Heartbeat Sensing and Control of the 3D LED Cube

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Abstract— **Recent advancement of sensing technology has fueled increasing interests in the development of cardiac monitoring systems. However, existing devices are limited in their ability to effectively characterize different disease patterns in a 3D way. An ECG sensing device with high visualizability can assist in the decision-making process of cardiovascular disease treatments. In this undergraduate project, we designed and developed a new device to characterize and visualize single-channel ECG signals in a 3D LED cube. Collected signals are processed using signal processing techniques, e.g., smoothing, gradient, and Laplacian. Processed signals are then used as inputs to control the hue, saturation and brightness of LEDs in a 3D LED cube. As such, disease characteristics of ECG signals are dynamically represented by colored patterns in the LED cube. This device shows strong potentials to increase the visibility and interpretability of information pertinent to the underlying complex cardiac activity.**

Keywords*: *Electrocardiogram, Cardiac monitoring, ECG sensing, LED Cube.

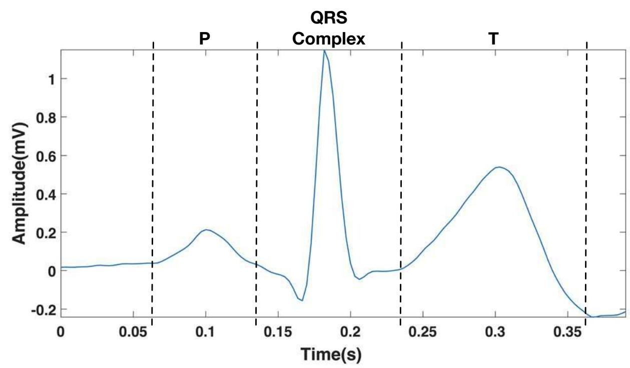

Fig. 1: An ECG cycle with P, QRS, T waves

I. INTRODUCTION

Cardiac diseases are the leading causes of death in the world. About 30% of global deaths (i.e., 17.3 million) are due to cardiac diseases. According to World Health Organization, this number will be increased to 23 million by 2030. Optimal management and treatment of cardiac diseases hinge on early identification of cardiac disorders and timely delivery of life-saving therapies. In clinical practice, electrocardiogram (ECG) is routinely used to assess the function of cardiovascular system. ECG contains a wealth of information pertinent to the spatiotemporal cardiac activity. As shown in Fig. 1, an ECG cycle consists of a P wave, a QRS complex, and a T wave, which are closely associated with electrical activities of heart chambers. P wave is associated with atrial depolarization, while QRS complex and T wave are always related to ventricular depolarization and repolarization. Many heart diseases occur in ventricles. For instance, Myocardial Infraction, as known as heart attack, usually happens in the ventricles [1].

In the past decade, rapid advancement of sensing technology has fueled increasing interests in the development of new monitoring systems. Various devices have been developed for the monitoring of ECG signals. Note that one of the previous studies harnessed the advantages of pervasive ECG sensing and developed a new generation of the cardiac mobile health system, namely the Internet of Hearts, which enables anytime anywhere patient monitoring and the recognition of real-time disease patterns [2].

However, existing ECG devices are limited in their abilities to effectively characterize and visualize complex patterns of cardiac activity in a 3D way. Most of them simply display the magnitude of single-channel ECG signals. Nevertheless, it's difficult to interpret the information that embedded in such 1-D visualization. For the recognition of cardiac diseases, detection of major characteristic waves, i.e., QRS complexes, P waves, and T waves, is always treated as one essential task in ECG analysis. However, it is difficult to have a reliable detection because of baseline wandering and irregular morphology of the waveforms [3].

In this present investigation, we designed and developed a new system for the precise and real-time visualization of the ECG in a 3D LED cube, which may also help to determine the characteristic waves of ECG. Specifically, an ECG sensing device is designed to capture single-channel ECG and remove the baseline wandering. The 3D parameters—magnitude, gradient, and Laplacian—are then derived, which also provide useful information to delineate local maxima and local minima of the ECG signals. Our design uses these three parameters to control the patterns of LEDs in an $8 \times 8 \times 8$ LED cube so that the characteristics of the 1-dimensional ECG signals are dynamically visualized by patterns in the colored 3-dimensional LED cube. This, in

This work is supported in part by the National Science Foundation (CMMI-1646660, CMMI-1617148, CMMI-1619648, and IOS-1146882).

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turn, significantly increases the visibility and interpretability of collected ECG signals. The remainder of this paper is organized as follows: Section II presents system architecture. Section III shows experimental results. Section IV includes the conclusions of this investigation.

II. SYSTEM DESIGN

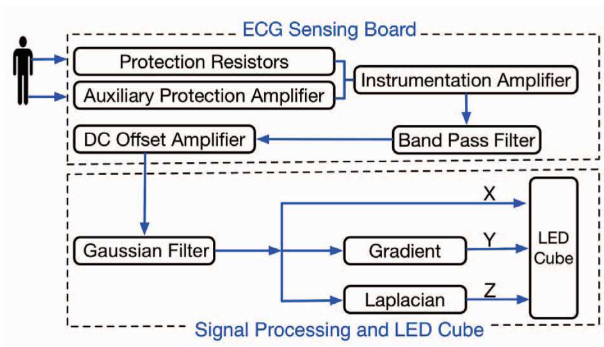


Fig. 2: Flowchart of the proposed system

As shown in Fig. 2, the system consists of two components:

1) ***ECG Sensing Board:*** The designed sensing board collects single-channel ECG from the left and right arms, which further processed by amplifiers and filters.
2) ***Signal Processing and LED Cube:*** The signals are then fed to the microcontroller (i.e., Arduino), and computed in order to extract more information to control the characteristics of LEDs for the demonstration of different ECG signals.

A. ECG Sensing Board

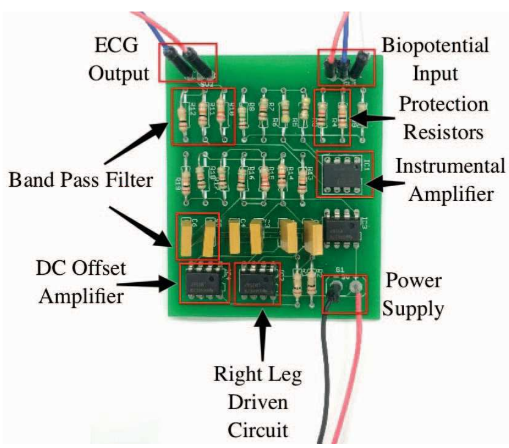


Fig. 3: The developed ECG sensing board in this project

As shown in Fig. 3, the developed ECG sensing board consists of multiple components, including signal inputs/outputs, instrumentation amplifier, band-pass filter and protection circuits. The board is powered by a 9V battery. Inputs to the board are electrical potentials that measured from left and right arms and right leg. Outputs are connected to analog pins of Arduino to control the LED cube.

It may be noted that ECG signals measured on body surface are between 0.3 to 2 mV, which poses a significant challenge for signal processing and visualization. In this study, an instrumentation amplifier is designed to amplify the signals as well as preventing the distortion. As opposed to traditional differential amplifier, the instrumentation amplifier has the following advantages:

1) *High input impedance:* The instrumentation amplifier contains two buffer amplifiers, i.e., the first two non-inverting amplifiers. As such, it provides high input impedance to minimize the loading effect, which is critical for the amplification of millivolt signals (e.g., ECG).
2) *High common-mode rejection ratio (CMRR):* One instrumentation amplifier works as a subtractor to boost the CMRR. This, in turn, facilitates the amplification of differential-model voltage while eliminating common-mode voltage.
3) *Low output impedance:* The output impedance of instrumentation amplifier is relatively low compared with input impedance on the Arduino. As such, the signal can be delivered as much as possible to maintain the high quality.

In addition to the instrumentation amplifier, a right leg driven circuit is designed to further increase the CMRR. Potentials measured by the electrode placed on the right leg are fed negatively to the ECG board. In this way, the common-mode voltage is reduced and CMRR increases.

After amplification, the ECG signals are processed by a band-pass filter. It may be noted that the frequency of P wave, QRS complex, and T wave (see Fig. 1) can be as high as 15 Hz. To include all essential information of ECG, our circuit sets the cutoff frequency as 17 Hz. In addition, since the baseline acts as a reference of our processing algorithm, the very critical step is to remove the baseline wandering of ECG by setting the high-pass frequency filter cutoff to be 0.8Hz [4]. Therefore, the passband of the analog filter in our design is set between 0.8 to 17.0 Hz to eliminate noises and baseline wandering.

It is noteworthy that the polarizable electrodes we used to measure body surface potentials generate 0.3V offset voltages. Further, offset voltages can also result from the op amps. In this study, a DC offset amplifier is added to eliminate the influence of offset voltage. Furthermore, it is important to ensure the users' safety with safe ECG sensing device. Therefore, a protection circuit is designed to prevent the current flowing back to the body. The backflow can be limited by the protection resistors as well as the right leg driven circuit.

B. Signal Processing and LED Cube

In this presented investigation, Arduino Uno is used for signal processing and controlling the LED cube for the visualization of ECG patterns.

1) *Filter Design:* It is noteworthy that the sensing circuit generates noises. Later operations, gradient and Laplacian, are numerical derivatives, which can amplify

noises. Thus, smoothing the original signal is the first step. Noises are high-frequency artifacts and can be removed by a Gaussian filter, which is a true low-pass filter. Therefore, at the beginning of our design, the signal is convoluted with a 3-element Gaussian filter $\{1\ 2\ 1\}$. It is worth mentioning that gradient generates the first derivative of the signal and Laplacian is the second derivative operation actually. Thus, the designed filters can be deduced by Taylor Series expansions, which can be described quantitatively as below:

$$\frac{f(x+h)-f(x-h)}{2h} = f'(x) + O(h^2)$$

$$\frac{f(x-h)-2f(x)+f(x+h)}{h^2} = f''(x) + O(h^2)$$

Both equations can be simplified to 3-element Gradient filter $\{1\ 0\ \text{-}1\}$ and Laplacian filter $\{1\ \text{-}2\ 1\}$. After convoluting these two filters with Gaussian low-pass filter $\{1\ 2\ 1\}$ designed above, the designed gradient filter is $\{1\ 2\ 0\ \text{-}2\ \text{-}1\}$ and the Laplacian filter is $\{1\ 0\ \text{-}2\ 0\ 1\}$. It is worth mentioning that the lengths of output filters are limited to 5, which is short enough to ensure the system to be real-time.

2) *Design of 3D LED cube patterns:* There are three parameters used to characterize ECG: original signal's magnitude, gradient, and Laplacian. Therefore, a device like LED cube, which presents 3 dimensions Cartesian Coordinate system straightforwardly, is selected as the displayer. In our design, the cube is $8 \times 8 \times 8$ in scale and combined with RGB LEDs. It may be noted that $8 \times 8 \times 8$ cube only has 8 levels in each dimension and such low resolution fails to display each parameter precisely. In order to increase the resolution, each LED should have three distinct features corresponding to three parameters. In our design, using Arduino, we can control the hue, saturation, and value (HSV) of each LED to correspond to magnitude, gradient, and Laplacian of the signal. Dividing each HSV feature into 100 levels can expand our resolution to $8 \times 100 = 800$ levels, which is high enough to identify essential characteristics of ECG. As such, the different cardiac dysfunctions can be represented by different patterns with different colors on the LED cube, which can be identified by human eyes straightforwardly.

III. RESULTS

To evaluate our design, ECG signals are simulated and fed into the system. After convoluting with the designed filters, all three outputs are shown in Fig. 4. Because of the 0.8 Hz high-pass analog filter in our designed sensing circuit, it may be noted that all three outputs have stable baselines. However, since the designed digital filters are unnormalized, the range of these three outputs varies greatly. This will influence the weight of each parameter.

To balance the weights of magnitude, gradient, and Laplacian, our design normalizes all the outputs to the range 0 to 800 and maps the magnitude, gradient, and Laplacian to X, Y, and Z in the 3D system (see Fig. 5(a)). It is worth mentioning that gradient is the first derivative and Laplacian is the second derivative of the signal. Therefore, presenting these three parameters at the same time will help the detection of P waves, QRS Complexes, and T waves in the ECG. In addition, the orthogonality property of each parameter prevents them from interfering with each other. Thus, this 3D coordinate system can represent features of the 1D ECG signal more precisely.

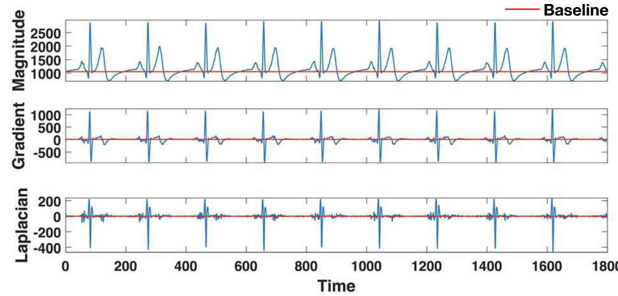
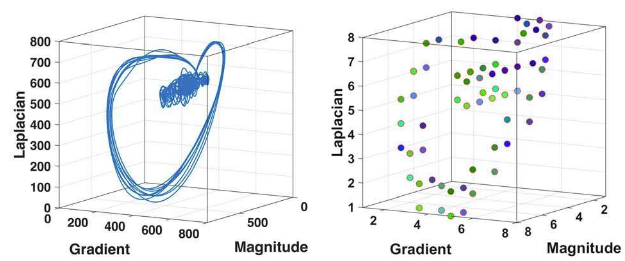


Fig. 4: Magnitude, Gradient, and Laplacian of the ECG signals



(a) 3D ECG trace (b) 3D scatter plot

Fig. 5: 3D visualization of ECG (X-magnitude, Y-gradient, Z-Laplacian)

It may be noted that building a large-scale LED cube with high resolution, e.g., $800 \times 800 \times 800$, has high complexity and occupies large room. Therefore, the size of our design is $8 \times 8 \times 8$. To upscale the small cube's resolution, we implemented the HSV (hue, saturation, and value) RGB color model in our design. As shown in Fig. 5, (b) is the virtual $8 \times 8 \times 8$ cube simulated to present each point in (a), which is $800 \times 800 \times 800$, and Fig. 6 is the hardware visualization

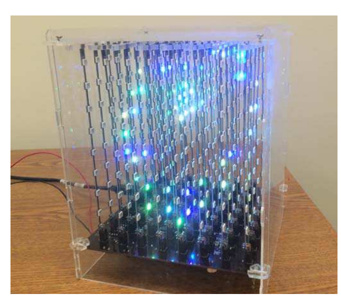


Fig. 6: 3D LED cube visualization. The video is available: http://www.personal.psu.edu/huy25/ECGLEDcube.mov

in the real world.

To evaluate the performance of our design, ECG from patients with two different kinds of heart diseases are fed to our system. The first ECG signal fed to the system is from a subject with the Left Bundle Branch Block (LBBB). As shown in Fig. 7, the 'M'-shaped QRS complexes should be considered as the major characteristic of this disease. The 'M'-shaped component extends the interval of QRS complex and the QRS durations of healthy ECG and LBBB are 131.6±11.3 ms and 165.2±17.8 ms. The means are apparently different, but the time ranges are overlapped. Therefore, it is demanding to design a composite parameter to represent time dissimilarities [5]. In our design, we use magnitude, gradient, and Laplacian to detect the local minimum of the 'M'-shaped component. Due to normalization, mapping the parameters from 800 to 8 scale causes the actual origin relocated to (2,4,3) in our cube's coordinate system. The valley of the 'M'-shaped segment is concave upward and located at high magnitude level. Concave upward means zero gradient and positive Laplacian. Therefore, the point (8,4,3) represent this valley.

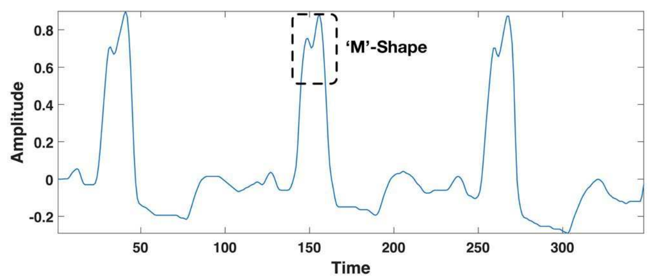
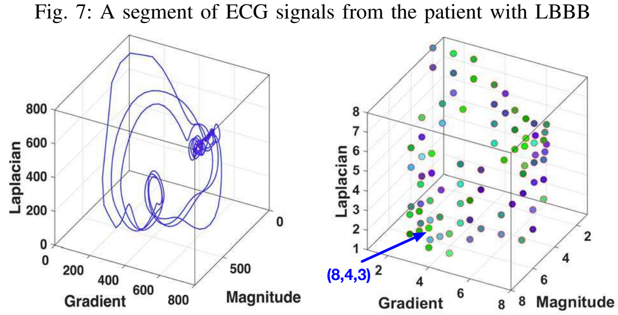


Fig. 7: A segment of ECG signals from the patient with LBBB



(a) 3D ECG trace (b) 3D scatter plot

Fig. 8: 3D visualization of ECG from LBBB

The second signal is from a subject with the myocardial infarction. There are a number of ECG alterations induced by myocardial infarction, e.g., significant Q wave, ST depression/elevation, and inverted T waves. Thus, in literature, there is no clear answer on how myocardial infarction change the characteristic waves, such as P waves, QRS complexes, and T waves in ECG [1]. Our design focuses on inverted T waves. As shown in Fig. 9, the morphology of this component is concave upward and located at medium magnitude level. As shown in Fig. 10(b), point (5,5,4), which has the medium magnitude, represents the valley of the inverted T wave.

It may be noted that the proposed LED cube visualization system for ECG morphology detection performs well in the detection of LBBB and myocardial infarction. Since magnitude, gradient, and Laplacian are three characteristic parameters to describe the morphology of 1D signals, our design has the strong potentials to determine the irregular waveforms induced by heart diseases.

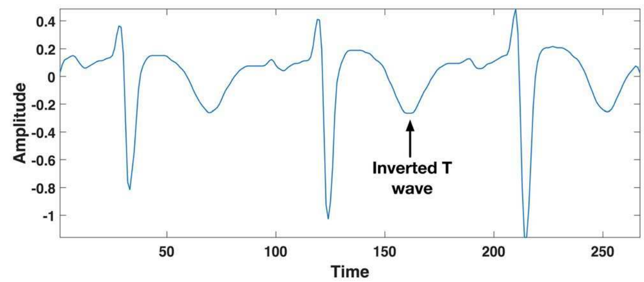
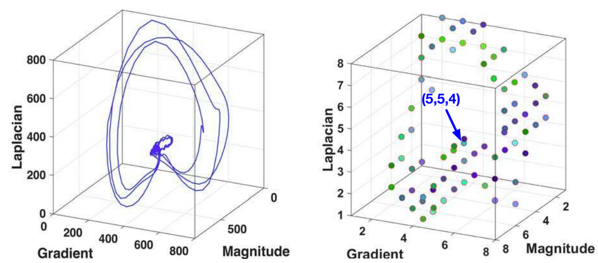


Fig. 9: A segment of ECG signals from the patient with MI



(a) 3D ECG trace (b) 3D scatter plot

Fig. 10: 3D visualization of ECG signals from MI

IV. Conclusions

Existing ECG sensing and monitoring devices are limited in their abilities to effectively characterize and visualize complex ECG patterns in a 3D way. This study presents a new visualization system, i.e., 3D LED cube to increase the visibility and interpretability of information pertinent to underlying complex cardiac activity. The experimental results have shown that our developed system has strong potentials to characterize and visualize real-time cardiac dynamics with various LED patterns and pave the way for better data-driven medical decision-making using ECG signals.

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