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# Integrated Vectorcardiogram (*i*VCG) Rotation Modeling and Compensation

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***Abstract*— We are designing an integrated wireless Vectorcardiogram (*i*VCG) that is portable and worn on the chest of the patient and is capable of continuously recording and transmitting the heart vector, which is a comprehensive measure of the electrical activity of the heart. The VCG contains the same information as the classic electrocardiogram (ECG). Although a physician or trained technician will initially install the *i*VCG device in the appropriate position, it is prone to subsequent rotation errors introduced by the patient placement of the device. In this paper we characterize the rotation errors and present a software solution to correct the effect of the rotation error on the *i*VCG signals.**

***Index Terms*—Electrocardiography (ECG), Vectorcardiogram (VCG), heart vector, minimum mean square error.**

## I. Introduction

Electrocardiography (ECG or EKG) is the process of recording the electrical activity of the heart over a period of time using electrodes placed on a patient's body. These electrodes detect the electrical changes on the skin that arise from the heart muscle depolarizing during each heartbeat. To the trained clinician, an ECG conveys a large amount of information about the structure of the heart and the function of its electrical conduction system. Among other things, an ECG can be used to measure the rate and rhythm of heartbeats, the size and position of the heart chambers, the presence of any damage to the heart's muscle cells or conduction system, the effects of cardiac drugs, and the function of implanted pacemakers [1]. The vectorcardiogram (VCG), which was invented in 1931, is an example of an ECG device. In recent work by the authors [2][3][4], the VCG concept was extended to enable real-time monitoring of the heart with the use of an integrated VCG (*i*VCG) device with a small form factor that can be worn on the body continuously. This wireless *i*VCG signal contains 3 orthogonal components that constitute the heart vector. The heart vector provides comprehensive, diagnostic-quality cardiac information that is equivalent in information content to the 12-lead ECG, albeit in a different format [5]. At the receiver the 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 an implanted pacemaker.

Although a physician or trained technician will initially install the *i*VCG in the appropriate position, it is prone to subsequent errors introduced by the patient's positioning of the device. In this paper, we discuss the problem arising from inadvertent rotation of the *i*VCG device and its effect on the *i*VCG signal [displacement errors will be discussed in a future paper]. We demonstrate that it is possible to compensate for this effect and reproduce the original signal using a purely algorithmic approach i.e., using only software processing. In section II we present a brief description of the *i*VCG, a description of how to convert the *i*VCG signal to the gold

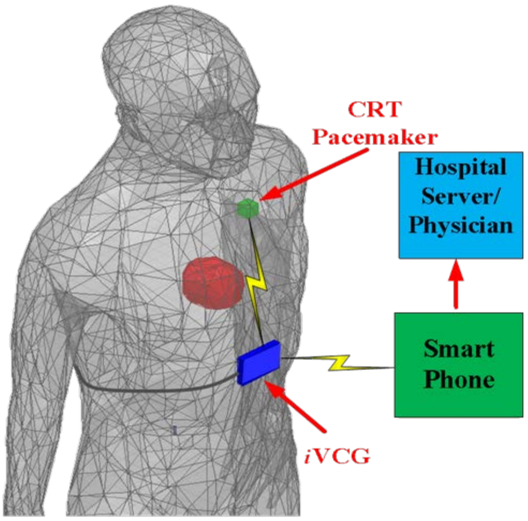


Fig. 1. Integrated Vectorcardiogram System (*i*VCG).

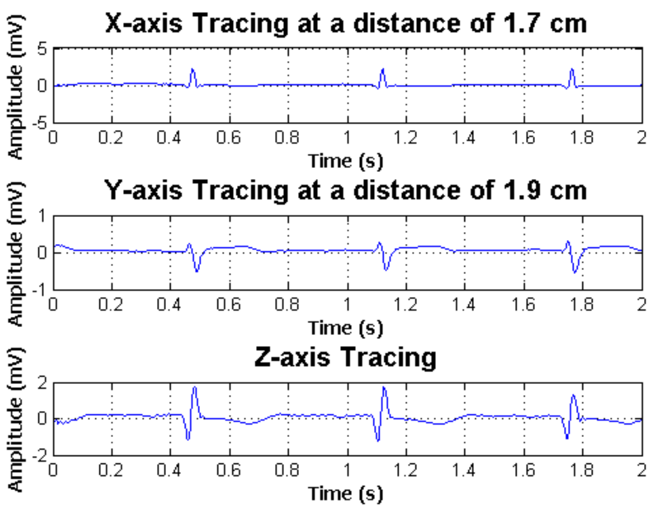


Fig. 2. X, Y, and Z leads of the *i*VCG system. These leads are viewed in the coronal (XY), sagittal (YZ) and transverse (XZ) planes

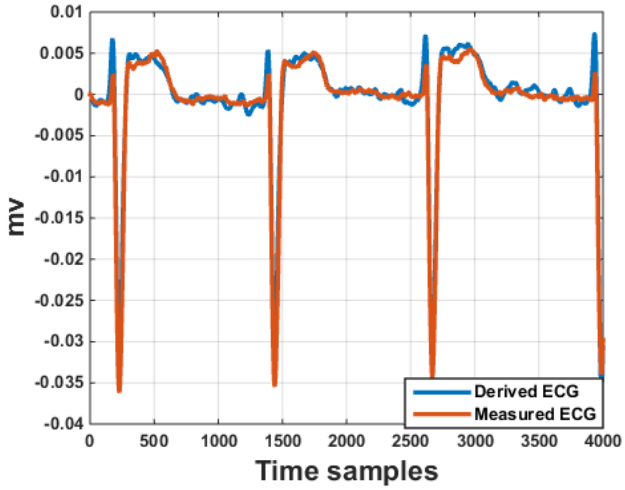


Fig. 3. Comparison of the reference and derived signals for lead aVF using the Least-Squares method.

standard 12-lead ECG (for reading by cardiologists), and a detailed description of the effects of inadvertent *i*VCG rotation, which we refer to as "the rotation problem." In section III we present preliminary results that demonstrate that the original form of *i*VCG signal recorded from a disoriented (i.e., rotated) device can be reproduced via software modeling and processing. In section IV we describe future work.

## II. Background

The contraction and expansion of the heart is caused by an electrical excitation in the heart muscle, which can be modeled as a time-varying electromotive field. This is measured as a 3-dimensional vector dubbed the heart vector [6]. 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 potential of this resultant electric field at that point.

The VCG measures the heart activity by placing electrodes along the X, Y and Z directions of the body [7]. In effect, the VCG measures the heart vector by measuring it's projection in three orthogonal directions, namely X, Y and Z. These projections are called the X, Y and Z leads and are viewed in the coronal (XY), sagittal (YZ) and transverse (XZ) planes.

### A. The iVCG System [2]

The integrated vectorcardiogram (*i*VCG) is a miniaturized version of the VCG, The electrodes that acquire the X and Y leads are integrated into a small wearable device. This is worn on the chest area by the patient. One of the Z leads is housed in the *i*VCG module while the other is attached on the back of the 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 Fig. 1. Figure 1 shows the form factor and placement of the *i*VCG. As shown, the *i*VCG can communicate with a pacemaker and a hospital server via a mobile data system such as a smartphone. 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 *i*VCG signal recorded at inter-electrode distances of 1.7 cm and 1.9 cm in X and Y leads respectively.

### B. iVCG Transformation

The familiar 12-lead ECG is the 'gold standard' in the medical industry and consists of 12 signals or leads read from 10 electrodes placed at different positions on the human body. The information contained in the *i*VCG leads and the 12-lead ECG is equivalent. Since physicians are trained to use the 12-lead ECG, it is essential to convert the *i*VCG signal to the 12-lead ECG for diagnosis by physicians. There is a linear relationship between the VCG and the 12-lead ECG [8]. Hence there is a 12x3 coefficient matrix that relates the VCG and ECG signals. In previous work [4], leads I, aVF and V2 of the 12-lead ECG, which are orthogonal to each other, were derived from the *i*VCG signal using a least squares algorithm. By 'orthogonality', it is meant that the leads are acquired from electrode positions that are spatially orthogonal to each other (similar to the X, Y and Z axes). The measured aVF lead and the derived aVF lead (derived from the *i*VCG leads) can be seen in Fig. 3.

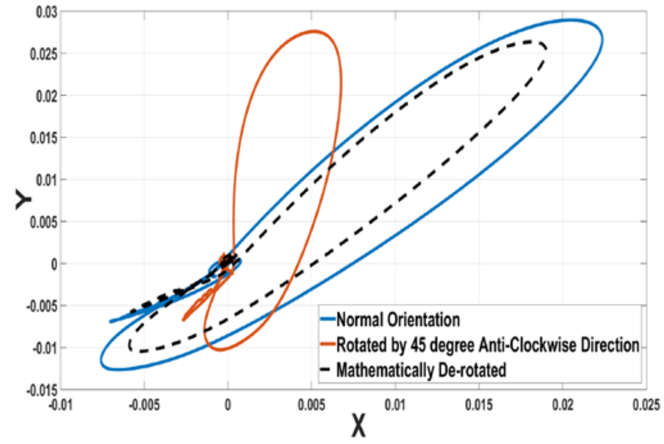


Fig. 4. Reference heart vector, $\boldsymbol{v}$ projected in XY plane with electrodes in normal position (blue), vector $\boldsymbol{v}_r$ from electrodes rotated in anticlockwise direction by 45 degrees (red), and software de-rotated vector $\boldsymbol{v}_s$ (black).

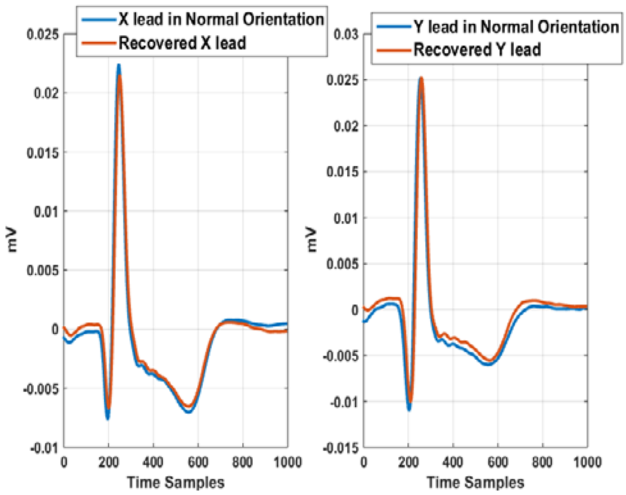


Fig. 5. Comparison of X and Y leads recorded with normal electrode placement and software recovered leads (electrodes were rotated in the anticlockwise direction).

### C. iVCG Alignment

Since there is no redundant information, in contrast to the significant redundancy in the ECG, the *i*VCG device is more sensitive to position than the 12-lead ECG. Alternatively, it can be said that the *i*VCG signal set is a sufficient statistic to comprehensively model the electrical activity of the heart [9]. A precise position is necessary to ensure orthogonality and an accurate conversion to 12-lead ECG.

It is expected that either a physician or trained technician will install the *i*VCG device on the patient to ensure precise positioning. The 12-lead ECG will also be attached at the time of installation so the *i*VCG device can calculate the 12x3 coefficient matrix. The *i*VCG device is designed to monitor the patient continuously round-the-clock, so the patient will likely remove it to charge it. When replaced, the device will be prone to misplacement in the form of displacement and rotation from the preferred original location and orientation.

The disorientation of the *i*VCG device will primarily occur in the coronal (XY) plane causing a shift in the projection of the heart vector in the coronal plane. Due to the curvature of the body the new X and Y-axes will also undergo individual inclination that will cause a loss of orthogonality. The angle of inclination depends on individual body type and cannot be estimated prior to installation of the *i*VCG device on the patient.

The angle of rotation in the coronal plane and the angles of inclination in X and Y must be estimated and (preferably) corrected in software.

## III. Results

In order to confirm that an algorithmic (software) correction of the *i*VCG signal from a disoriented device is possible, we performed an experiment where the electrodes were rotated by a known angle and the recorded signal was mathematically de-rotated using the rotation matrix. Specifically, the *i*VCG signal was captured in normal orientation. This is called the reference vector and is denoted as $\boldsymbol{v}$. It was then rotated by 45 degrees in clockwise and anti-clockwise direction. This vector is denoted as $\boldsymbol{v_r}$ .The signal is de-rotated in software by multiplying the vector, $\boldsymbol{v_r}$ by the rotation matrix $\mathbf{R}_\theta$.

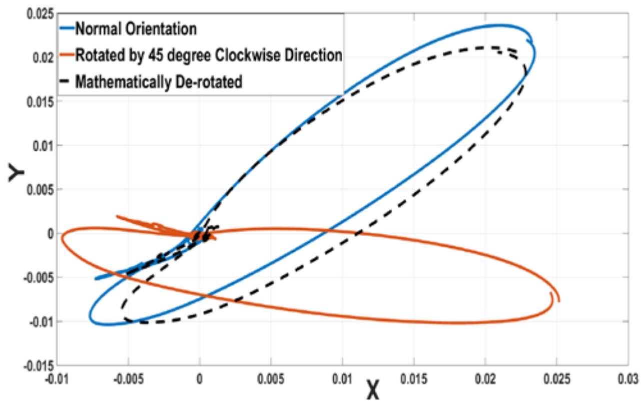


Fig. 6. Reference heart vector, $\boldsymbol{v}$ projected in XY plane with electrodes in normal position (blue), vector $\boldsymbol{v_r}$ from electrodes rotated in clockwise direction by 45 degrees (red,) and software de-rotated vector $\boldsymbol{v_s}$ (black)

$$\mathbf{v_s} = \mathbf{R}_\theta\, \mathbf{v_r} \tag{1}$$

where $\boldsymbol{v_s}$ is the software de-rotated vector and,

$$\mathbf{R}_\theta = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

The angle θ indicates the angle of error rotation. It is + or – 45 degrees in the case of the above described experiment.

Figures 4 shows the heart vector projected in the coronal plane 1) when electrodes are in normal position, 2) when electrodes are oriented by 45 degrees in the anticlockwise direction and 3) after software de-rotation. Figure 5 shows a comparison of X and Y leads when recorded with normal electrode placement vs. X and Y leads software-recovered from electrode placement, which were rotated in the anticlockwise direction. Figures 6 and 7 show the same results as Figs. 4 and 5 but when the electrodes are rotated 45 degrees in the clockwise direction.

### A. Method for detecting angle of rotation using the minimum mean square error (MMSE)

We present an approach to determine the angle of rotation, θ and algorithmically correct the distorted signal $\boldsymbol{v_r}$ acquired from a disoriented *i*VCG device. At the time of installation of the *i*VCG device, the reference heart vector, $\boldsymbol{v}$ can be recorded for N heartbeats at the correct orientation and placement as judged by the physician. The angle of orientation can be determined by minimizing the mean square error between the reference heart vector, $\boldsymbol{v}$ and the software de-rotated $\boldsymbol{v_s}$.
The mean square error (MSE) of the $\boldsymbol{v}$ and $\boldsymbol{v_s}$ can be written as,

$$E = \sum_{i=1}^{kN} \left\| \mathbf{v^i} - \mathbf{v_s}^{\mathbf{i}} \right\|^2 \tag{3}$$

where, k is the number of samples in the heart beat and N is the number of heartbeats of the recorded reference.

Substituting the expression for $\boldsymbol{v_s}$ from (1), the MSE is

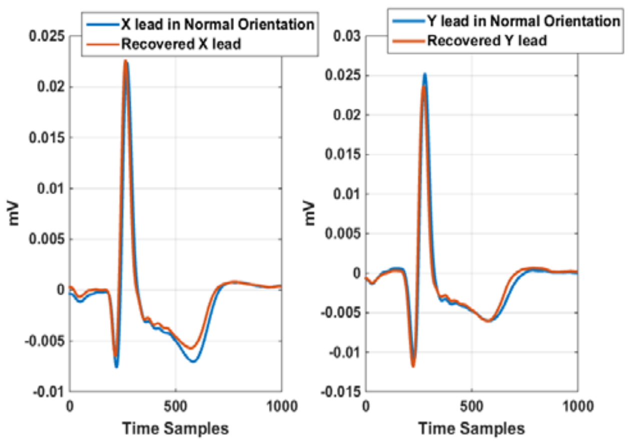


Fig. 7. Comparison of X and Y leads recorded with normal electrode placement and software recovered leads (electrodes were rotated by 45 degrees in clockwise direction).

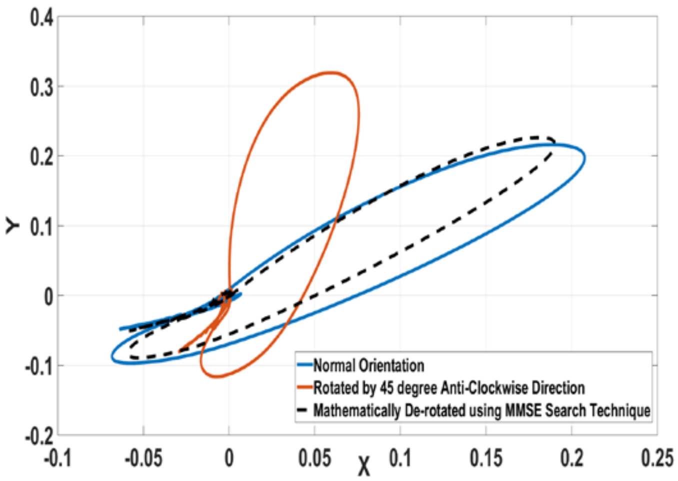


Fig. 8. Reference heart vector, ***v*** projected in XY plane with electrodes in normal position (blue), vector $\boldsymbol{v_r}$ from electrodes rotated in anticlockwise direction by 45 degrees (red), software de-rotated vector $\boldsymbol{v_s}$ using the MMSE search technique (black)

$$E = \sum_{i=1}^{kN} \left\|\mathbf{v}^{\mathbf{i}} - R_\theta \mathbf{v_r}^{\mathbf{i}}\right\|^2 \quad (4)$$

The value of θ that minimizes the value of E is regarded as an accurate estimate of the actual angle of rotation and the original signal is then recovered using (1).

Figures 8 show the reference heart vector ***v***, anticlockwise-rotated vector $\boldsymbol{v_r}$ and the corrected clockwise-rotated vector $\boldsymbol{v_s}$. Figure 9 shows a similar figure but for a clockwise-rotated vector $\boldsymbol{v_r}$.

## IV. Conclusion and Future Work

### *A. X and Y angles of inclination*

Depending upon an individual's body contour, the X and Y-axes of the *i*VCG will undergo some inclination when rotated in the coronal plane. These angles of inclinations angles are denoted as $\varphi_x$ and $\varphi_y$. Below we discuss a potential means to correct the effects of the inclination.

As mentioned before, the 12-lead ECG will be used during *i*VCG installation for calibration. Using an inverse coefficient matrix, it is possible to calculate the true orthogonal vector, $\boldsymbol{v_o}$ from the 12-lead ECG, We will then attach the *i*VCG device and compute the heart vector, $\boldsymbol{v_i}$ which is prone to have some inclination in X and Y direction. We can then calculate the angles $\varphi_x$ and $\varphi_y$ given $\boldsymbol{v_o}$. The $\varphi_x$ and $\varphi_y$ values due to subsequent rotations in the coronal plane can also be calculated using $\boldsymbol{v_o}$.

In future work, we will generate the inverse coefficient matrix that yields the orthogonal vector, $\boldsymbol{v_o}$. and we will also address the effect of displacement of the *i*VCG device.

## Acknowledgment

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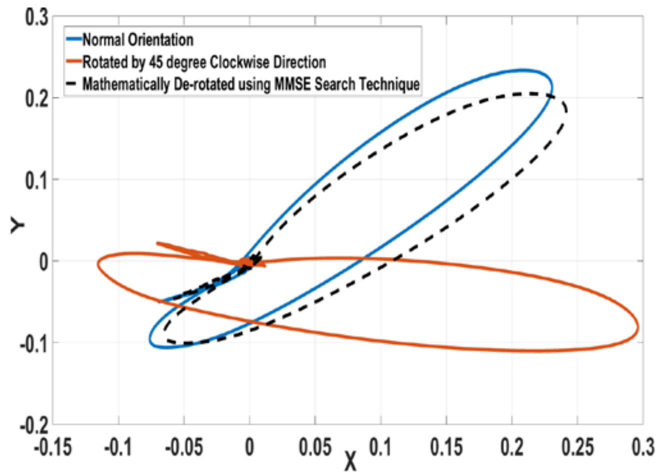


Fig. 9. Reference heart vector, ***v*** projected in XY plane with electrodes in normal position (blue), vector $\boldsymbol{v_r}$ from electrodes rotated in clockwise direction by 45 degrees (red), and software de-rotated vector $\boldsymbol{v_s}$ using the MMSE technique (black)

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