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Wireless *iVCG* Optimization Using A Least-Squares Fit

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***Abstract*— We are designing an integrated wireless Vectorcardiogram (*iVCG*) that is portable and placed on the chest of the patient and is capable of recording and transmitting cardiac rhythm signals. We present a solution to the problem of transforming the three VCG component signals to the familiar 12-lead ECG for the convenience of cardiologists. The least squares (LS) method is employed on the VCG signals and the reference (training) orthogonal ECG subset (leads I, aVF and V2) to obtain a 3x3 transformation matrix to generate the real-time ECG signals from the VCG signals. In future, we will apply this method to obtain all 12 leads of the 12-lead ECG. With this capability, the *iVCG* may become a truly transformative wireless medical device enabling continuous (24x7) cardiac diagnosis.**

***Index Terms* — Cardiac Rhythm Monitoring (CRM), Vectorcardiogram (VCG); ECG; wireless medical device; adaptive filtering; least-squares method;**

I. Introduction

Cardiac Rhythm Monitoring (CRM) is the field of cardiovascular disease therapy that relates to the detection of abnormally fast and slow heart rhythms. The vectorcardiogram (VCG), which was invented in 1931, [1] is an example of a CRM device. In recent work by the authors [2][3], the VCG concept was extended to enable real-time monitoring of the heart with the use of an integrated VCG (*iVCG*) device with a small form factor that can be worn on the body for long periods of time. This wireless VCG signal contains 3 orthogonal components that provide comprehensive, diagnostic-quality cardiac information that is equivalent in information content to the 12-lead ECG, albeit in a different format. At the receiver the VCG signals are transformed into a 12-lead ECG signal by a 3x12 matrix and either analyzed or transmitted to the physician/hospital for further scrutiny. The VCG system may also communicate with a pacemaker.

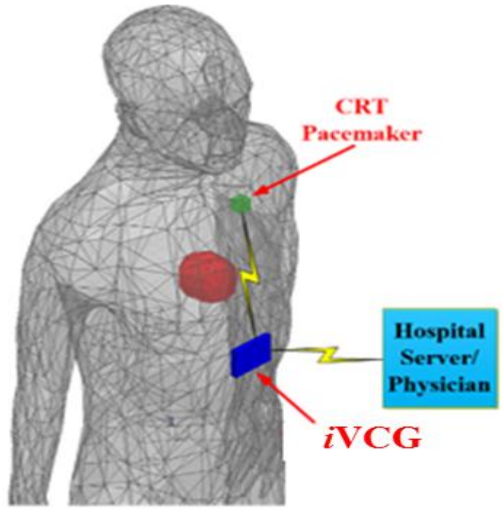

Fig. 1. Integrated Vector Cardiogram System (*iVCG*).

In this paper, we present a solution to the problem of transforming noisy and attenuated VCG signals to the 12-lead ECG. In section II, we present a brief description of cardiac rhythm monitoring, summarize the recent work of the authors on the *iVCG* and discuss recent efforts to transform the VCG signals to a 12-lead ECG. In section III, we present results using the least-square (LS) method to find the preliminary 3x3 transformation matrix that transforms the 3 component VCG to a subset of the 12-lead ECG namely lead I, aVF and V2. Finally, in section IV, we present conclusions and future directions.

II. Background

A. Cardiac Monitoring

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

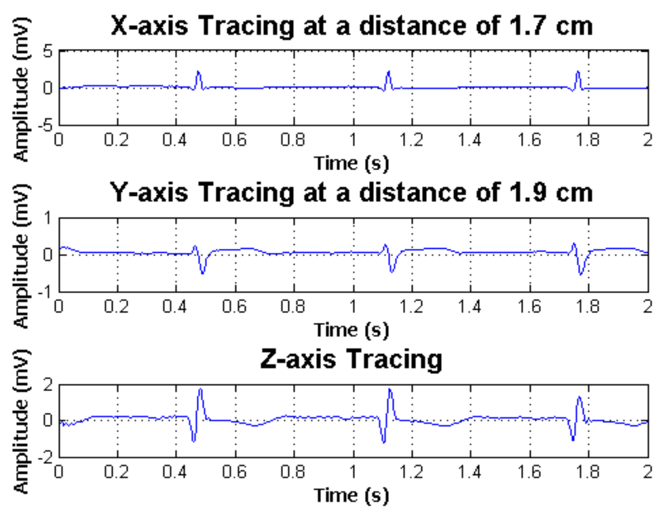

Fig. 2. X,Y, and Z signals of the *iVCG* system.

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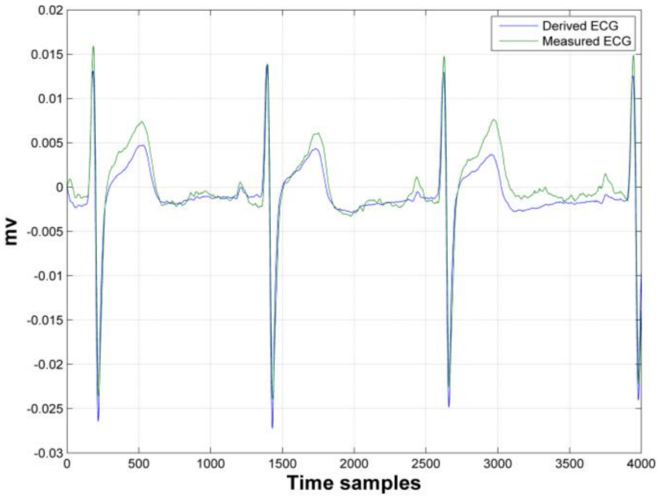

Fig. 5. Comparison of the refernce and derived signals for lead I using the LS method.

surface, which is called lead, is the magnitude of this resultant electric field at that point on the body [4]. The familiar 12-lead ECG is the 'gold standard' in the medical industry. The 12-lead 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, V1, V2, V3, V4, V5, and V6. Leads I, aVF and V2 are considered to be orthogonal to each other. In this paper they are referred to as the orthogonal ECG subset.

B. *The VCG 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 patient and connected via a wire to the VCG. The VCG system is being designed with a form factor that is small enough to be unobtrusive to daily patient activity, as shown in Fig. 1. Due to this form factor constraint, a greatly reduced inter-electrode distance (from the classic VCG) is required and has been realized by the authors in [2]. Figure 2 shows the VCG signal recorded at the lowest achieved inter-electrode distances.

C. *Transformation of VCG to ECG: Previous Results*

It has been shown that there is a linear transformation from the 3-component VCG signal to the 12-component ECG signal [5]. Due to their training and practice, cardiologists prefer to study the 12-lead ECG signal derived from the VCG signal.

In our previous work, we used the least mean square (LMS) algorithm to obtain the matrix values or coefficients [3]. Our approach was to pass the VCG signals into an adaptive filter to derive an ECG signal, called ECG', and determine the coefficients that minimize the mean square error, between the derived ECG' signal and a reference 12-lead ECG signal, using the LMS algorithm.

We encountered some limitations while using the LMS approach. It was found that there was a loss in fidelity in signals derived from coefficients obtained through this method. Upon investigation, we observed that the location of the heart changes slightly in position from beat to beat and hence the cardiac waveforms are not identical. Consequently the LMS algorithm would not be suitable in such a case.

TABLE I. 3X3 TRANSFORMATION MATRIX

Lead	**T matrix**		
	a	***b***	***c***
I	0.97	-0.06	0
aVF	-0.27	0.19	1.45
V2	-0.50	-0.03	1.4

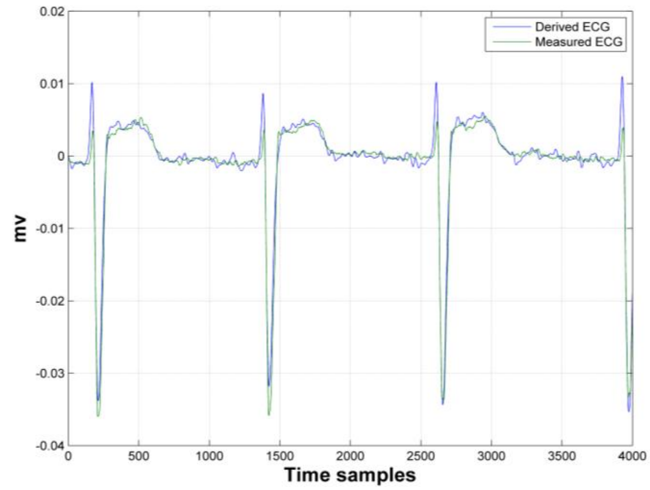

Fig. 3. Comparison of the refernce and derived signals for lead aVF using the LS method.

III. RESULTS

In this paper, we determine the 3x3 matrix that characterizes the transformation between the VCG signals and the orthogonal ECG subset using the least-squares approach.

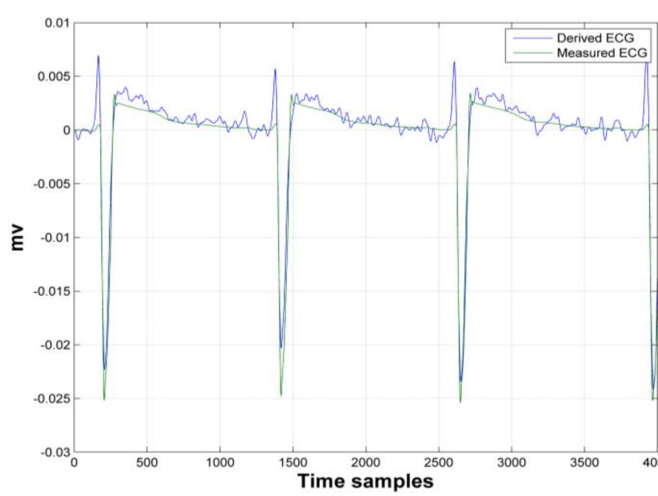

Fig. 4. Comparison of the refernce and derived signals for lead V2 using the LS method.

A. Signal Acquisition

Leads I, aVF and V2 were recorded along with the VCG signals using a hardware acquisition board that was designed at the University of South Florida. The board was used to capture four records of 45-second recordings.

The recordings were processed using Matlab to remove high frequency and 60 Hz power-line noise. Each lead was segmented such that each segment represented one heartbeat. Each segment contained 1391 samples.

B. Least Squares Method

The LS method is a statistical tool used for analytically approximating an unknown relationship between two or more observed variables. For example, if there is an unknown relationship between variables y (this is known as a dependent variable) and x_1, x_2,…x_n (these are known as independent variables), we may use the least square method to realize a reliable model, y' that approximates this relationship. This model is a function of the observed independent variables.

$$y' = f(x_1,x_2..x_n) = a_1x_1+a_2x_2+...a_nx_n \quad (1)$$

The solution for a_1, a_2,...a_n *is* one that minimizes a system parameter such as the sum of squared errors (**E**). In our case, we modelled the relationship between the VCG signals, x, y, and z (independent variables) and the measured ECG lead, e (dependent variable) for each heartbeat segment.

$$e_n' = ax_n+by_n+cz_n \quad (2)$$

$$\mathbf{E} = \sum_{n=1}^{1391} (e_n-e_n')^2 \quad (3)$$

Here, n denotes the sample index. To obtain the a, b and c coefficients for the minimum sum of squared errors, we solved (4) given below. We derived (4) by differentiating (3) with respect to a, b and c respectively and equating to zero.

$$\begin{pmatrix} \Sigma x_n^2 & \Sigma y_n x_n & \Sigma z_n x_n \\ \Sigma y_n x_n & \Sigma y_n^2 & \Sigma y_n z_n \\ \Sigma z_n x_n & \Sigma y_n z_n & \Sigma z_n^2 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} \Sigma x_n e'_n \\ \Sigma y_n e'_n \\ \Sigma z_n e'_n \end{pmatrix} \quad (4)$$

We repeated this process for each lead of the orthogonal ECG subset. We took the average of these coefficients over all the heartbeat segments and applied it to the VCG record. The results are plotted in Figs. 3-5. The figures show the measured ECG lead and the derived ECG lead obtained by applying the coefficients on the corresponding VCG record. The figures show good visual agreement between the measured orthogonal ECG subset and derived signals. Table 1 shows the 3x3 transformation matrix.

IV. Conclusion and Future Research

The transformation matrix that determines the relationship between x, y and z leads of the *iVCG* and a reference orthogonal ECG subset was accurately determined using the LS method. In the future, we will apply this method to determine all 12 leads and validate this procedure for a large test set of subjects and study the resultant coefficients to resolve important issues such as: 1) determine one transformation matrix that can be used for all users and 2) determine the best location to place the *iVCG*. We will also develop machine-learning algorithms that are designed to process the recorded *iVCG* data and predict the occurrence of cardiac events. Motion tracking algorithms will be designed in order to counteract the effects of displacement due to long term and continuous usage. Power harvesting technology will be implemented to increase power efficiency of the device. With these capabilities, the *iVCG* may become a truly transformative wireless medical device enabling continuous cardiac diagnosis.

Acknowledgment

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