A Novel Hardware Implementation For Joint Heart Rate, Respiration Rate, And Gait Analysis Applied To Body Area Networks

M. Khazraee*, A. R. Zamani*, M. Hallajian*, S. P. Ehsani*, H. A. Moghaddam*, A. Parsafar*, M. Shabany*
*EE Department, Sharif University of Technology

***Abstract*—Continuous and remote monitoring of vital health-related and physical activity signs of a patient is one of the most important technology-oriented applications to monitor the health-care of ill individuals. In this paper, an innovative framework for a wireless Body Area Network (BAN) system, based on the IEEE 802.15.6 standard, with three types of sensors is proposed and implemented. These include Electrocardiogram (ECG), Force Sensitive Resistor (FSR) and Gyroscope. The proposed design is a novel implementation of an embedded system for the real-time processing and analyzing of the ECG signal, gait phases, and detection of the respiration rate from the ECG signal, by means of small applicable sensors and wireless data communication. Gait analysis is essential for the precise ECG and respiration analysis according to the body posture. A new comprehensive high-speed six-state design is utilized to cover all walking habits. Moreover, the collected data is sent to an external device for further monitoring. The proposed framework is optimized for hardware implementation and targeted for low power applications. The optimized joint implementation of these health-related sensors makes the proposed design distinct from the previous work.**

I. Introduction

Continuous and remote monitoring of vital health-related and physical activity signs of a patient is one of the most important technology-oriented applications to monitor the health-care of ill individuals. Examples of these signs are the heart rate (HR), respiration rate (RR) and walking phases. Each sign is monitored by a sensor. A body area network (BAN) is a network of these sensors, with internal signal processing core, making decisions on person's health condition and reports the result to a third party for further action through SMS, phone call, or email, which is currently standardizing by IEEE (802.15.6). The integration of different sensors and joint processing of the resulting signals has been a challenging task in the literature and there are very limited number of designs addressing a complete framework, some of which are explained in the sequel.

The goal of this paper is to propose and implement a framework for a BAN system with three types of sensors including Electrocardiogram (ECG) for HR and RR analysis, and Force Sensitive Resistor (FSR) and Gyroscope for gait analysis. Previous algorithms for the ECG signal processing and gait analysis needed considerable processing power, which makes their real-time implementation on hardware as an embedded system very challenging [1], [2].

In this paper, new algorithms are developed to determine six states of walking (i.e. gait analysis) and to find out the HR and the RR, which are fully analyzed and jointly designed for hardware implementation. Small applicable sensors with wireless connections are used in order to provide a comfortable experience for the expected users. At the end, the results are accumulated by a BAN central node and sent to an external device via a wireless connection for further monitoring and making a database of the vital health-related and physical activity signs. The proposed design in this paper is a novel framework for the real time processing of the ECG signal and gait phases and detecting the RR form the ECG signal.

II. Network Structure

The proposed network (Fig. 1) is implemented in a star configuration consisting of one Shimmer module and two TelosB modules,

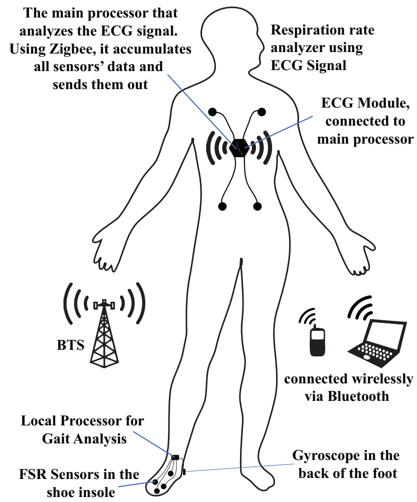

Fig. 1: The proposed BAN system

where the Shimmer module plays as the central node. The modules are programmed based on the TinyOS operating system, which utilizes the 802.15.4 protocol, designed for Zigbee-based networks. The central node accumulates sensors' data via Zigbee connections and transmits the results to another TelosB module, which is connected to a computer (see Fig. 1).

The proposed network performs two major health-related analysis, i.e., the gait detection analysis through FSRs and a gyroscope, and the HR and RR analysis through four chest leads connected to the ECG sensors.

In fact, gait detection results, computed by a local processor, are sent to one TelosB module and are monitored by this module. If there is any change in the gait state, it informs the central node. Moreover, four chest leads are connected to an ECG module, which sends the ECG signals to the central node for further processing, resulting in critical decisions on the patient's health condition. Different parts of the network are described in detail in the sequel.

III. Gait Analysis

Gait analysis is a process through which a person's walking states are determined. It is very useful especially for ill persons with injuries in legs that cause difficulties in their walking. It is also beneficial for handicapped people to improve their walking skills. Moreover, by analyzing the gait, a parameter proportional to the speed of walking or running can be extracted, which is essential for the heart signal analysis. For instance, higher HR is reasonable during running. Finally, gait analysis can be effectively used for professional trainers in different sport settings. There are several methods for gait analysis using different kinds of sensors, such as utilizing manual switches, force sensitive resistors, inclinometers, gyroscopes, accelerometers, and electromyography sensors. However, it is shown that the combination of FSRs and gyroscope can produce

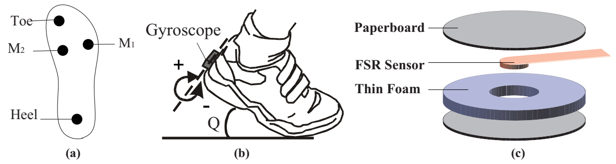

Fig. 2: (a) FSR sensors positioning in the shoe insole (b) Gyroscope sensor (c) The devised solution to improve FSRs' effectiveness.

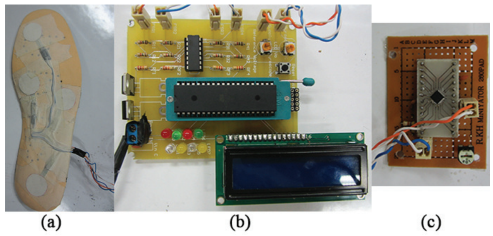

Fig. 3: The implemented hardware: (a) shoe insole (b) Processor board (c) gyroscope

more reliable results [3]. In this paper, a novel six-state design is proposed to determine the walking states using four FSRs and one gyroscope. The location and the placement of FSRs are carefully designed to obtain the required precision (see Fig. 2 (a) and (b)).

A. The Proposed Hardware

1) Force Sensitive Resistor Sensors: An FSR sensor is a resistor whose value is a function of the force applied to its surface. FSRs normally need an extra circuit to convert the applied force to a voltage, ultimately used for analog to digital converters. Two main limiting factors of the FSRs are the maximum electrical current and the maximum applied force, which were carefully handled in the proposed design in this paper.

The FSR sensors may malfunction after a few consecutive uses. This is mainly because of the fact that their internal structure may deformed under pressure, which happens during walking. Moreover, the issue with the use of FSRs for gait analysis is their small sensing area and inadequate recovery response time after being pushed. In order to avoid these complications and to improve the results, in the proposed design in this paper, each FSR sensor is located in a hole in the middle of a thin foam and between two paperboards (Fig. 2 (c)). The added foam prevents the sticking problem and improves the response time. The paperboards help to distribute the pressure uniformly that ultimately avoids possible damages to the sensors and makes the sensing area sufficiently wide.

2) Gyroscope: A small gyroscope is employed to determine the rotational velocity of the foot. It has a very high accuracy, with internal noise removal methods to avoid high sensitivity of MEMS gyroscopes to temperature. However, it still has some errors, which is calibrated as explained in the sequel.

3) Processing Unit: The outputs of the FSR circuit are sent to the ADCs of microcontroller to measure the pressure. Moreover, the serial connection to the gyroscope is established through an I^2C connection. The 8-bit RISC processor works at 8 MHz and sensor signals are sampled at 100Hz, with 8-bit resolution for FSRs and 16 bits for the rotational velocity. Previous algorithms used more powerful processors like 20 MHz 32-bit RISC microcontroller in Hitachi SH7032 board or workstations.

The implemented -fully tested- hardware of gait detection is depicted in Fig. 3.

B. Sensors' Calibration

It is essential to calibrate the gyroscope through software to obtain proper results. The results were averaged for five minutes to calculate the offset. In addition, a high-pass filter is implemented by setting a threshold for the acceptable results. This avoids very small results caused by the noise of the environment.

C. Algorithm

Previous work such as the one in [2], used a fuzzy logic algorithm to detect the walking states; however, such algorithms normally need a high processing power. Moreover, in [2], air pressure sensors were used to overcome the small sensing area of FSR sensors' problem. This problem is properly solved by using the paperboard and foam solution in this paper. In addition, air pressure sensors along silicon tubes are more expensive, harder to implement and need a FIR filter to become usable, which is not a cost-effective solution. Furthermore, in each processing step, the likelihood of each state must be calculated, which increases the required processing power. Finally, abnormalities according to the order of gait phases is detected by a six-dimensional vector processing algorithm, which obviously increases the required process as well.

To resolve the above issues, an efficient six-state FSM is proposed in this paper, which is the most complete model to-date, by using four FSR sensors under the shoe insole plus a gyroscope. The FSRs operate as an on-off switch to show whether or not they are pushed. On the other side, gyroscope measures the rotational velocity of the foot, with its sensing axis oriented perpendicular to the sagittal plane. The proposed design in this paper requires a small processing power and detects all six states by using an extra FSR sensor toward [3], which is located under the thumb. Moreover, as opposed to the previous works, this algorithm distinguishes the real walking from cases like shifting the weight between legs by utilizing the gyroscope. The new proposed FSM consist of six states with 18 possible transitions. The proposed six states are as follows:

- **Initial State**: heel strike with the ground.
- **Loading Response**: initial contact of forefoot with ground that results in loading a part of the body weight on the leg.
- **Mid Stance**: the phase with the maximum pressure on the leg, since the other foot is in the air.
- **Terminal Stance**: lifting the heel from the ground causing a rotation in the foot.
- **Pre-Swing**: the moment before starting the swing where there is a high pressure on the toe.
- **Swing**: moving the leg on the air.

The proposed FSM is represented in Fig. 4. H, M_1, M_2 and T refer to the four FSRs in the shoe insole, under the heel, first and fourth head of metatarsal bones and thumb, respectively. For instance, H denotes that there is a pressure on the heel sensor whereas ∼H means the lack of pressure on it. Q is the angle computed through the results measured by the gyroscope. Q_1 and Q_2 are thresholds used to make sure that the foot is lifted sufficiently for transitions to the heel-off and pre-swing steps, respectively, which are used to distinguish the cases like shifting the weight between legs. In addition, E_w and E_A are thresholds for the angular velocity and acceleration. If these values are small enough, it means that the leg is in a stable posture, which is used to detect the stance phase in the cases like stairs or ramps. Finally, gyroscope data needs to be reset occasionally to avoid the offset of errors in a long run. Therefore, before starting of mid-stance and terminal-stance phases, angle is initialized to zero.

To accommodate for abnormal walking habits of some patients, few extra transitions are devised while trying to make the FSM as

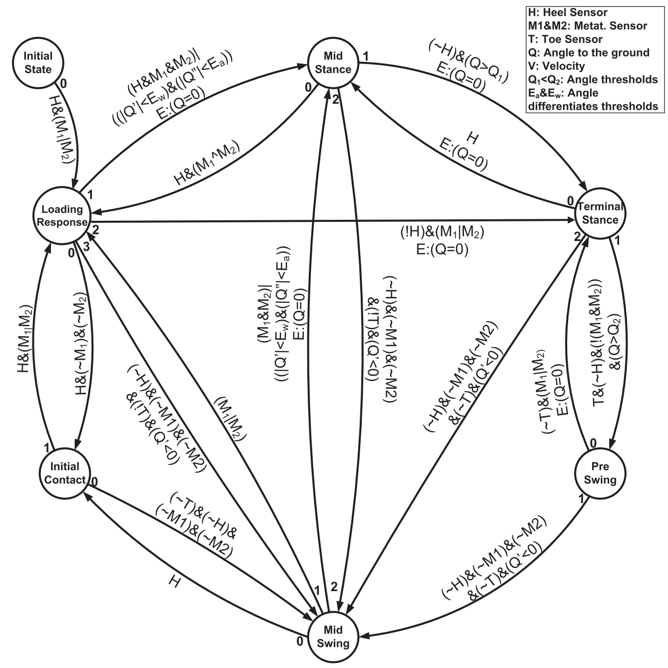

Fig. 4: The proposed 6-state FSM for gait analysis

simple as possible. Some of the transitions are intentionally removed as they cannot occur in practice. An example would be a transition from the initial contact to the terminal stance. Moreover, due to the high rate of sensing and calculation, some of the transitions could occur in two steps without any undesirable results. For instance, the transition from the initial contact to mid-stance, while skipping the loading response phase, occurs in the beginning of walking and it is not abnormal. As a result, the proposed efficient yet simple FSM requires less processing power, which allows higher rates of sensing and calculation. Furthermore, some patients may repeat an action due to a weakness in their foot muscles. To accommodate this, some backward transitions for each state are devised as well [3]. In addition, these transitions make the FSM moving back to the correct state in a negligible time, which minimizes the computation error.

Finally, transitions are prioritized due to the fact that some consecutive states may be skipped, which corresponds to abnormality in walking. This results in faster transitions with more precision corresponding to the possible actions in walking and detects the abnormalities without any further computing.

IV. Electrocardiogram Signal Processing

Electrocardiogram (ECG), indicating the electrical activity of the heart, is of vital importance in patient care and disease diagnosis. Reflecting abnormalities in the function of the heart, as the most crucial organ of the body, as well as revealing valuable information about patient's medical profile such as the RR increased the inclination towards processing of ECG signals.

The previous work proves the modulation of the ECG signal by the respirations [4]. Unfolding this information and producing ECG-Derived Respiration (EDR) signal can create a good approximation of respiration [4]. In [1] and [5] some algorithms have been developed to derive EDR. However, these algorithms suffer either from the low accuracy or high complexity, which makes them inappropriate for embedded hardware implementations.

In the proposed system in this paper, in addition to the determination of the HR, approximation of the number of patient's respiration has been derived by means of the ECG signal processing. To do so, some modifications to the algorithm have been proposed in this paper to make it executable for real-time embedded systems. A summary of each part is given in the following sections.

A. Heart Rate

The Pan and Tompkins R-wave detection algorithm is normally used to obtain the position of each QRS complex using the high amplitudes of R-points [6]. Based on the number of samples between two adjacent R points and the sampling frequency, the HR can be easily calculated.

B. Respiration Rate

The focus of the ECG signal processing part was to obtain an algorithm that not only satisfies the required accuracy for patient monitoring but also be simple enough to be implemented on hardware. Toward this goal, in this paper, effective modifications and simplifications on the typical algorithms, such as the one in [5], have been proposed in order to improve the efficiency of the algorithm and make it feasible for the hardware implementation.

The proposed algorithm consists of two main parts: 1. Removing baseline wander noise and finding the correct values of R-peaks, which are contaminated by baseline noise. This is because in the following steps of the algorithm the amplitudes of R-peaks will be used, so the removal of the baseline noise is crucial for the perfect estimation of R-peaks amplitudes. 2. Unfolding the influence of the respiration on clean samples of ECG in order to derive EDR.

In order to remove the baseline noise, a linear interpolation is proposed to be used between R-R midpoints. This interpolation while having acceptable accuracy for detecting the baseline noise, avoids sophisticated calculations of cubic splines used in other works such as the one in [5]. The other contribution, proposed here, is to use the differential amplitude of R-point with its adjacent S-point instead of the absolute amplitudes of R-peaks. This is because the rate of changes in baseline is much less than that of the QRS complex. Thus, it is rational to assume that the effect of baseline is the same for adjacent R and S points.

The effect of respiration on ECG can be modeled as an amplitude modulation. Thus, after removing the additional noise and baseline, the formulation of the n^{th} sample of the R-S differential amplitude can be written as $RS_n(t) = a_n(t) * rs$, where rs is the true value of R-S amplitude without considering the respiration effect and can be modeled as a constant. Based on this, a suitable approximation of $a_n(t)$, the amplitude modulation due to respiration, is:

$$a_n(t) \simeq \frac{RS_n(t)}{avg(RS_n(t))}. \quad (1)$$

Finally, EDR can be derived by a linear interpolation of $a_n(t)$, followed by a smoothing low-pass filter. This modification can further assist the aim of simplification with elimination of spline calculations. Figure 5 depicts block diagrams of both algorithms. The modified and proposed blocks in this paper are shaded.

V. Results

In order to verify the results of gait analysis, two tests were performed. First, a short period of walking was recorded with a slow-motion camera to verify the determination of states. In addition, to have a more qualitative analysis, the number of steps was counted and verified precisely. Each step is counted if the swing phase and one of the heel strike, loading response or mid-stance phases

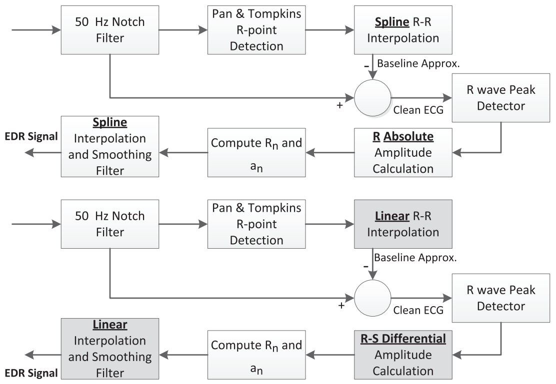

Fig. 5: The design of the algorithm in [5] (up) and the proposed algorithm in this paper (down) to obtain the EDR Signal from ECG.

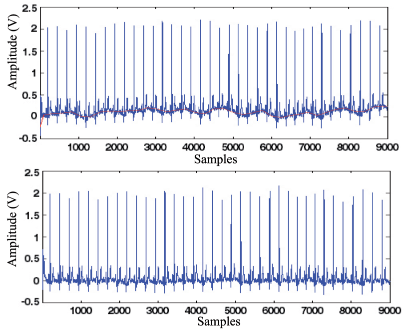

Fig. 6: Up: Input ECG Signal. Down: after baseline removal

occurred in order. By defining ”error” as the difference between real and calculated steps, during the course of testing, the accuracy of more than 99 percent was achieved. Furthermore, in resulting tests of unusual conditions like ramp or stairs, the accuracy is about 98 percent.

In addition, for evaluating the efficiency of the designed system for computing the HR, the design was verified by both databases of *QT Physionet Database* [7] and experimental samples of our mounted sensors. In both cases, the accuracy was proved to be higher than 99%. In order to assess the performance of the proposed algorithm for detecting the RR, the *Fantasia database of Physionet* [7], consisting of both ECG and actual respiration signals of patients was used. Figure 6 depicts the result of the first stage of the proposed algorithm to remove the baseline noise and shows the satisfying performance of the linear interpolation. The final result of the algorithm and computation of EDR, in comparison with the actual respiration signal, is illustrated in the Fig. 7. According to the aim of this system, total number of respirations per minute, i.e. peaks of EDR, in comparison with the actual RR determines the efficiency of the proposed algorithm. The total error of 3.47% was achieved for the presented algorithm. The flop counts and the elapsed time of the algorithm execution time, calculated for processing different samples of the ECG with duration of 2 minutes, show saving in the hardware realization as well as a higher processing speed. This justifies a minor increase in the total error rate (Table I).

Finally, the results of these three analyses are accumulated by the implemented network. In addition, the collected data is sent to an external resource for further monitoring and analyzing. A parameter proportional to person's speed is extracted by calculating

TABLE I: Features of the previous and the presented algorithms.

Algorithm	Avg. Flop Counts	Avg. Elapsed Time	Error Rate
presented in [5]	2.741e6	2.648 sec	1.75 (%)
presented in this work	2.290e6	2.112 sec	3.47(%)

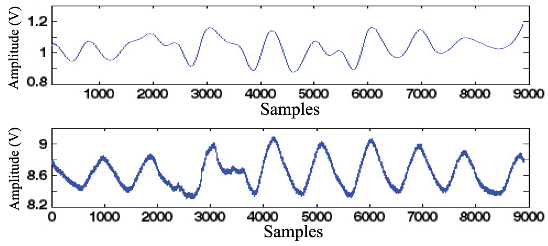

Fig. 7: EDR signal (up) in comparison with its actual respiration signal (bottom)

the frequency of changing the gait states. It is seen that by increase of speed or a sufficient period of walking, the heart and respirations rates are increased consequently.

VI. Conclusion

In this paper, a novel framework for BAN systems performing patient monitoring is proposed. Medical signals of heart rate, respiration rate and gait analysis were sampled, processed and collected in the central node of the network. The ability of simultaneous processing and analyzing different data of movement speed, heart and respiration rate is one of the main features of the proposed system, which makes it distinct from other works. In addition, the practical challenges were resolved in hardware, which have not been taken into consideration in previous works. In future, the proposed design will be implemented in shorter parts for practical purposes.

References

[1] K. Madhav, M. Raghuram, E. Krishna, K. Reddy, and K. Reddy, “Extraction of respiration rate from ECG and BP signals using order reduced-modified covariance AR technique,” in *Image and Sig. Proc. (CISP), 3rd Intern. Congress on*, vol. 9, pp. 4059–4063, IEEE, 2010.

[2] K. Kong and M. Tomizuka, “A gait monitoring system based on air pressure sensors embedded in a shoe,” *Mechatronics, IEEE/ASME Trans. on*, vol. 14, no. 3, pp. 358–370, 2009.

[3] I. Pappas, M. Popovic, T. Keller, V. Dietz, and M. Morari, “A reliable gait phase detection system,” *Neural Systems and Rehabilitation Engineering, IEEE Trans. on*, vol. 9, no. 2, pp. 113–125, 2001.

[4] H. Riekkinen and P. Rautaharju, “Body position, electrode level, and respiration effects on the frank lead electrocardiogram,” *Circulation*, vol. 53, no. 1, pp. 40–45, 1976.

[5] S. Arunachalam and L. Brown, “Real-time estimation of the ECG-derived respiration (EDR) signal using a new algorithm for baseline wander noise removal,” in *Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual Intern. Conference of the IEEE*, pp. 5681–5684, IEEE, 2009.

[6] J. Pan and W. Tompkins, “A real-time QRS detection algorithm,” *Biomedical Engineering, IEEE Trans. on*, no. 3, pp. 230–236, 1985.

[7] “Qt/fantasia physionet database.” avialable on http://www.physionet.org/physiobank/database.