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A Wireless Modular Multi-Modal Multi-Node Patch Platform for Robust Biosignal Monitoring

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***Abstract*—In this paper a wireless modular, multi-modal, multi-node patch platform is described. The platform comprises low-cost semi-disposable patch design aiming at unobtrusive ambulatory monitoring of multiple physiological parameters. Owing to its modular design it can be interfaced with various low-power RF communication and data storage technologies, while the data fusion of multi-modal and multi-node features facilitates measurement of several biosignals from multiple on-body locations for robust feature extraction. Preliminary results of the patch platform are presented which illustrate the capability to extract respiration rate from three different independent metrics, which combined together can give a more robust estimate of the actual respiratory rate.**

I. Introduction

THE United States spends more on health care than any other nation, resulting in health expenditure per capita that exceeded $8,086 in 2009 and more than 75% of the total expenditure in on the health care of people with chronic conditions. A total of 133 million Americans (almost half of adult population) suffer at least one chronic illness, resulting in approximately one-fourth of people with chronic conditions having some daily activity limitations [1, 2].

An example of the burden of chronic health care in the United States is cardiovascular disease, as it is the leading cause of death for men and women; in this condition, a major cause of the economical burden to the public health is recurrent hospitalization. It has been reported that non-pharmacological strategies, such as the improvement to health care access to the patient, improves survival and reduces hospitalization [3].

As a response to the unmet need to improve accessibility to health care access, other groups have devised wearable physiological monitors, mainly concentrated on cardio-vascular activity. In particular, these efforts are centered on the continuous monitoring of the electrocardiogram (ECG) through a single disposable "patch" affixed on the chest of the patient, which measures a pre-established lead of the ECG. The result of these initiatives is relatively expensive and limited in use-case scenarios.

It would, therefore, be beneficial to have a modular platform structure to measure a variety of different physiological and environmental parameters in a form factor that lowers the cost to the end user, and can be applied to various conditions beyond only cardiovascular diseases.

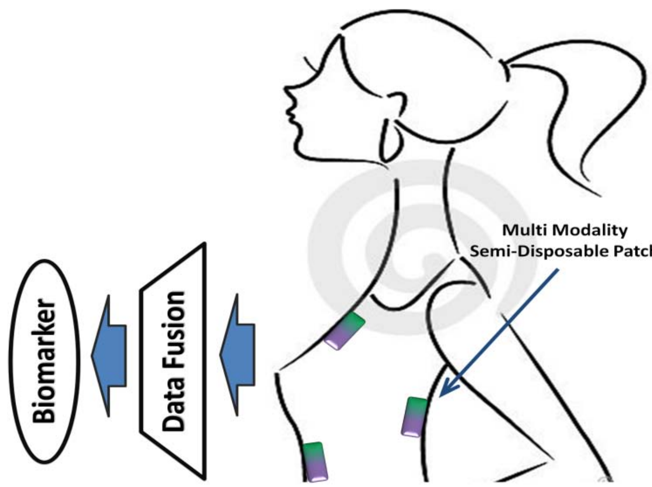

Fig. 1. Illustration of multi-modal, multi-node sensing in patch form factor for robust feature extraction.

In this paper we introduce a multi-node patch platform that is designed to address limitations of previous approaches using a modular low-cost semi-disposable design. In order to show the system versatility, we have selected to measure respiration rate, as this variable is a highly relevant parameter in many chronic conditions such as asthma, congestive heart failure and sleep apnea.

II. Hardware and Software Architecture

Fig.1 demonstrates the patch platform concepts. Each patch includes multiple sensing capabilities (e.g. ECG, accelerometer, reflective pulse-oximetry etc.) and packaged in reusable electronics on flexible substrate employing disposable electrodes. The patches are placed in the proper physical position for biosignal recording. Data fusion algorithm combines the wireless data on either a central node or an external mobile gateway device (e.g. a smartphone or tablet), to cooperatively extract desired biomarker (e.g. Respiration).

This semi-disposable, patch design could practically bring down the cost of home monitoring, while collaborative feature extraction increases the reliability of measured biomarkers in such an ambulatory setup. The rest of this section describes the hardware design of fabricated prototype patch including sensing, control, communication and gateway structure.

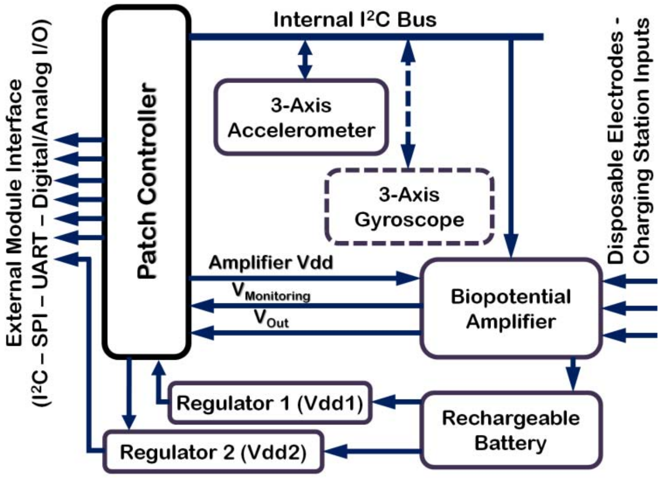

Fig. 2. Block diagram of the patch demonstrating various sensors and external connectivity. The input connector is shared between electrodes in on-body mode and charging leads in charging mode.

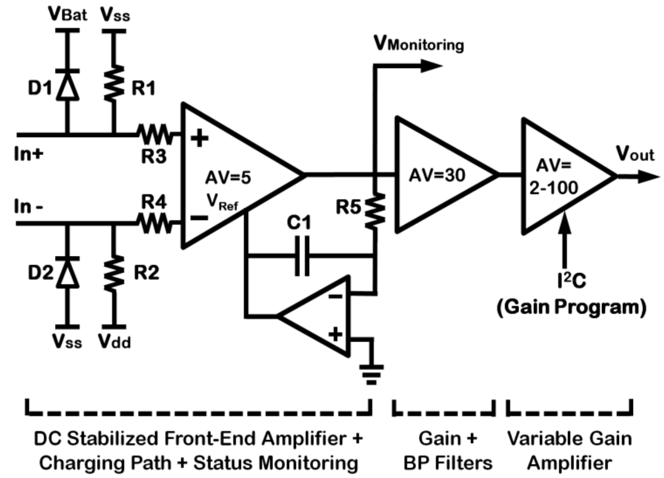

Fig. 3. Front end bio-electrical amplifier comprising gain programmability and operation mode detection.

A. System Architecture

Fig. 2 depicts the overall system diagram of patch hardware. A central microcontroller communicates with configurable biopotential amplifier as well as various sensors on-board using I^2C and embedded 10-bit successive approximation analog-digital convertor. The modular design comprises accommodation of external sensors, local data storage and various communication modules. A seven-pin connector provides flexible external peripheral connectivity. It includes a 3.3V regulated voltage, controlled by the patch, and five I/O pins that could be individually configured as general purpose digital or analog I/Os. The pins are also reprogrammable to form either I^2C, SPI or UART interfaces.

The system is powered from a 60mAh 3.7V Lithium Polymer battery regulated by a low-dropout, low-quiescent-current 3.3V voltage regulator. During the idle mode, the patch controller periodically wakes-up from the sleep and turns on the amplifier. As it is described later in section II.B, the amplifier automatically identifies the status of patch to be either on-body, on-charge or off-body and turns-on internal and external sensors, accordingly.

B. Sensor Interfaces and Charging Mechanism

The current version of the patch includes comprehensive motion detection hardware including a 3-axis MEMS accelerometer as well as a 3-axis gyroscope that is optionally assembled as needed for the use case. It also includes a low power, gain programmable amplifier that accommodates various biopotential signals (i.e. ECG, EMG and EEG).

Fig. 3 depicts the simplified amplifier circuit diagram. During normal operation of the circuit front-end low-leakage diodes (i.e. D_1, D_2) are reverse biased therefore they don't influence the functionality. In order to recharge the battery, charging station applies battery's nominal charging voltage plus twice of the diode forward voltage (i.e. $4.2V+2\times V_F$) to the inputs with a maximum current limited at 60mA. Therefore, diodes provide charging path.

R_3 and R_4 are introduced to limit the charging current dissipation through ESD protection circuitry of the input instrumentation amplifier within the acceptable range. $V_{Monitoring}$ is monitored by the controller to identify the operation status of the patch. In off-body and charging mode, it saturates around negative and positive rail accordingly. In on-body mode $V_{Monitoring}$ stays within close to the mid supply range (i.e. ground).

The patch has been designed and fabricated using a three-layer fully flexible polyimide circuit board. Fig. 4 demonstrates the fabricated device and its packaging.

C. Gateway and Wireless Communication

Following the modular design principle the patch can be equipped with different radio technologies depending on the requirements of the given application.

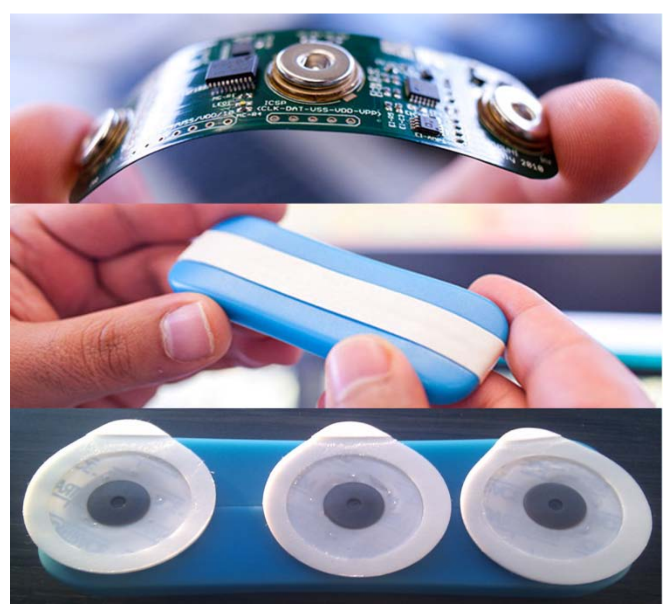

Fig. 4. Fabricated patch on a flexible PCB (Top), Flexible patch package (Middle) and disposable electrodes mounted on the patch (Bottom). Circuit components and snap connector for electors are placed in front. Battery and external module (e.g. radio) are in the back.

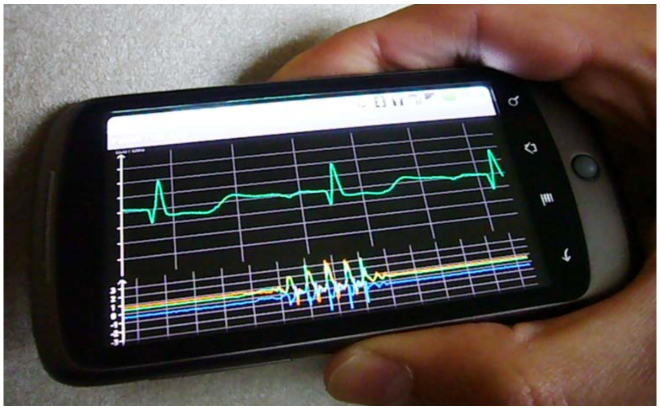

Fig. 5. Real-time ECG and 3-axis accelerometer data visualized on an Android-enabled phone.

We have evaluated and fully implemented the operation of the patch with Bluetooth and ANT radio technologies, while we are also in the process of embedding the interface to Zigbee and Bluetooth Low Energy (BLE) radios. Bluetooth has the major advantage of offering high burst data rates and being ubiquitous in consumer electronic devices such as smart-phones and tablet computers. The downside of using Bluetooth radio is high power consumption of the transceiver which in turn limits the operational lifetime of the patch and the fact that the only supported network topology is a Star Network without support for multicast, which makes data synchronization from multiple patches a real challenge. Fig. 5 shows ECG and 3-axis accelerometer data collected from one patch and visualized in real-time on the Android enabled Nexus One.

To address the limitations of standard Bluetooth radio we have also fully implemented ANT radio connectivity on the Patch. ANT has the following competitive advantages over Bluetooth 1) significantly lower transceiver power consumption [4], 2) smaller software stack, 3) support of complex network topologies and 4) multi-node synchronization with a beacon-like mechanism. The downside is that although ANT can be found in several sport and wellness devices such as Garmin chest belts, it is not widely available in mobile devices and phones. However, an ANT Android Application Programming Interface (API) was recently released [5] which makes the ANT radio found on some Android enabled phones available to developers. For our tests with ANT-enabled patches we have utilized the Sony Ericsson Xperia X8, which includes ANT radio.

III. Measuring Respiration

A. Concept

As mentioned in the introduction, respiration monitoring is a key element in the management of several chronic diseases, such as CHF, Asthma and COPD. Respiration effort can be measured using a variety of methods such as inductive [6] or impedance plethysmography [4], chest-wall or abdomen movement quantification using piezoresistive or capacitive sensor bands [7] or it can even be indirectly extracted from other biosignals such as the ECG [8] and the photoplethysmogram (PPG) [9]. In this paper we investigate the feasibility of determining a robust measure of the respiration rate by looking at more than breathing measures. The selected measures are modulation of R-peak amplitude of the ECG, modulation of R-to-R interval of the ECG, and chest wall and abdomen movement quantified with accelerometers.

B. Experimental Setup

We performed a 18-min experiment with a male volunteer whereby he had 3 patches placed on his body, one over the heart on the chest, one horizontally placed on the abdomen and one more on the same level as the second one only placed on the side of the individual. The user performed various activities during the given time interval, which were: sitting, standing, walking slowly, standing and rotating left and right, walking fast and lying down on his back. The patch on the chest recorded ECG in lead II configuration and 3-axial acceleration and the other two patches captured only the acceleration signals. During the whole test the user was holding an Android enabled phone and was asked to press a button on a custom App at the end of each of his inhalation cycles. These instances were time stamped and were used to evaluate the extracted respiration metrics.

C. Signal Processing and Results

We extracted 3 individual respiration metrics: First, from the modulation of the R peak amplitude and, second, from the modulation of the RR interval of the ECG and third from the frontal plane acceleration signal of the patch placed on the user's abdomen. The first step in extracting signals from ECG (i.e. first and second method) was to detect the R peaks in the recorded signal. The task was performed using the well-known Hamilton-Tomkins algorithm [10]. After determining the locations of the R peaks we create the RR interval and the R-peak amplitude signals. Since these two time series contain a small number of samples, they do not lend themselves well to further signal processing, so to increase their comprehensibility we cubic-spline interpolated them. Then we subsampled the signals to 20 Hz and we applied a band-pass filter to limit the frequency content in the approximate range of the respiration bandwidth (e.g. 0.1-0.8Hz or equivalently 6-48 breaths/min). On these resulting waveforms we applied a peak detection algorithm to estimate the time instances of each breath.

Extracting a respiration indicator from accelerometer recordings is a challenge since in case the user is moving the much-lower-amplitude respiration component from the movement of the thorax or the abdomen gets buried in the body motion noise. Having this challenge in mind we investigated the use of three different locations for extracting a respiration metric from accelerometer signals. Our test shows that for our test conditions abdomen provides the best monitoring location for calculating an estimation of respiratory rate from on-body accelerometers.

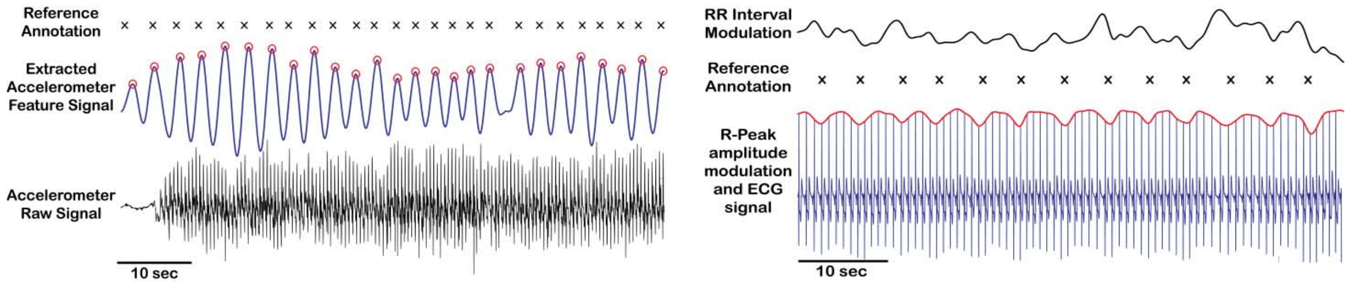

Fig. 6. Respiration rate extraction using accelerometer (left) and ECG signal with two different techniques (right).

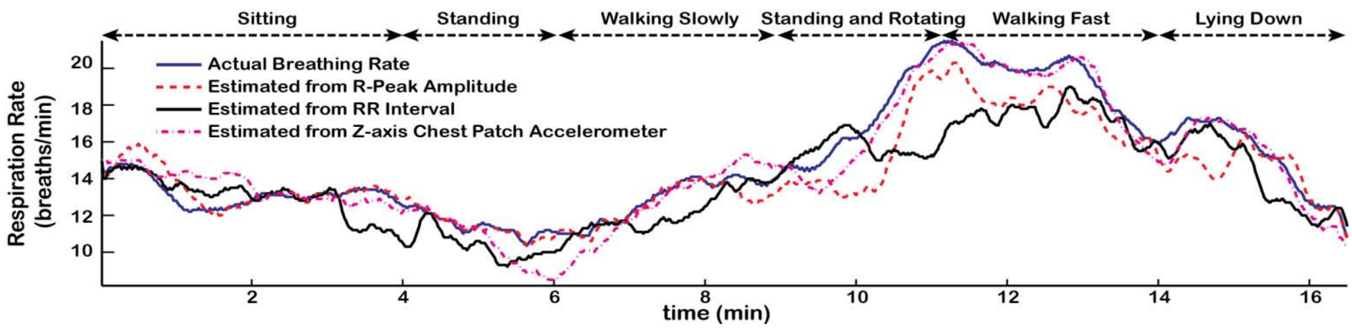

Fig. 7. Actual respiration rate and estimated respiration rate from the three different metrics described in Fig. 6.

In order to isolate the respiratory component present in the accelerometer signal recorded on the abdomen we utilized a stationary biorthogonal wavelet transform using the “bior4.4” MATLAB wavelet. Using this transform we were able to isolate a breathing component (detail signal in the 7^{th} detail scale corresponding to the 0.1-0.5Hz frequency band) that is strongly correlated with the manually recorded respiration annotations. This proved to be a robust metric even during the fast walking period of the user.

The performance of the 3 extracted breathing rate metrics is shown in Fig. 7, where we can see the R peak amplitude modulation and the accelerometer derived signal follow really well the variations of the actual respiration rate. To be more specific the R peak amplitude derived signal had a 0.94 correlation with the actual respiration annotations, whereas the same number was 0.89 for the RR derived one and 0.99 for the accelerometer-derived metric.

IV. Conclusion

In this paper we presented in detail a new multi-modal multi-node scalable patch platform for robust and unobtrusive measurement of a variety of biosignals. We presented initial results using this new technology for measuring respiration rate using a combination of different breathing metrics extracted from the ECG and accelerometers. The current version of the patch is in the process of undertaking feasibility trials in suitable clinical settings. Additional sensing modalities are also being integrated with the current design to combining these multiple metrics together using a signal quality index for each instance in order to derive a more robust final estimation of the user’s respiratory rate.

The described patch platform system is a patent pending engineering prototype. It is an investigational device and is not available for commercial distribution or professional use.

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