Textile Sensor System for Electrocardiogram Monitoring

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Abstract— **Wearable self-powered medical devices have long been a goal of the medical community. The ability to constantly monitor the patient's vital signs for abnormalities, in addition to alerting first responders to immediate problems, would allow for more rapid medical treatment. As the population of the United States ages, low-cost and ubiquitous medical devices will improve the ability of medical personnel to diagnose potential health issues early, thus increasing the survival rate and decreasing the potential complications. Electrocardiograms are a major focus of the medical community due to the prevalence of heart issues among elderly Americans, and as the cost of sensors and wireless communication decreases, new devices are possible. This paper describes a Bluetooth-based, dry electrode electrocardiogram monitoring system seamlessly integrated into a T-shirt. The shirt used three dry silver-based electrodes to collect the ECG signal and streamed the resulting signal to an Android smartphone for analysis.**

Keywords—Electrocardiogram; wearables; dry electrodes; signal processing; motion filtering; medical signal processing; Bluetooth Low Energy

I. Introduction

Cardiovascular disease is a leading cause of death in the United States [1]. The standard treatment protocol for cardiovascular disease after an event involves the use of Holter monitors or event monitors to record the patient's electrocardiogram (ECG) over the period of 24 to 48 hours. These devices are expensive, bulky, conspicuous, and often uncomfortable for the patient. Holter monitors use wet electrodes, which require gels and adhesives and may fall out of place during normal everyday activity. Additionally, they can be uncomfortable due to the wires connecting the electrodes to the monitoring device, and the motion can cause the wires to become disconnected from the electrodes. The user must also be careful to avoid electric blankets or magnets due to the potential to corrupt the signal [2], [3].

Due to the limited monitoring time, the Holter monitor is limited in its ability to detect all potential heart issues. A recent alternative consists of a small adhesive patch (Zio Patch) with embedded electronics designed to monitor the patient for 14 days [4]. The patch removes many of the issues associated with the Holter monitor such as comfort and short detection time. While the patch still requires wet, adhesive electrodes to be applied to the patient, there are no bulky wires with which to be concerned. The patch also has limited signal quality and detecting abilities when compared to the Holter monitor [4].

The patch alternative, while a novel approach to mobile cardiac monitoring, does not solve the issue of processing time. Both the Holter monitor and the patch do not feature real-time monitoring capabilities. While an event monitor allows some real-time monitoring, most do not have the ability to communicate in real time with a doctor. The current patches require the device to be removed and shipped to an analysis center for processing similar to a Holter monitor. This lengthy delay could potentially postpone diagnosis of common cardiac issues as well as treatment for life-threatening illnesses. A more optimal solution would detect abnormalities, log events and inform medical personnel in real time about potential issues.

This project solves two of the major issues currently associated with ECG monitors by removing the wired, wet electrodes from the Holter monitor and the analysis time required for a patch device. Due to the prototype nature of the device, the signal quality and detection capabilities in comparison to alternatives were not tested. Our device seamlessly integrates dry, textile-based ECG electrodes into a wearable garment and transmits the resulting heart information to an Android smartphone for analysis and display purposes. Dry electrodes do not require the use of gels or adhesives, and the modular design gives the user more flexibility. The electronics can be removed from the shirt so that the shirt can be machine washed. Since the device transmits the ECG data in real time to a smartphone, the app has the potential to analyze the received electrocardiogram signal for possible cardiac issues. If a critical or life-threatening issue is detected, the app could promptly alert the user as well as medical personnel and thus increase the chance of survival for the patient.

II. Device Design

The shirt itself is composed of a microfiber polyester, which is a moisture-wicking synthetic fabric commonly used in athletic clothing. The fabric was chosen due to the elastic nature of the material. The three dry electrodes are approximately 5cm by 5cm squares and made of silver woven conductive fabric (Adafruit, NYC). A 30 gauge stranded wire was secured to each electrode using a silver conductive epoxy (MG Chemicals, Ontario Canada). The epoxy increased the stiffness of the material which improved the signal quality.

The placement and pressure of the dry electrodes were critical in achieving good signal quality. Without consistent skin contact, the dry electrodes produce distortions in the resulting signal. The electrodes are sewn onto two elastic bands (Dritzt, Spartanburg, SC) which pass through the shirt around the body and are secured using Velcro to achieve a snug fit as shown in Figure 1. The top electrodes pass underneath the pectoral muscles and the ground electrode is placed on the abdomen at the same level as the belly button. Figure 2 shows the relative locations of the bands and the electrodes. The two main electrodes were placed below the pectoral muscles to minimize noise due to motion artifacts from the pectoral muscles [5].

Figure 1: Electrode Integration into Shirt (inside)

Figure 2: Location of Electrodes

The stranded wires from the electrodes were securely fed through fabric channels within the shirt. The fabric channels were used to minimize potential noise due to movement of the wires. Waterproof wire connectors (Posi-Products, St Augustine, FL) were used to connect the electrode wires to the enclosure containing the electronics. These connections allowed the user to remove the electronics so that the shirt could be washed. The electronics were housed in a 3D printed box and secured in a side pocket on the shirt while in use.

III. Software and Hardware

The hardware mounted on the shirt consisted of a printed circuit board and a 3D printed enclosure. The circuit board contained a CR2330 battery holder and 2.5 volt regulator, an RFduino SMT module (RFduino, Hermosa Beach, CA), and an AD8232 ECG frontend chip (Analog Devices, Norwood, MA). The RFduino module allows quick Bluetooth Low Energy (BLE) prototyping by simplifying the programming environment. The RFduino module contains an ARM microcontroller and Nordic Semiconductor BLE chip on a single package. The AD8232 is a single lead, heart rate monitor front end device which accepted the input electrode signals and output an analog ECG signal. Figure 3 shows the full system diagram consisting of the sensors, hardware, and smartphone application.

On the microcontroller, the ECG data from the AD8232 was sampled at a rate of 200 Hz using 10-bit resolution across a 5 volt range using the built-in ADC. The microcontroller removed the baseline drift and "mapped" the ECG waveform to a 2 volt interval. Before transmission to the Android app via BLE, the ECG data was filtered to remove artifacts due to noise. The signal processing section will discuss this in more detail. The transmitted data was encoded using an 8-bit resolution across a 2 volt range to allow a higher sample rate to be used by sending the data as an 8-bit integer. The decreased resolution did not pose any issues in the analysis of the signal.

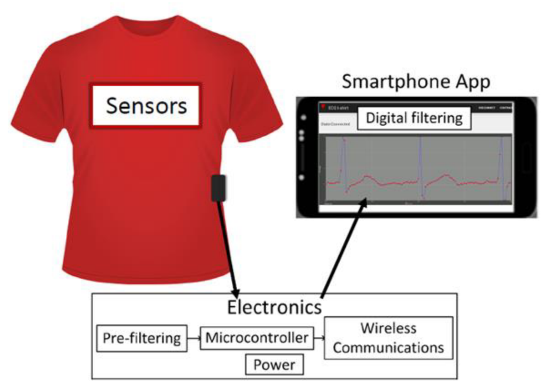

Figure 3: System Diagram

The custom Android application was designed to connect to the hardware mounted on the shirt and receive the rudimentary data for further filtering and analysis. The app was designed to filter and denoise the received signal, save the data, and display the ECG signal in real time. Figure 4 shows actual received and filtered ECG data from the application. In the future, the application would also analyze the signal for potential cardiac events and issues and include provisions for alerting medical personnel to the issue. This would allow our device to fully replace a Holter monitor-like device.

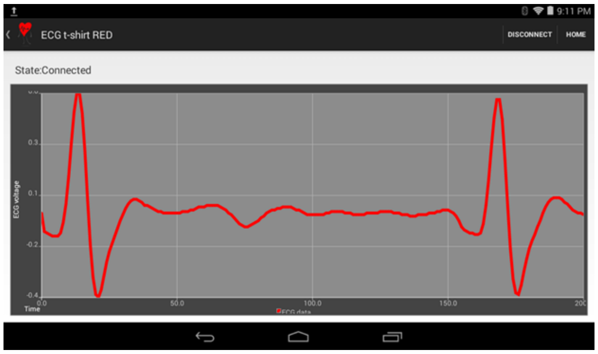

Figure 4: Received ECG data on the Android Application

IV. Signal Processing

Noise artifacts are additive signals which interfere and corrupt the electrocardiogram signals. These signals can come from external sources, such as power lines, or sources on the wearer, such as poor electrode-to-skin contact or muscle activations. Using signal processing, the corruption of the ECG signals can be minimized, and make the signal useful for medical practitioners. A useful signal would contain the standard features of an ECG signal such as the P wave, the QRS complex, and the T wave [6]. Each of these features corresponds to the actual blood flow through the heart and allows the medical practitioner, or the automated algorithm, to detect abnormalities corresponding to coronary disease.

The signal processing was performed in two components. The AD8232 front end chip provided an amplifier as well as several filters which provided the initial analog ECG waveform [5]. After being sampled by the onboard ADC, the signal was improved by digital filters on the RFduino microcontroller before being transmitted via BLE to the Android app. The digital filtering on the microcontroller introduces a bandpass filter for the range of 5 to 12 Hz used in the Pan-Tompkins peak searching algorithm [7] to eliminate frequencies which do not correspond to the desired ECG frequency spectrum. This step reduced the noise of the final signal. The initial signal processing was performed on the microcontroller to reduce processing delays introduced by the filtering which could compromise the sampling rate.

The second stage of the filtering was done on the Android app. After receiving the signal over BLE from the shirt, we further filtered the signal and used the Pan-Tompkins peak searching algorithm. The Pan-Tompkins algorithm is an automatic QRS complex detection designed for detection of the beat-to-beat intervals (RR). Figure 5 shows the process on the Android application of filtering the data. The algorithm was effective for our purposes, but the noise cancellation stage was crude and did not deal with noise inside the frequency band preserved for use with Pan-Tompkins.

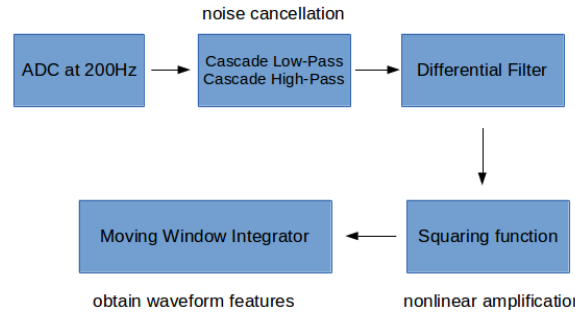

Figure 5: Pan-Tompkins QRS Complex Detection

Figure 4 shows the results of the filtering method on an actual ECG signal. It allowed visual inspection of the signal to detect the QRS complex, in addition to the P and T wave. We did not develop the signal processing algorithms to the point where it allowed automatic detection of the features of the signal. The algorithms had reasonable success with motion characterization and elimination, but further work should still be done in this area.

V. Further Work

Since this was a two semester senior design project, there was limited time to fully expand the project in all desired areas. While the project was a success and met the initial specifications, there are a few areas we would like to improve upon, such as the mechanical connections used in the system for the battery and the electrodes. On the software side, many features could be added to the application to improve functionality. Further research into modifications in the electrode size and placement should be performed. Due to varying sizes of patients, some electrode placement and sizes could work better.

The mechanical connections are a weak point in the system. We designed the shirt so that the electronics could be removed, but this requires the user to reconnect the electrodes to the electronics. Simpler wire connections would improve usability when connecting the shirt to the hardware. The current connections require the user to correctly connect the three individual connections in the correct order. A better designed system would help prevent the user from improperly connecting the electrodes on the shirt to their corresponding ports on the hardware by, for example, using a single connector that combines all three electrodes instead of a separate connector for each electrode.

The current battery system is not suitable for a final product. With some modifications to the hardware, a rechargeable battery could be added. This would decrease user cost and increase usability. A multipurpose USB port would allow data to be saved on the device and transferred over USB to the computer and simultaneously charge the battery. The current 220mAh coin cell can power the device for approximately 17 hours at full transmission power, but increased battery life would be necessary for a full product. The majority of the power budget is used for data transmission;

if those power requirements could be reduced further, the battery life of the system could be extended.

In addition, other features could be implemented on the app side, such as an emergency detection system or arrhythmia detection tool. Current products record information and send that information to specialists for analysis, and once the analysis is complete, the information and possible diagnosis is sent to the patient's physician. However, a lot of this overhead could be eliminated with a cardiac diagnostic tool built inside the smartphone app which could detect cardiac issues such as sinus arrhythmia and atrial fibrillation as well as more life-threatening issues like ventricular fibrillation. Even more valuable, a tool like this could alert medical personnel if the patient is exhibiting symptoms of ventricular fibrillation or even heart attack. Some initial work has been done to start developing a tool like this but has not been implemented into this version of the project.

Using more aggressive signal processing to remove motion artifacts located in the same frequency spectrum as an ECG signal could further improve the overall signal quality during intense physical movement. These signals may often corrupt an ECG signal up to a point where an R peak is no longer detectable by the human eye. There have been several different methods which introduce more sophisticated algorithms using ECG data alone [11],[12] while others introduce accelerometer or impedance sensors [8],[9],[10] which help identify and eliminate more challenging noise artifacts. The circuit board includes an accelerometer that was not used in this version of the project but could be added to improve the signal processing.

VI. Conclusion

The noise cancellation capabilities of the project showed the efficacy of dry electrodes even in a high motion environment with the proper motion canceling signal processing. The device performed better under motion than had been originally hypothesized. We tested the device on treadmills while jogging, and during vigorous motion we were still able to visually confirm the QRS complex as well as the P and T waves. Due to time constraints, statistical characterizations to rigorously determine the similarity of the noisy versus clean signals was not performed. With the inclusion of the accelerometer into the system, we feel confident an even higher degree of noise cancellation could be achieved.

The other major success of the project was the real-time streaming capabilities of the system using Bluetooth Low Energy. Due to the structure of the BLE protocol, which is designed to reduce transmission power cost, transmission capabilities are more limited in comparison to standard Bluetooth protocol. We were able to compress the data to a sufficient degree to allow sufficient data to be transmitted, and the wearer of the device was able to view their complete ECG in real time on their smartphone.

While not yet suitable for mass production and sale due to lack of testing, our device shows the potential for low-cost wearable medical sensors. As shown with our device, the largest issue still facing mass market approval involves power requirements. The issues surrounding sensors and signal processing are rapidly being solved, but the battery remains a limitation. If the battery life and size of these devices can be further decreased by novel technology or simply clever applications of the current technology, the barrier to consumer acceptance will be decreased. As our clothing becomes smarter and technology size decreases, the technology itself will disappear allowing patients and doctors to focus on health care.

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