

Demonstration of A Novel Wireless Three-pad ECG System for Generating Conventional 12-lead Signals *

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ABSTRACT

Wireless monitoring of a patient's electrocardiogram (ECG) is a typical application in mobile healthcare area. Inspired by application of linear transformations to ECG signals obtained in a vectorcardiographic system, we propose the wireless three-pad ECG system (W3ECG). Signals obtained from these three pads, plus their placement information, make it possible to synthesize conventional 12-lead ECG signals. W3ECG's system-level design, pad placements and evaluations are presented in a separate paper. This paper details W3ECG's pad design, software implementation, and experimental studies.

Categories and Subject Descriptors

H.4 [Information Systems Applications]: Miscellaneous

1. INTRODUCTION

Wireless monitoring of a patient's electrocardiogram (ECG) is a typical application in mobile healthcare area [2]. In order to make ambulatory ECG systems portable, easy to setup, comfortable to patients and tolerant of artifacts, endeavours have been made to develop wireless single-pad ECG systems [3][6]. A pad is a self-contained board, which has a front-end amplification circuit and two/three electrodes attached. It is also equipped with a radio to enable wireless transmissions of registered ECG signal to a gateway/server nearby. However, as ECG signal is dependent on placement position of electrodes, using such a single-pad approach, it is impossible to render caregivers conventional 12-lead ECG waveforms, which they have been trained to read [5].

Inspired by application of linear transformations to ECG signals obtained in a vectorcardiographic system [8], we propose the wireless three-pad ECG system (W3ECG) [3]. Two

more pads than the single-pad approach are introduced to the system to register electronic heart activities from distinct aspects. Signals obtained from these three pads, plus their placement information, make it possible to synthesize conventional 12-lead ECG signals.

System-level design, pad placements and evaluations of W3ECG are presented in [3]. This short paper details the pad design, software implementation, and experimental studies of W3ECG, each of which is discussed in a following section.

2. W3ECG PAD DESIGN

2.1 ECG Front-end Circuit

Texas Instruments' instrumentation amplifier INA333 and operational amplifier OPA333 are chosen for our ECG front-end circuit [10]. INA333 is reported to be the industry's lowest power zero-drift instrumentation amplifier. It operates with a 1.8V power supply, a 75uA quiescent current, and a 25uV offset voltage. OPA333 features a power supply of 1.8V and very low offset voltage of 10uV. Together they make it possible to use a coin cell (e.g., CR2032) as the power supply.

Figure 1 is a snapshot of our front-end prototypes. The four items in Figure 1, from left to right, are the circuit's front side, back side, back side with mount buttons, and back side mounted with electrodes, respectively. The upper and lower electrodes are two input electrodes which take in potentials; the middle one is an output electrode, which feeds back AC noise and helps set the body at the appropriate potential. Disposable electrodes are used, which can be easily mounted and unmounted through snap buttons.

2.2 Interface with TelosB

The front-end circuit board is interfaced with an off-the-shelf radio platform, TelosB [9], to enable wireless uploading of registered ECG signal. Figure 2 shows a front and side views of the combined "pad". Since the distance between two input electrodes (refer to the next sub-section) is close to the TelosB's length, our front-end prototype has been made in the same size as a TelosB.

The coin cell battery that is installed on the front-end circuit supplies power to the TelosB directly. The front-end circuit is in turn supplied by filtered DC voltage from the TelosB. Amplified ECG signal is fed to an analog-to-digital converter (ADC) port on the TelosB.

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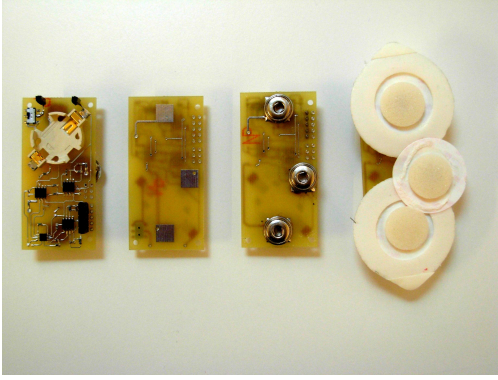


Figure 1: A snapshot of ECG front-end prototypes.

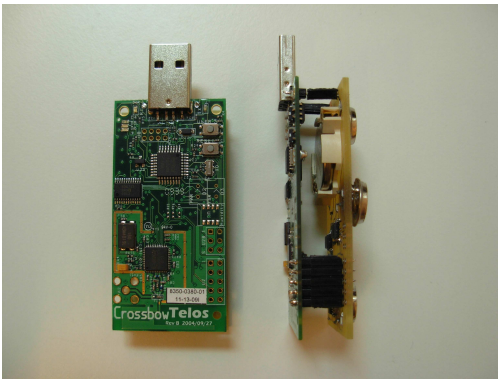


Figure 2: The front-end circuit interfaced with TelosB.

2.3 Standardization of Distance between Two Input Electrodes

Pad placements in W3ECG is based on the Dalhousie’s torso model [1][3], in which from neck to waist, numbered transverse levels are 1 inch apart, and positions around transverse sections are supposed to be equiangularly divided. Since the average waistline of an adult is from 37 to 39.7 inches [4], an estimate of the distance between two adjacent nodes in the transverse plane is from 1.15 to 1.24 inches.

On one hand, the smaller a W3ECG pad is (equivalently smaller distance between two input electrodes), the more comfort it offers; on the other hand, the farther away the two input electrodes are, the larger signal-to-noise ratio the pad obtains. The distance has been determined to be two inches, as a good design trade-off that complies with Dalhousie’s torso model, and achieves a good signal-to-noise ratio.

3. SOFTWARE PACKAGE

W3ECG’s software consists of three parts, which are all based on the TinyOS software platform [11]. Two of the three are nesC codes for manipulating the TelosB (TelosB interfaced with the front-end circuit, and TelosB acting as a gateway), and the other one is Java code running in a server.

3.1 Sampling and Radio Communications on A Pad

The nesC codes for manipulating pads and the gateway are based on an existing implementation of the IEEE 802.15.4 beacon-enabled mode in TinyOS [7].

3.1.1 ADC Configurations

The ADC equipped with MSP430F1611 chip on TelosB provides a 12-bit resolution, and can be configured in four different modes. The single-channel-repeat mode is chosen because only one channel will be continuously used on each pad. The ACLK clock is sourced to ADC to provide a more accurate sampling frequency than SMCLK. The sampling frequency is set to 256 Hz. All the configurations are done through TinyOS interface `Msp430Adc12SingleChannel` of component `Msp430Adc12ClientAutoRVGC()`. An event `SingleChannel.multipleDataReady()` is triggered whenever there are 16 (which is the current maximum allowable value) ADC samples available.

3.1.2 Data Buffer Design

A data buffer is created to temporarily store ECG samples before transmission. It is separated from the payload buffer of a TinyOS packet. In other words, ECG samples are firstly moved from this data buffer to the payload buffer, and then forwarded to the radio.

Cyclic array has been chosen as the data structure for the data buffer, and two pointers (write and read) are assigned to provide synchronized access to the buffer. The synchronization is achieved by using the *atomic* keyword for operations involving the two pointers. Each time the event for new ADC samples is triggered, samples are written to the buffer with the write pointer as the offset. As the event is triggered for every 16 samples, the offset specified by either the write or the read pointer is a multiple of 16.

3.2 Beacon-frame Generation and Data Forwarding on The Gateway

The gateway, known as the PAN coordinator in an IEEE 802.15.4 network, generates a beacon-frame at the beginning of every superframe, and accepts association from each pad (end device in IEEE 802.15.4). We added an implementation to enable serial communications of commands between the gateway and server. Whenever the gateway acknowledges association, a message is created to notify the server of this decision and the corresponding pad ID.

We also implemented the functionality to instruct all pads to synchronize their sampling processes, by adding specific beacon-frame payloads. This is triggered by a command from the server end through a serial connection. Everytime the gateway sends a beacon-frame, it checks whether there is a need to indicate in the payload to start or synchronize the sampling processes on the pads. If so, it sets the corresponding fields and transmits the beacon-frame. As soon as it is done, these fields are reset.

ECG data packets’ payloads from each pad are wrapped in TinyOS frames at the gateway, and forwarded to the server over the serial link. No processing on the data is done at the gateway. When wrapping up the payload data, the length, AM type fields in the serial TinyOS frame are set. The AM Type is used to differentiate this packet from the above one for the notification of association.

3.3 Graphical User Interface and Database on The Server

The server runs a graphical user interface (GUI) based on the TinyOS Oscilloscope implementation. We polished the GUI to display three ECG waveforms in separate graphs as shown in Figure 3, and added tabs to enable switching between 12-lead waveforms.

When the server has been notified by associations from all three pads, it pops up a window and asks if the user wishes to start the system. The system can also be started by clicking the "Start" button, in case the user decides to deploy less than three pads.

The GUI displays a limited duration of ECG waveforms, but stores all samples in a MySQL database. The database currently contains three tables, each of which registers data from one pad. Sampling time and value are registered in each table.

4. EXPERIMENTAL STUDIES

According to suggested pad placements in [3], three pads can be deployed at the positions as shown in Figure 4. Placement positions of electrodes for RA, LA and LL are also included as references.

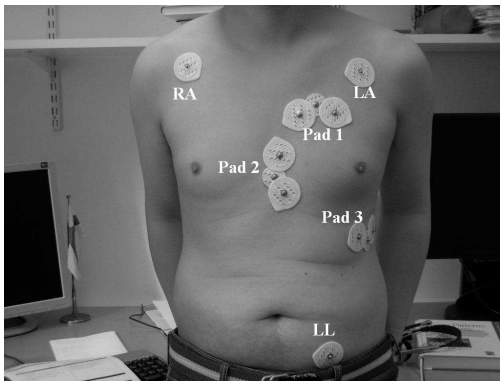


Figure 4: Placement positions of electrodes for RA, LA and LL, and three sets of electrodes for W3ECG system.

Based on the above W3ECG deployment, synthesized 12-lead ECG waveforms are compared to directly observed 12-lead waveforms, one lead at a time. An additional pad is used to directly register waveform of one of the 12 leads, and compared to the synthesized waveform (synthesized from signals obtained on three W3ECG pads) of the same lead. This setup facilitates time synchronization between the two versions of ECG waveforms, and also enables cross-correlation analysis. However, wires which is subject to AC interference, are used to connect electrodes placed on the torso according to conventional 12-lead placements.

Figures 5 to 8 show the waveforms of the two versions for Lead I, Lead aVR, Lead V1 and Lead V4 as examples. Cross-correlation coefficients of the conventional 12 leads can be found in [3].

5. ACKNOWLEDGMENTS

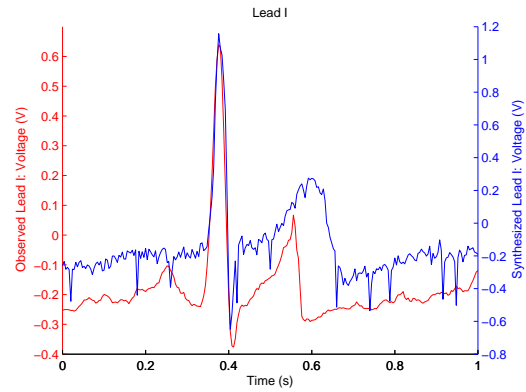


Figure 5: Comparison between observed and synthesized Lead I signals.

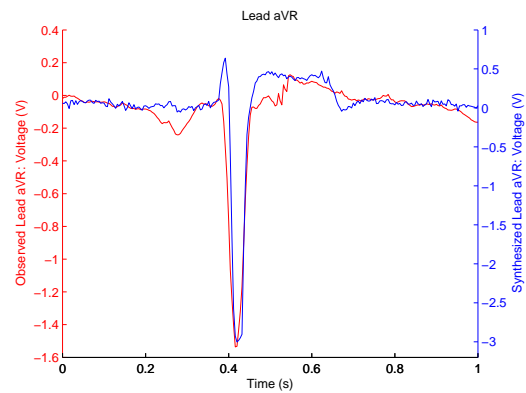


Figure 6: Comparison between observed and synthesized Lead aVR signals.

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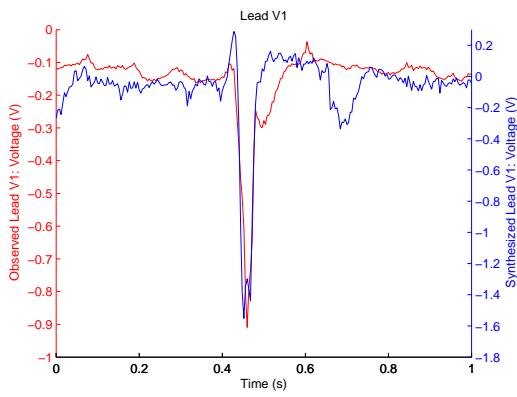


Figure 7: Comparison between observed and synthesized Lead V1 signals.

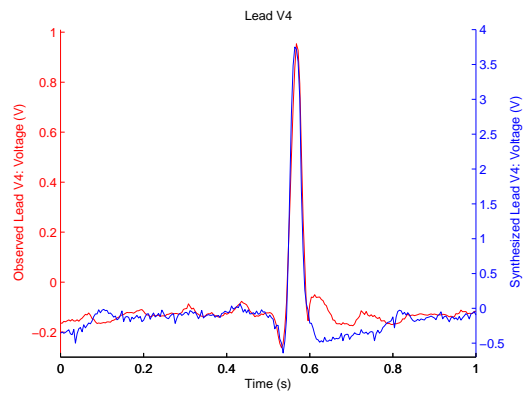


Figure 8: Comparison between observed and synthesized Lead V4 signals.

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Figure 3: A snapshot of W3ECG server GUI (Red, white and green traces represent synchronized ECG waveforms from Pad 1, Pad 2 and Pad 3, respectively).