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Wireless Vectorcardiogram System Optimization using Adaptive Signal Processing

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***Abstract*—We are designing an integrated wireless Vectorcardiogram (*i*VCG) that is of diagnostic quality, extremely small form factor, and is placed on the chest of the patient. In this paper, we consider the problem of transforming the three VCG component signals to the familiar 12-lead ECG for the convenience of cardiologists. We used an adaptive signal processing technique to obtain an ECG signal from the VCG measurements. The least mean-square (LMS) adaptive algorithm is employed to obtain the optimum 12x3 transformation matrix by minimizing the overall mean-square-error between the reference ECG (that is present during VCG configuration) signal and the ECG signal derived from the VCG. With this capability, the *i*VCG may become a truly transformative wireless medical device enabling continuous cardiac diagnosis.**

***Index Terms* — Vectorcardiogram (VCG); ECG; wireless medical device; Adaptive Filtering; LMS algorithm;**

I. Introduction

Cardiac Rhythm Monitoring (CRM) is the field of cardiovascular disease therapy that relates to the detection of abnormally fast and abnormally slow heart rhythms. The vectorcardiogram (VCG) is an example of a CRM [1]. In recent work by the authors [2], the VCG concept was extended to enable real-time monitoring of the heart with the use of an integrated VCG device, dubbed the *i*VCG, with a small form factor that can be worn on the body for long periods of time. This wireless *i*VCG uses 3 orthogonal leads to provide comprehensive cardiac information that is equivalent in information content to the 12-lead ECG, albeit in a different format. At the receiver the *i*VCG signals are transformed into a 12-lead ECG signal by a 12x3 matrix and either analyzed or transmitted to the physician/hospital for further scrutiny. The *i*VCG system may also communicate with a pacemaker.

In this paper, we address the problem of transforming noisy, attenuated and degraded *i*VCG signals to the 12-lead ECG using an adaptive signal processing algorithm. In section II, we present a brief description of cardiac rhythm monitoring and summarize the recent work of the authors on the *i*VCG. In section III, we discuss the VCG to ECG matrix transformation problem. We present some preliminary results using the Least-Mean-Square (LMS) adaptive algorithm to find the optimal transformation matrix in section IV. Finally, in section V, we present the conclusions and future direction.

II. Background

A. Cardiac Monitoring: 12- Lead ECG and VCG

The contraction and expansion of the heart is caused by an electrical excitation in the heart muscle resulting in the formation of an electromotive field within the heart, dubbed the heart vector (HV). An electric field is created in the rest of the body and the signal that is read from a point on the skin surface, which is called *lead*, is the magnitude of this resultant electric field at that point on the body [3]. The familiar 12-lead ECG is the 'gold standard' in the medical industry. The ECG consists of 12 signals or leads read from 10 electrodes placed at different positions on the human body. The 12 leads are named I, II, III, aVR, aVL, aVF, V_1, V_2, V_3, V_4, V_5, and V_6. In this paper, we will denote these signals as e_1 to e_{12}, respectively. Of course, these signals are functions of time.

B. The iVCG System [2]

The system contains three pairs of leads: the X, Y and Z leads. The electrodes that acquire the X and Y leads are integrated into a small wearable device. This is located on the chest area. One of the Z leads is attached on the back of the

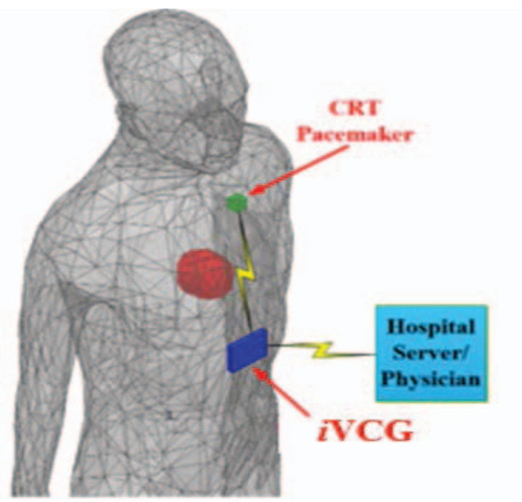

Fig. 1. Integrated Vector Cardiogram System (*i*VCG).

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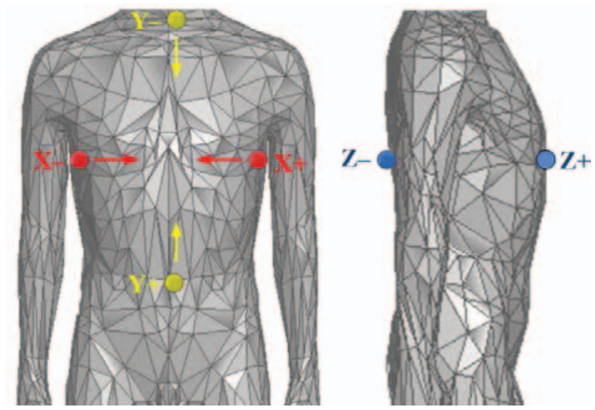

Fig. 2. Positions for the X, Y and Z leads of the *i*VCG system.

patient and connected via a wire to the *i*VCG. The *i*VCG system is being designed with a form factor that is small enough to be unobtrusive to daily patient activity, as shown in Figs. 1 and 2. Due to this form factor constraint, a greatly reduced inter-lead distance (from the classic ECG) is required. Preliminary experiments indicated that even with distances of 1.7 cm in the X-axis, and 1.9 cm in the Y-axis, the VCG signals on the leads were still deemed of diagnostic quality by physicians. The signals on the X, Y and Z leads after passing them through a 60Hz notch filter to remove inherent 60Hz power-line noise and a low pass filter to remove high frequency noise are shown in Fig. 3.

III. Transformation of VCG to 12-Lead ECG

It has been shown that there is a linear transformation from the 3-component VCG signal to the 12-component ECG signal [1]. Cardiologists prefer to study the 12-lead ECG signal derived from the VCG signal. The objective of this paper is to demonstrate an effective means of determining the 12x3 matrix that characterizes this transformation for each person. In practice, the *i*VCG device will be fitted on the patient along with a 12-lead ECG at configuration. Our approach is to use

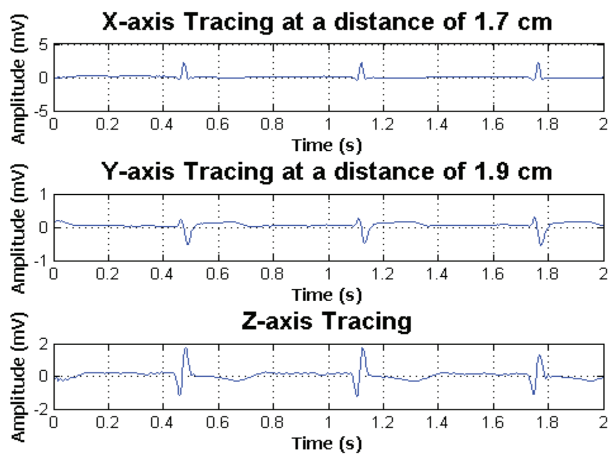

Fig. 3. X,Y, and Z signals of the *i*VCG system.

the VCG to derive an ECG signal, called ECG', and determine the matrix coefficients that minimize the difference, or errors, between the derived ECG signals and the reference ECG signals. As we show below, we use the LMS algorithm to minimize the mean square error (MSE) and adaptively derive the optimum 12x3 transformation matrix.

IV. Results

A. Notation

We represent the coefficients to transform the VCG signal vector **v** to a 12-lead derived ECG signal $\hat{\mathbf{e}}$ by the matrix relationship

$$T\mathbf{v}=\hat{\mathbf{e}} \quad (1)$$

where **v** is the vector of the x, y, and z components of the VCG signal, $\hat{e}$ is the 12-component derived ECG signal and T is the 12x3 transformation matrix. Observe that we are suppressing the time dependency of the signals. The transposed matrix T' can be written as,

$$T'=[\mathbf{a}_1' \; \mathbf{a}_2' \; \mathbf{a}_3' \; \mathbf{a}_4' \; \mathbf{a}_5' \; \mathbf{a}_6' \; \mathbf{a}_7' \; \mathbf{a}_8' \; \mathbf{a}_9' \; \mathbf{a}_{10}' \; \mathbf{a}_{11}' \; \mathbf{a}_{12}'] \quad (2)$$

where $\mathbf{a}_i'$ denotes the transpose of the 3x1 vector $\mathbf{a}_i$. Note that the i^{th} component of $\hat{\mathbf{e}}$ can be written compactly as

$$\hat{e}_i = \mathbf{a}_i'\mathbf{v} \quad i=1,2,\ldots, 12 \quad (3)$$

so that the i^{th} component of the derived ECG signal is given by the dot product (3) and only depends on the vector $\mathbf{a}_i$.

As noted earlier we will use the mean-square error [MSE] between the reference ECG signal vector **e** and filter output $\hat{\mathbf{e}}$ to derive the optimum transformation matrix. Since the i^{th} output $\hat{e}_i$ only depends on the $\mathbf{a}_i$ vector, we can separately minimize the 12 components of the MSE

$$E[\varepsilon_i^2]=E[(\hat{e}_i-e_i)^2], \quad i=1,2,\ldots,12 \quad (4)$$

where E denotes the average or expected value. The adaptive algorithm modifies $\mathbf{a}_i$ in order to minimize the MSE. The MSE can be given by,

$$MSE_i = E[(\varepsilon_i)^2] \quad (5)$$

$$= E[(e_i-\hat{e}_i)^2] \quad (6)$$

$$= E[(e_i^2-2\, e_i\hat{e}_i+\hat{e}_i^2] \quad (7)$$

$$= E[(e_i^2-2.e_i.\mathbf{a}_i'\mathbf{v}+(\mathbf{a}_i'\mathbf{v})^2] \quad (8)$$

The MSE becomes

$$MSE = \mathbf{a}_i'2R.\mathbf{a}_i-2.\mathbf{a}_i'\mathbf{p}_i+E(e_i^2) \quad (9)$$

where $E(e_i^2)$ is the mean-square value of the i^{th} 12-lead ECG signal, $E(e_i.\mathbf{v})$ is the cross correlation vector of the ECG signal and the input vector **v** and can be called $\mathbf{p}_i$ for the i^{th} ECG lead and $E(\mathbf{v}.\mathbf{v}')$ is the VCG signal correlation matrix and is called R.

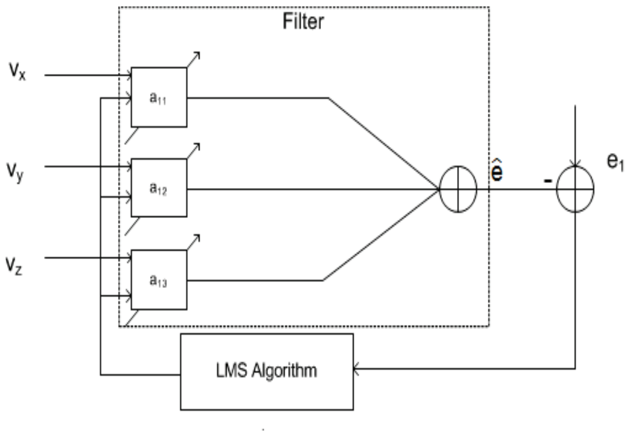

Fig. 5. Block Diagram of LMS algorithm used to determine the VCG Transformation Matrix

The gradient vector g_{a_i} of the MSE function is

$$g_{a_i} = \frac{\partial(\mathrm{MSE}_i)}{\partial \mathbf{a}_i} = -2.\mathbf{p_i} + 2\mathrm{R}.\mathbf{a}_i \qquad (10)$$

and for the minimum value of the MSE the gradient vector is set to 0 and the optimum value of the i^{th} row of the T is

$$[\mathbf{a}_i]_{opt} = \mathrm{R}^{-1}\mathbf{p_i} \qquad (11)$$

This approach, while giving the optimum value, requires knowledge of R and **p**. Below we show how to adaptively compute the optimum transformation in an iterative and adaptive manner using the Least Mean Square (LMS) algorithm that does not require knowledge of these quantities.

B. Data Acquisition

As noted above, we can compute the i^{th} row of the matrix by focusing on the i^{th} error signal. The LMS algorithm was used to compute coefficients to minimize the mean squared error between the i^{th} derived ECG signal and the corresponding reference signal. The ECG and VCG signals were recorded with a sampling rate of 500 Hz. The inter-lead distance in the X-axis was 6.5 cm and 5.5 cm in the Y-axis for this paper. A total of 22,000 samples (i.e. 44 seconds) were recorded. The 60 Hz power-line and high frequency noise was removed from the signals by filtering, and the LMS algorithm was implemented in MATLAB.

C. Adaptive Filtering via the Least Mean-Square Algorithm

The gradient vector can also be expressed as

$$g_{a_i} = \frac{\partial(E(\varepsilon_i)^2)}{\partial \mathbf{a}_i} = E(2\varepsilon_i \frac{\partial(\varepsilon_i)}{\partial \mathbf{a}_i}) = E(2\varepsilon_i.\mathbf{v}) \qquad (12)$$

The LMS algorithm uses the instantaneous values of (12) to find the optimal coefficients, and is given by

$$\mathbf{a}_i(k+1) = \mathbf{a}_i(k) + \mu\varepsilon_i(k)\mathbf{v}(k)\ ,\ k=1,2,\ldots \qquad (13)$$

where μ is the step size and k is the time sample number of the signal. Fig. 4 shows the block diagram of the LMS algorithm for lead I (e_1) and Fig. 5 shows the close agreement between

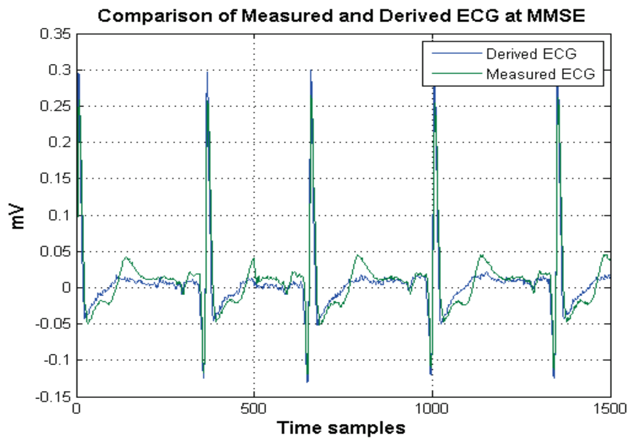

Fig. 4. Comparison of the refernce and derived signals for lead I.

the derived and reference signals. The overall, or cumulative, MMSE (CMMSE) for all the leads is given by,

$$\mathrm{CMMSE} = \sum_{i=1}^{12} w_i \,.\, \mathrm{MMSE}_i \quad , \qquad (14)$$

where w_i is a weighting factor. Future experiments will determine how the MMSE of different 12-lead ECG leads may be weighted to achieve a more accurate transformation matrix, as well as the variation of the optimum matrix between individuals.

V. Conclusion

The transformation matrix that determines the relationship between the signal components on the X, Y and Z leads of the *i*VCG and a reference 12-lead ECG was accurately determined using the LMS algorithm. With this capability, the *i*VCG may become a truly transformative wireless medical device enabling continuous cardiac diagnosis.

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