developed belt has piezoelectric sensors incorporated onto it. The system has a high capacity to detect foetal movements, isolating them from external interferences.

As future work, we propose to implement other types of communication systems that may work together with the existing ones. For example, create a webpage where we can scroll through all the data produced in real time while sharing the information with other medical institutions. Another proposal is to implement algorithms for signal source separation, noise and motion artefact signal suppression, as well as to implement advanced algorithms for data treatment and aggregation.

Further work is needed to upgrade the signal conditioning circuitry, the processing software (to accomplish a real time filtering) and statistical techniques to detect the foetal movements in the piezoelectric belt. The data collected from the belt contains signals from the mother and foetus. An alternative approach to distinguish the different signals detected with the belt may be based on a spectral analysis instead of time domain analysis, facilitating the separation of the different signals, such as the mother respiration, foetus movements, mother's heart beat and motion artefacts. Other techniques may be based on the Fast Fourier Transform (FFT), which detects a peak from a signal composed by signals with different frequencies, or blind source separation.

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## References

1. Cao, H., Leung, V., Chow, C., Chan, H.: Enabling Technologies for Wireless Body Area Networks: A Survey and Outlook. IEEE Communications Magazine 47(12), 84–93 (2009)
2. Evaggelos, C., Karvounis, E., Papaloukas, C., Tsipouras, M., Bougia, P., Dimitrios, I., Naka, K.: Remote maternal and fetal health monitoring during pregnancy. In: Proc. Information Technology Applications in Biomedicine - ITAB 2006, Ioannina, Greece (2006)
3. Barroca, N., Velez, F.J., Lebres, A.S. (2009) Energy-Aware Medium Access Control Protocols for Wireless Sensor Network Applications, MSc thesis, Universidade da Beira Interior (September 2009)
4. Gribbin, C., James, D.: Assessing fetal health. Current Obstetrics & Gynaecology - Elsevier 15(4), 221–227 (2005)
5. `http://www.hibaby.co.uk/acatalog/Angelsound_Fetal_Doppler.html`, Angelsound Fetal Doppler (September 2009)
6. Borges, L.M., Rente, A., Velez, F.J., Salvado, L.R., Lebres, A.S., Oliveira, J.M., Araújo, P., Ferro, J.: Overview of Progress in Smart-Clothing Project for Health Monitoring and Sport Applications. In: Proc. 1st International Symposium on applied Sciences in Biomedical and Communication Technologies - ISABEL 2008, Aalborg, Denmark, pp. 160–166 (2008)
7. `http://www.e-projects.ubi.pt/smartclothing/photo_galley.html/` Smart-Clothing Project (September 2009)
8. Sohraby, K., Minoli, D., Znati, T.: Wireless Sensor Networks Technology, Protocols, and Applications. John Wiley & Sons, Hoboken (2007)
9. `http://www.adinstruments.com/products/hardware/research/product/MLT1010D/` ADInstruments (September 2009)

10. Vullings, R., Peters, C., Mischi, M., Sluijter, R., Oei, G., Bergmans, J.: Artifact reduction in maternal abdominal ECG recordings for fetal ECG estimation. In: Proc. 29th Annual International Conference of the IEEE - EMBS, Lyon, France, pp. 43–46 (2007)
11. http://www.respisense.com/en/index.php Respisense (September 2009)
12. http://www.meas-spec.com/searchresults.aspx?search=Polyvinylidene%20Fluoride# Measurement Specialities (September 2009)