A SMART WEARABLE SYSTEM FOR SUDDEN INFANT DEATH SYNDROME MONITORING

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ABSTRACT

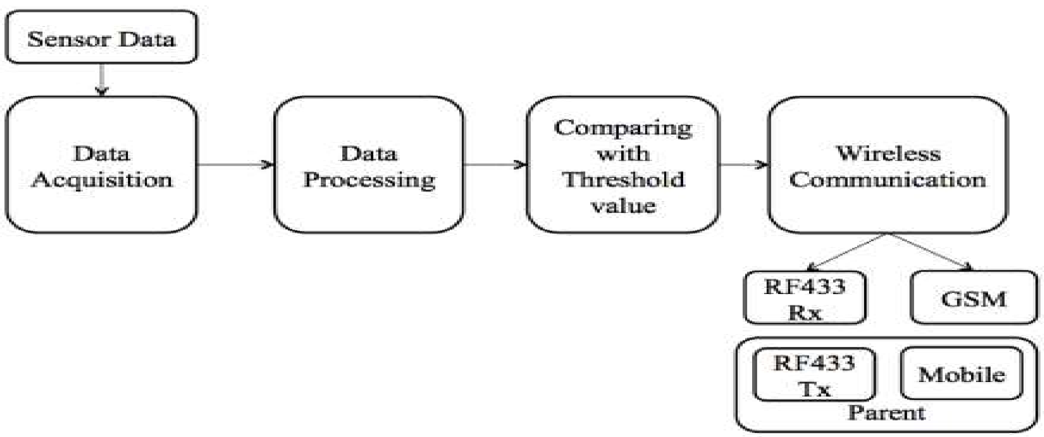
Sudden Infant Death Syndrome (SIDS) is one of the major causes of death among infants during their sleep. To increase the safety of the infants, we matched different emergent research fields for the development of Baby Night Watch. This Smart Wearable System (SWS), developed under the context of the European Texas Instruments Innovation Challenge (TIIC) 2015, is composed by the following elements: a Wearable IoT Device, a Gateway and the H Medical Interface. The Wearable IoT Device is a wireless sensor node integrated in a Chest Belt, and it has the capacity to monitor the following parameters: body temperature, heart and breathing rates and body position. After a minimal data processing, this set of information is sent to the Gateway, via ZigBee technology, and it is accessible to the user through the H Medical Interface. If a critical event occurs, the device will trigger an alarm, visible and audible in the proximity, and sends a distress message to a mobile application. The Baby Night Watch is an important tool for medical studies, since it allows the visualization of previous physiological data and export it to different types of datasets. Experimental tests have proven that the SWS has the potential to identify situations that could be potentially life-threatening for an infant.

KEY WORDS: Sudden Infant Death Syndrome, Medical Interface, Baby Night Watch

INTRODUCTION

Sudden Infant Death Syndrome (SIDS) is one of the major causes of death among infants, and it was the main motivator to design a Smart Wearable System (SWS) capable of increasing the safety of the infant. The "Baby Night Watch" project is a combination of emergent technologies, such as: wearable devices; smart textiles; embedded systems; wireless communications; web interfaces; and mobile applications, aiming to monitor the infants during their sleep. This SWS is composed by a Wearable IoT device, a Gateway, and an H Medical Interface. The Wearable IoT Device is the sensing unit, in the form of a Chest Belt, and is responsible for monitoring the body temperature, the heart and breathing rates and the body position. This set of parameters is vital for the identification of SIDS scenarios and for the evaluation of the quality of the sleep. During sleep, doctors state that the infants should sleep on their back and they must not sleep on their stomach, as the infants are particularly vulnerable to SIDS due the risk of asphyxiation. Thus, we have developed an algorithm for the continuous monitoring of the position of the infant during the sleep. This algorithm is based on the data retrieved from an accelerometer and it is able to identify all four possible positions of the infant during the sleep: lying on his back; lying on his side; lying on his stomach. Moreover, the two of the major signs that SIDS may be about to happen is abnormal breathing pattern and heart rate. For the newborns the typically breathing rate is between 30 to 60 breaths per minute, 40 breaths per minute for infants, and it decreases to 24 to 30 breaths per minute after the first year. For the detection of the breathing rate, we used the same 3D accelerometer, and we have developed a low complexity algorithm with low overhead. Through the use of textile electrodes, knitted in the chest belt and with dedicated electronic, the heart rate is measured by our system. The textiles revealed to be an excellent interface for bio-signal sensing, as they are flexible, stretchable and conform to the body (increasing the physical comfort of the infant), rendering them an interesting solution for ubiquitous, continuous health monitoring. For the infants the normal heart rate is above 100 beats per minute . For the body temperature monitoring we use a small contactless infrared temperature sensor. The main goal of the Baby Night Watch is to reduce the response time in a SIDS scenario. This SWS is able to send different types of alarms (sound, light and, distress messages to smartphones), increasing the reliability of the system. Along with the metrics reliability and latency, the system has to operate continuously for long periods of time (over 8 hours), making the energy efficiency an important metric of the system. Like WSN and WBSN, in SWS main cause of energy consumption are the wireless communications, corresponding to > 60% of the total of energy consumption. Therefore, to improve the lifetime of the battery some features of the wireless transceiver were explored, these techniques are described. In the last decade, the research community and the industry have been taking special attention to wearable systems. These are designed for a vast range of applications, such as: health monitoring sleep quality evaluation; athletes' performance assessment; or detection of injuries, just to mention a few. It is common to find SWS that are able to monitor multiple vital signs and access if the user is in an emergency situation. Some of the parameters that can be monitored by a SWS are: electrocardiogram signals (ECG); electroencephalogram (EEG); electromyogram (EMG); heart rate; activity of the user; fall; breathing rate; blood pressure; blood glucose; blood oxygen; perspiration (sweating) or skin conductivity; and body or skin temperature. Several design approaches have been tested to make the SWS more "wearable" and less intrusive, like wristwatches, shirts, jackets, gloves, socks, chest bands, or pajamas. But the use of intrusive technologies, like cables, cuffs, and devices with big dimensions, make those SWS not truly wearable and in some cases uncomfortable for the user. The use of smart textiles like textile electrodes or printed sensors allows the user to have more freedom of movements and comfort in its use, but some of those technologies are still a prototype. Several types of wireless communications technologies (Bluetooth, ZigBee and 3G) are used in SWS for offbody communications with the Base Station, Smartphones and/or Graphic User Interface. Although multiple technologies have been already created to prevent SIDS, they do not seem to be comfortable or they do not have the capacity to measure all the required parameters. Also, alongside with the prevention, Baby Night Watch tries to be a continuous tool to study what may cause this Syndrome. Storing the information of any variation of patterns may be helpful to understand this syndrome.

Infant care has become a great challenge in daily life. In many families, both the parents need to work, so it has become a great difficulty in monitoring their infants. If a system is developed to constantly monitor the infant, it will become easier for the female parent who has to manage lot of workload both in the working place and in their house. The system can constantly monitor the infant with the help of sensors placed on the infant and if any sensor crosses the threshold, the indication can be sent through communication modules. Usually, when a young infant cries, the cause is one of the following reasons i.e. high body temperature, high moisture level or low oxygen level present around the crib. So in this paper, we have developed a system, which can monitor the activities of the infants as well as their condition and give this necessary information to their parents. The prototype of the entire system placed on the infant should be made compact, so that it won't cause any sort of discomfort to child. Various kinds of wearable sensors have emerged for different purposes with the development of sensing technologies. Other systems were developed in such a way that it can be easily wearable by the infants. We have developed the prototypes on the same line, but it solves most of the issues faced by the infant and parents will get updated information on a real-time basis by extending the use of wireless communication technologies.



INFANT MONITORING FRAMEWORK

In the present scenario for prosperous living in the fast moving world, both parents should do some job to lead a happy life. But this adds a threat to the personal life, i.e, lack of monitoring of their infants. This will always be disturbing on their mind and even it will affect their day-to-day work. There is great need of a new system which has to monitor the infants and this will bring some sort of relief to the parents. They will get continuous messages based on the information collected from the sensors attached to the crib of the infant through an attached wireless module. The proposed framework of the infant monitoring system. First, the data collected from the sensors will be processed and analysed based on fixed thresholds. Any sensor value which crosses the threshold, the information will be communicated through wireless media. This will be an effective solution for monitoring the infants.

Wearable technology for baby monitoring

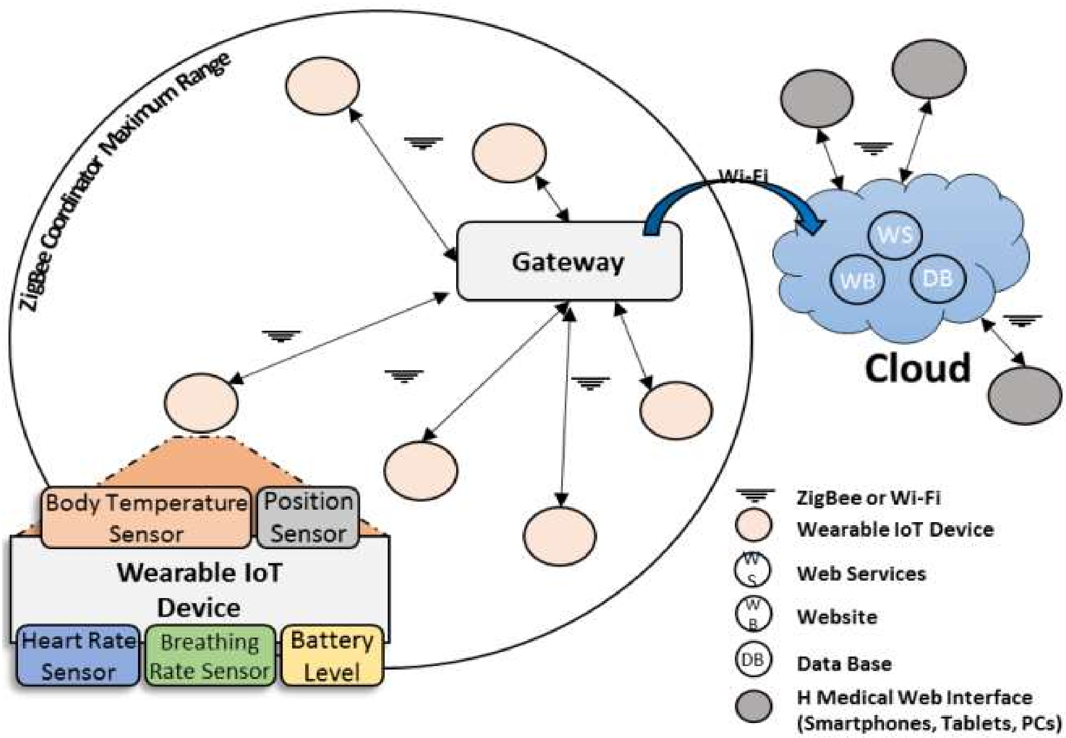
Baby monitoring technology includes different types of products such as movement monitor, audio-video monitor, health vitals monitor with or without an audio-video facility. The movement monitors are sensitive and can detect even the slightest movements of a baby and generate an alarm when a baby does not move. Mat monitor is a type of movement monitor where sensors are integrated under the mattress. This baby monitor generates an alarm if a baby stops movements for 15 to 20 seconds. Audio and video baby monitoring is another type of baby monitoring system to observe a baby without tracking baby vital signs. However, these babies monitoring have some constraints of realtime data monitoring, lack of fitting, and inaccuracy of information. To solve all these difficulties wearable baby monitoring technology has emerged. Currently, smartphones, smart watch, and smart clothing are the main wearable products available in the market with healthcare functions. Smartphones are ubiquitous with a big screen allowing effective human-computer interactions. Smart watches can ensure continuous contact with human skin providing health monitoring data continuously. Whereas smart clothing offers more precise and spontaneous health vitals monitoring. Both smart watch and smart clothing can be connected to the smartphone to review the whole health statistics which provides suggestions for improvement also. Therefore, most of the wearable baby monitoring technology is either in the form of wearable devices or smart clothing while both of these products can be wirelessly connected to smartphones. Bodily worn baby monitoring products to ensure better contact with the baby body and efficiently collect baby health vitals and transmit real-time data to connected devices. In the following section, we discuss, to date, the most popular health monitoring smart wearable systems, their functions, and operational workflow.

SYSTEM DESIGN AND ARCHITECTURE

The architecture and the design methodologies that were chosen for the development of the Baby Night Watch.

SYSTEM OVERVIEW

The illustrates the architecture of the Baby Night Watch, where the different components and communication technologies used are depicted. The Wearable IoT Device collects different types of physiological data and send those parameters to the Gateway, which is inside of the communication range of the wearable IoT Device. This offbody communication is made using the IEEE 802.15.4- compilant wireless transceiver radio, SoC CC2530, over the 2.4 GHz Industrial Scientific and Medical (ISM) band. The software of the gateway analyses all the information sent by the Wearable IoT Device. If an unexpected event occurred, the Gateway will start buzzing and sending alarms to the Cloud Storage Center. The cloud stores the data and communicates with the H Medical Interface and the mobile applications connected to it. The H Medical Interface allows users to check the condition of the baby, retrieve previous stored data, visualize the collected information and export information in different types of files. To assure this interface is available in any device, the interface was totally implemented in web programming languages (Javascript, PHP and SQL), markup language (HTML5) and stylesheet language (CSS3).

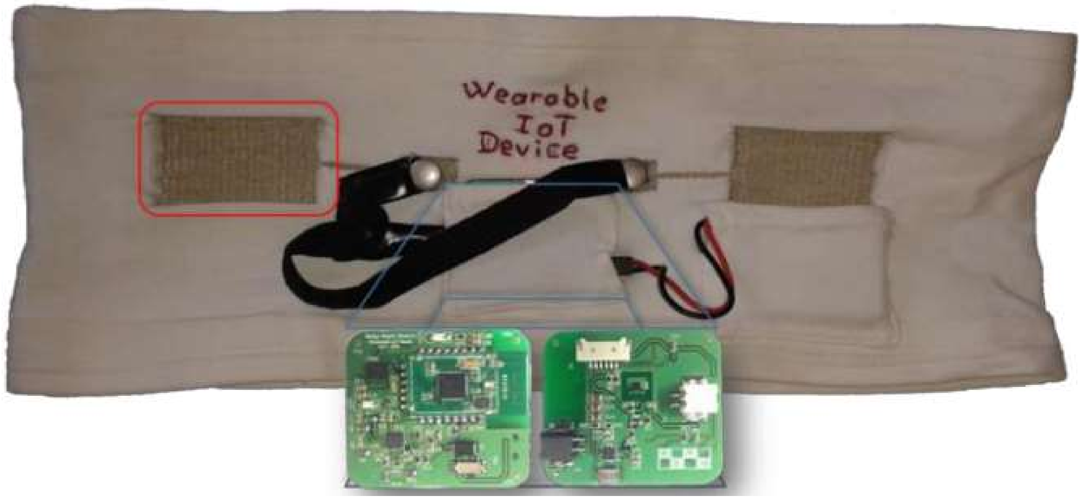


OVERVIEW OF THE BABY NIGHT WATCH

WEARABLE IOT DEVICE

The Wearable IoT Device acquires the physiological parameters of the infant, parses it and sends the processed data to the Gateway using the CC2530 SoC from Texas Instruments, through ZigBee wireless technology. The ZigBee stack selected for this project was the Z-Stack API. To reduce the size of the module we use the GB2530-L from GBAN (CC2530 with small form factor). A PCB with reduced dimensions (4.3x3.8x0.9cm) was designed to make it more comfortable. Since the device is battery powered, it uses a power supply system that includes the TI's TPS63060 to maximize the battery usage and its lifetime. The final PCB. Since the battery voltage can be 3.7V (full battery charge) and the maximum voltage that can be read from an

ADC pin on the CC2530 SoC is 3.3V (supplied voltage from the buck-boost), a resistor divider was used to measure the battery voltage. To minimize the power consumption of the Wearable IoT Device, a P-Mosfet was used to enable/disable this readout circuitry.



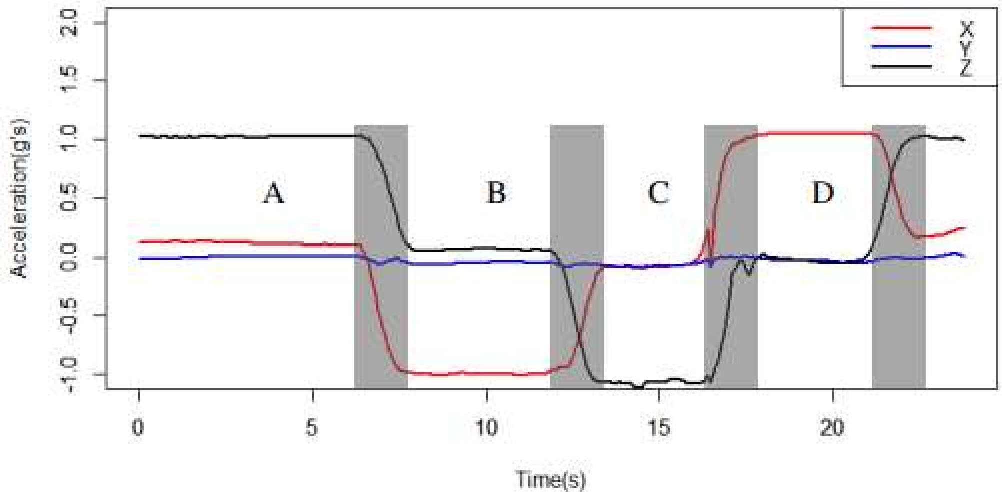
Wearable IoT Device: illustration of the chest belt with the textile electrodes for the heart rate acquisition (red rectangle); and an inset of developed hardware for the acquisition of the parameters (front and back)

HEART RATE SENSOR

The acquisition of the full ECG is a very resource consuming task. As it requires many computational resources, which are usually not available on wearable systems due to the power and size constraints, or a big power source for the data transmission . Thus, considering the requirements and constraints of the Wearable IoT Device, we will only acquire the heart rate information. For the chest belt a two-electrode sensor configuration was chosen, these textile electrodes were made based on the patent [20]. The electrodes were knitted by the base-fabric, using a silver coated textured polyamide elastic yarn from Elitex, with low electrical resistance (in the order of tens of Ω/m). The wearable chest belt, composed by textile electrodes and conductive leads (to connect these elements to the analog frontend) were knitted by a MERZ MBS seamless knitting machine. For the electrode area, a particularly voluminous structure was developed, making the electrode area stand out of the rest of the fabric, and thus, improving the contact between skin and textile electrode. To ensure 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. It was concluded that the best position is below the pectoral muscles, where the electrodes are closer to the ribs, avoiding electromyography interference. To implement the heart rate measurement conditioning circuitry, an AD8232 was used and the heart rate monitor was designed to measure small biopotencial signals in noisy conditions. The Instrumentation Amplifier has a gain of 100 V/V. Regarding the cutoff frequencies, 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 SallenKey configuration, attenuates the line noise and other interference. To compute the heart rate value, a CC2530 microcontroller was used in combination with the AD8232. Using its ultralowpower internal analog comparator, it is possible to compare the filtered ECG wave with an external voltage level. The analog comparator solution compares the voltage reference with the level of the ECG signal and the output changes when the ECG signal drops below the voltage divider value (voltage reference set to 300 mV). To calculate the infant's heart rate, a timer of the CC2530 is used to measure the time between two heart rate pulses.

INFANT'S POSTURE

To detect the position of the infants during the sleep, the LSM330DLC inertial sensor from STMicroelectronics was used. In this project we did not use the built-in gyroscope. The LSM330DLC has 3 independent acceleration channels, a dynamically user-selectable full-scale range and, a SPI/I2C serial interface. From the different positions of the infants are easily recognized by the force that the earth's gravity (±1g or ±9.81m/s2) applies to each axis. The gravity force on the YY's axis is almost zero for all of the four possible positions and, therefore, YY is not used to determine the infant's position. When the infant is lying on his backs (scenario A), in the ZZ's axis we will have ≈1g and on the XX's axis ≈0g. In scenarios B and D the infant is lying on his side, in the ZZ's axis we have ≈0g and in the XX's axis ≈-1g when the infant is lying over his left arm (scenario B) and ≈1g when the infant is lying over his right arm (scenario D).

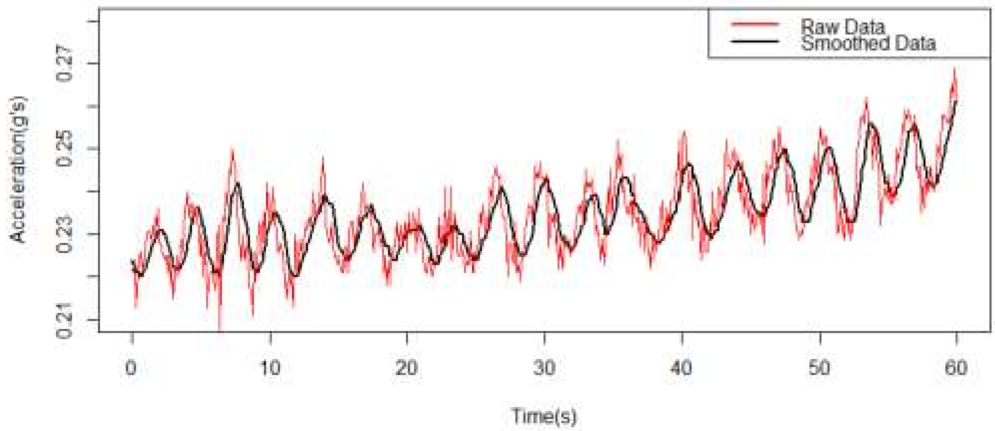


ACCELERATION VARIATION ON EACH AXIS OVER POSITIONS CHANGES

In scenario C the infant is lying on his stomach and, in the ZZ's axis we have ≈-1g and in the XX's ≈0g. Also in the gray bars represent the transient stages between each position. Based on the information depicted, we have developed an algorithm for position recognition. To minimize the small fluctuations that can occur between accelerometer readings, a threshold value was defined that allows to control the tilt angle in which a position is defined. So, the working principle of the proposed algorithm is: if the accelerometer reading in one axis is higher than the threshold value and the reading of the other axis is lower than the defined threshold, the position is set according to the values read (i.e. if the value in the ZZ's axis is +1 g and the value in the XX's axis is 0, then the position of the infant is defined as lying on his back). To prevent unnecessary energy consumption, the position updates will only be send to the Gateway when a valid position change is detected.

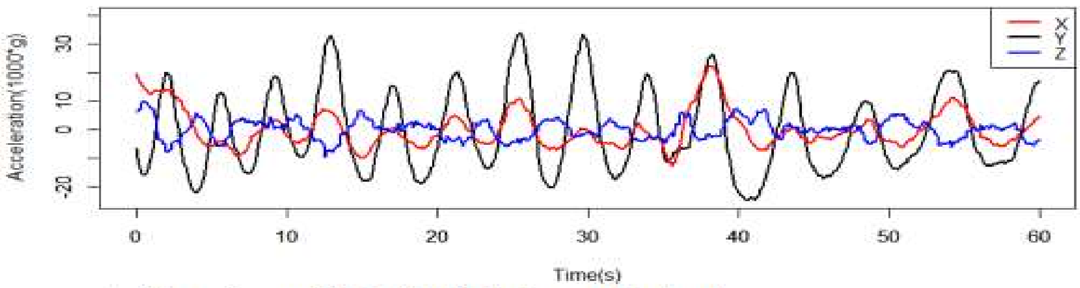
BREATHING RATE SENSOR

For measuring of the breathing rate, the same 3D accelerometer described above is used. The sampling rate for the 3D accelerometer was set to 10 Hz, since it acquires the data at least ten times higher than the maximum frequency of the signal (60 breaths per minute). The data acquired in one of the accelerometer axis over a period of one minute. Due to the huge variations of the original signal between each sample (represented by the red line), a smoothing algorithm based on the sliding window technique was employed, with a window of 10 samples or 1 second. As, the implementation of the smoothing algorithm results on a signal very similar to a breathing pattern and the data fluctuation is almost nonexistent.

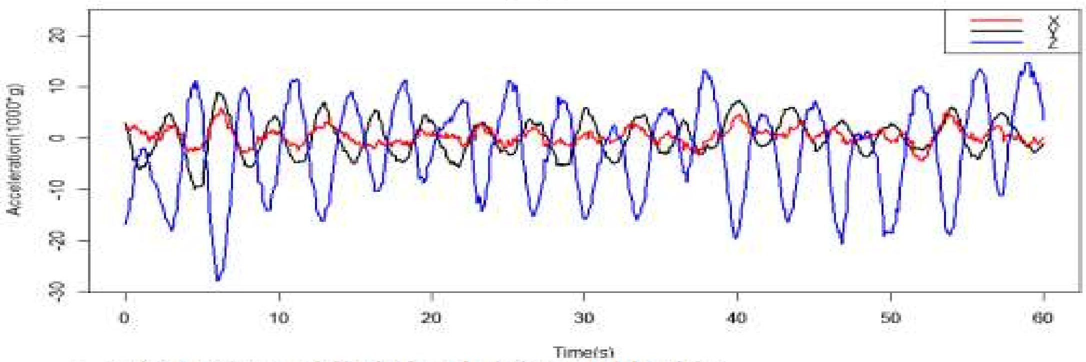


SMOOTHED AND UNSMOOTHED DATA ACQUIRED FROM THE 3D ACCELEROMETER

Since each breathing cycle has different amplitude and the techniques for peak detection require too much computational resources and, therefore have a huge energy consumption, a state machine with three possible states (Middle, High and Low) was used for obtaining the breathing rate, in order to minimize power consumption [22]. For the correct recognition and validation of a breathing cycle, the signal must follow this sequence: start on the Middle state; High state; Middle state; Low state and; Middle state again. The Middle state is defined by a threshold interval that sets the maximum and minimum breathing signal values. The selection of the threshold range is one of the key factors for the correct performance of the breathing rate sensor because, if this interval is too narrow the algorithm is likely to miss the transition between the Middle state, and if the interval is too large it is likely that the state machine never reach the Low or High state. Since the amplitude of the signal can be very small (0.219 g to 0.25 g), the selection of the threshold interval is very difficult due to the proximity of the values. So, the original signal was amplified on an order of a thousand times to make the selection of the threshold interval simpler. As it can also be seen in the mean value of the breathing waveform can vary over the time. In order to prevent that this fluctuation might cause inaccuracies due to a static threshold interval, an average value of the signal over a limited period of time was used, then this value was subtracted to the current smoothed value. With the implementation of this technique the system removes the continuous component of our signal and the resulting signal is the breathing pattern. Besides this, the system can use a static threshold interval, which means that it does not need to periodically compute the thresholds limits. This results in a reduction of the computation resources required and, consequently, on a more energy efficient algorithm.



Axis's values while infant is lying on his back.



Axis's values while infant is lying on his side.

Through the analyses of both figures we can conclude, based on the signal amplitude, that the better representation of the breathing pattern is performed by the YY's axis and the ZZ's axis when the infant is lying on his back and when he is lying on his side, respectively. If we give a closer look, it is possible to observe that although the ZZ's axis has a better breathing pattern (higher amplitude), some of the breathing cycles are below or slightly above of zero. This will means that the algorithm will be unable to recognize those cycles and this will lead to errors on the estimation of the number of breaths per minute. On the other hand, the breathing pattern of the YY's axis is more reliable because, although it has a lower amplitude, the breathing waveform is always around zero. So, with a careful selection of the threshold limits the algorithm is able to achieve a good performance.

GATEWAY

A BeagleBone Black, with a Debian Wheezy image installed, acts as a Gateway. A lighttpd server with PHP 5.1 was installed on it to provide the network services. A shield, to the BeagleBone Black, with a buzzer, RGB led, push-button and a CC2530 was designed and implemented. For the communication between the CC2530 and the BeagleBone a Serial Port communication protocol was used. The RGB led and the Buzzer are used to notify the user every time an emergency situation is detected. Different colors are used to notify the users which event occurred. The wireless USB adapter TL-WN725N is used to connect the Gateway to the router.

The BeagleBone stores the data received into the database. Unless some risk event occurs, the information received will only be store at regular intervals.

GATEWAY: SHIELD PLACEMENT ON THE BEAGLEBONE BLACK

H MEDICAL WEB INTERFACE

The H Medical Web Interface, it was designed to help the user to retrieve the information collected/processed from the SWS. The web interface was developed in PHP, SQL, Javascript, HTML5 and CSS3. The main idea was to develop a full operational interface, which will work on any device, independently of the OS. To develop an interface that runs in a development board such as the BeagleBone Black, some of the processing power was switched to the user's side. To be able to do that we used Javascript Programming Language. Besides Javascript taking off some of the processor work from BeagleBone it also turns the interface into a dynamic webpage, making it possible to monitor the baby in real-time. Some background PHP applications were created to fetch information to the web interface, and to deal with the connection to the database. The H Medical Web Interface also allows the user to generate charts, time-lapse animations, and export data into different types of files. It also allows to add new users and monitor multiple infants.

CONCLUSION

The Baby Night Watch is capable of detecting unexpected events and registering several physiological parameters, making it a powerful medical tool to understand SIDS, and a reliable real-time monitor of infants. The project proved that with a small amount of hardware a huge number of parameters can be measured, improving the users experience and safety of the infant. The data rate produced by the Wearable IoT Device is in the order of 35 bytes per minute, easily supported by ZigBee. In the future some changes must be made to improve this SWS: placing the Cloud Storage Center into a webserver, allowing the users to retrieve information without having to be connected to the Gateway; implement some functionalities of the H Medical Web

Interface in Python to improve stability and speed; use a more accurate thermophile sensor for the acquisition of the body temperature; improve the connection between the textile electrodes and the sensor node; and use a commercial breathing rate sensor to compare the results of our system during longer periods.

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