Principle and Application of Biological Signals Gained from the Sensor on Smart Watch

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Abstract. The smart watch is a prevalent wearable device in the consumer electronics market. Its multifunctionality and handiness are the main advantages of the smart watch. Inside the smart watch, multiple miniature sensors make the smart watch available to realize various functions such as measuring sports kinetic parameters, monitoring oxygen saturation and calculating deep sleep time of its owner. Among the sensors, the photoplethysmography sensor, the electrocardiogram sensor and the electrodermal activity sensor take crucial parts of collecting and analyzing biological signal. Based on those, the heart rate, blood oxygen, level of physiological stress and anxiety can be easily shown to users. This paper, starting from the needs of smart watch users for the collection and analysis of biological signals during daily life, reviews academic writing about the latest developments on wearable device sensors. The principle of those sensors will be introduced, and their applications will be discussed, including methods of handling original signals, some ways to optimize the components of the sensors and their future in the wearable device market. The study methods being used in this paper are literature review method and case study method.

Keywords: Biological Signal, Electrocardiogram, Sensor, Photoplethysmography, Electrodermal Activity

1 Introduction

Wearable devices, such as smart watches, smart band, smart clothes and AR smart glasses are electronic devices which can be directly worn on humans' bodies or integrated on clothes. Its portability, multifunctionality and intelligent interaction are the most apparent advantages. As a result of those advantages above, their visibility is still increasing in human society. According to ZION Market Research, it is predicted that the global wearable technology market size will increase from USD 55.5 billion in 2022 to USD 142.4 billion in 2030. Another more optimistic study shows that by 2032 the size of the global wearable technology market will reach USD 466 billion [1]. Among those increasingly welcomed devices, the smart watch is the one which are developed, designed and published by amounts of international companies such as

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Apple, Samsung, Garmin and ASUS. For instance, Apple Watch has various functions such as health monitoring, fitness tracking, notifications and communications and SOS call and so on. It can collect and store data of health information, fitness records, then report to the user if it is required. When there are notifications on the user's smart phone, the smart watch can notice you at once even though the phone isn't on the hand and being muted. Moreover, when wearing the smart watch, it is light enough to minimize its existence. For example, the weight of Apple Watch Series 8 (41mm) is about 33grams. Based on those details above, advantages of the smart watch are clear enough.

Health functions, including heart rate monitoring, blood oxygen monitoring, sleep monitoring and mental health monitoring are the key point of smart watch products. By gaining biological signals from sensors integrated into the body of the smart watch, the device will come out data based on the signals above, then report data to the user, making it convenient to being informed of biological information. Due to the ability to constantly detecting and analyzing users' daily health information, users or guardians can use this information to take care of their bodies; therefore, they are an excellent choice for many people with dementia, depression, high-stress conditions, and athletes who need to monitor their physical fitness [2]. In this article, from the signals received from sensors to statistics stored and shown to users, the process of health functions of the smart watch is introduced. The discussion of this article is mainly about how to operate the original signals received from sensors, then the optimizing the process to minimize the disturbances, then finally come out with the result which is reliable and accordance with the actual value.

2 Photoplethysmography Sensor (PPG sensor)

The PPG signal is a signal that reflects cardiac activity by detecting changes in blood volume within biological tissues (usually the finger, earlobe, or wrist). These changes are caused by the flow of blood in the blood vessels due to the beating of the heart, which in turn causes changes in light absorption within the tissue. According to a study, it's a method of accurately capturing pulse wave signals using a photoelectric oximeter probe. This method is convenient and simple [3].

2.1 Hardware components

Photoplethysmography sensors are constructed with many parts. They are light source, light detector, signal processing circuit and chemical sensor substrate.

2.2 Working principle

The light source typically includes a red light (660nm waveform) and a near-infrared light (850nm to 940 nm waveform). Due to the stronger penetration capabilities in biological tissues, the near-infrared light is employed for detecting blood volume changes in the deeper tissues, while the red light is employed for superficial tissues.

The tissue being propagated through by the light absorbs and scatters the light with blood. The light is detected by the light detector, which is generally employed by a photodiode after being absorbed and scattered.

As the LED light traverses through the various layers of the fingertip, tissues like muscles, bones, and veins exhibit relatively stable light absorption characteristics. In contrast, the light absorption by arteries fluctuates periodically in response to blood flow. Consequently, the photodetector (PD) can capture and record the transmitted or reflected light, generating the photoplethysmography (PPG) signal. This signal includes both a direct current (DC) component, arising from tissues like muscles, bones, and veins, and an alternating current (AC) component, resulting from the pulsations of the arteries.

Depending on the different light signals captured by the photodetector, PPG devices have two main operating modes which are transmission mode and reflection mode. Here is the main difference between the two modes. In the transmission mode, the transmitted light is captured by positioning the fingertip between the LED and the photodetector (PD). In contrast, in the reflection mode, the LED and PD are placed on the same side of the fingertip (adjacent to each other) to detect the reflected light.

When referring to the PPG waveform detected by the sensor, during each cycle, the signal exhibits clear features corresponding to diastole and systole. Those diastole and features are of high correlation with the human pulse waveform and are related to the release of tension in the cardiac muscle that facilitates the return of blood to the cardiac chambers and the heart muscle's pumping motion, which respectively pumps blood to the body [4]. By contrast, the reflection mode are away more welcomed on the wearable device, for this way doesn't require the sensor to be affixed to both sides of the skin. As a result, the upcoming phases will only discuss the reflection mode.

The signal processing circuit contains the amplifier which is used to amplify the weak electrical signals output by the PD, and the filter which is used to improve the signal quality by removing noise as it is shown on figure 1 (a). Common filters include low-pass filters (to remove high-frequency noise) and high-pass filters (to remove DC bias). Finally, the analog-to-digital converter (ADC) on figure 1(b) converts the analog signal into a digital signal for further digital signal processing.

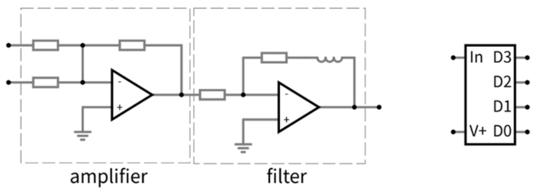

Fig. 1. (a) Amplifier and filter; (b) ADC (Picture credit : Original)

2.3 Optimization

Since choosing the reflection mode to discuss, the most two significant problem is low quality reflected signal due to human lower part tissue's high scattering and managing the distance between the light source and the light detector. According to a design from a academic paper, it employs an LED array to enhance the quality of the signal. For the second issue, a Monte Carlo simulation method is adopted, which closely mimics the reflection of light within human tissue. To ensure that the sampled digital signal more accurately represents the human pulse wave, we apply a low-pass filter to the digital signal. Through simulation, we determine the optimal distance between the light source and the photodetector. When the effective penetration depth of the light reaches the bottom of the blood layer, according to the spacing between the light source and the receiver, the detector should receive two backscattered signals with the greatest difference in two distinct blood oxygenation states. To capture this difference in backscattered signals, the optimal distance, based on the Monte Carlo simulation results, suggests that all parameter selections should be around a wavelength of 940 nm [5].

2.4 Application

Among the latest smart watch market, PPG sensor is widely employed in many famous smart watch brands such as Apple, Garmin, Samsung. In short, PPG sensors have become a staple in the smartwatch industry due to their versatility and the valuable health metrics they provide. Some apparent reasons of PPG sensors becoming popular are those: continuous and non-invasive measurement, giving high suitability for users, high precision and reliability, low power consumption, miniaturization cost-effectiveness and multi-functionality which can measure not only heart rate, blood oxygen, but also sleep monitoring, stress monitoring, and heart rate variability (HRV) analysis.

3 Electrocardiogram Sensor (ECG sensor)

The ECG (electrocardiogram) signal is a type of signal that reflects cardiac function by detecting cardiac electrical activity. This method is non-invasive and involves using electrodes placed on the body's surface to detect the electrical signals produced by the heart's activity. The electrical signals detected by these electrodes reveal the heart's electrophysiological properties and are utilized to assess physiological parameters like heart rate, cardiac rhythm, and the presence of arrhythmia.

3.1 Hardware components

Electrocardiogram sensors are constructed with many parts. They are electrodes, leads, signal processing circuits and chemical sensor substrates.

3.2 Working principle

Every heartbeat is accompanied by electrical activities, which are generated by the depolarization and repolarization processes of myocardial cells. That means when placing electrodes on the skin, the electrical activity formed by the heartbeat can be detected. The detector of electrical signals are called leads. Conventional ECG sensors are designed with 10 electrodes that create 12 leads, offering a comprehensive view of the heart's electrical activity. On wearable devices, fewer electrodes and leads are employed to simplify the measurements and promote accessibility. As indicated in a study, heartbeats are initiated by low-amplitude bioelectric signals produced by specialized cardiac cells. Electrocardiography (ECG) converts these electrical signals into numerical data, enabling their use in various applications. The bipolar configuration is optimal for minimizing noise. The fundamental principle of recording bio-signals involves directly capturing and amplifying electrical potentials from organs and tissues, or converting other physical phenomena generated during bodily activity into electrical signals. The frequency range of bio-signals is most often limited to a few hundred Hertz, while, for example, in an ECG for standard clinical use, the frequency band is in the range from 0.05 Hz to 100 Hz. Bio-signals provide a link between biosystems and are our main source of information about their behavior. Bio signals, like all signals, must be carried by some form of energy. It should also be noted that each living cell is a source of bioelectronic activity and is characterized by individual impulses. The heart is also a muscle. Recording the electrical potential of the heart is called an electrocardiogram [6].

On the signal processing operation, signals detected by the leads are preprocessed, QRS detected, delineated by wave.

The reason for preprocessing is to filter signals and minimize powerline interferences and muscle noise. In this process, high-pass filters, low-pass filters, and band-pass filters play essential roles. Research has shown that significant effort has been devoted to designing filters aimed at eliminating baseline wander and powerline interference. These types of disturbances necessitate the development of narrowband filters. Addressing noise from muscle activity presents another challenging filtering issue, as it is significantly more complex to manage due to the considerable spectral overlap between the ECG signal and muscle noise. Nevertheless, muscle noise in the ECG can be mitigated when it is feasible to utilize techniques that leverage the recurrent nature of the ECG signal. Filtering techniques are predominantly employed for signal preprocessing and have been widely integrated into various ECG analysis systems. It is important to note that ECG filtering should be context-specific and applied only when it does not distort the desired information. This key concept can be illustrated through the example of filtering to eliminate powerline interference [7].

During QRS data classification and delineation, as it is shown in a study, existing beat detection methods include morphology analysis (e.g., QRS slope, amplitude, width), digital filtering, wavelet transformation, and machine learning or deep learning techniques. These QRS detection methods work well on public datasets like MIT-BIH. Identifying QRS positions helps assess heart rate variability, detect minima and maxima, and identify pauses. For more detailed ECG analysis, common beat types can be identified (Fig. 2), including normal beats, premature atrial contractions (PAC), and premature ventricular contractions (PVC). Once these beat types are recognized, specific pathological patterns formed by sequences of beats can be analyzed. For instance, we can automatically detect specific arrhythmia patterns such as PVC couplets, triplets, sustained or persistent ventricular tachycardia, and episodes of supraventricular tachycardia [8].

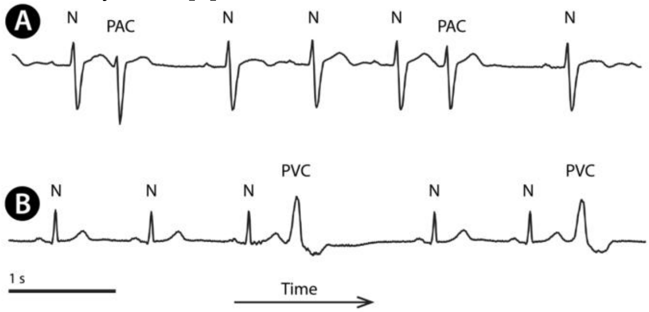

Fig. 2. Normal beat signal [8]

3.3 Optimization

Electrodes are the parts of the EEG sensor in the smartwatch that come into direct contact with the skin. Which means, if there are ingredients in the electrodes causing skin allergies, the suitability will be seriously impacted. The traditional electrodes are metals such as copper. Despite it is generally considered safe for most people, direct skin contact or trace amounts of nickel contained in the copper may cause allergies. Moreover, the oxidation of the copper effects efficiency as electrodes. In that case, a replacement of copper is required. There are some materials with different kinds of advantages. High-end smartwatches typically use Ag/AgCl electrodes or graphene electrodes for high precision and stable ECG signals. Smartwatches focusing on cost-effectiveness and comfort may opt for conductive polymer or conductive fabric electrodes. Metal electrodes, such as stainless steel or titanium, are more commonly used in sports-oriented smartwatches that require high durability and corrosion resistance.

3.4 Application

Due to the high cost of hardware materials and research difficulty, it is a standard only in high-end smart watches. Whether the rest of the watches employ ECG sensors depends on the needs of the users and the decision made by manufacturers. Moreover, the extra power consumption is the reason why long battery life watches aren't willing to use ECG sensors. However, with the user needs of getting data of electrical activity of the hart activity, the rhythm of heartbeat, part of the non-high-end smart watches such as part of the Xiaomi S1, Fitbit Versa 3, Garmin Venu 2.

4 Electrodermal Activity Sensor (EDA sensor)

It is used to measure skin electrical activity. In this way, the stress level, emotional states, or physiological responses are monitored when the user is wearing a smart watch with EDA sensor inside. EDA is used as a non-invasive marker of the autonomic nervous system in applications like emotional arousal, stress, pain, and decision-making. It measures skin electrical conductivity changes due to sweat gland activity. Typically, EDA is measured by applying a low, constant voltage between two closely spaced electrodes and monitoring the changes in skin conductance [9].

4.1 Hardware components

Electrodermal activity sensors are constructed by many parts. They are electrodes, signal processing, Analog-to-Digital Converter (ADC) and microcontroller unit (MCU), which is the core control unit of the entire EDA sensor system. The microcontroller unit receives digital signals output by the ADC and processes and analyzes data, such as calculating skin electrical conductivity or identifying emotional states.

4.2 Working principle

Electrodermal activity sensors detect skin conductance. By placing two electrodes on the skin surface and giving them a low voltage, the skin conductance can be calculated. The continuous data collected by sensors can reveal emotional and psychological states, primarily driven by the activity of the human autonomic nervous system (ANS) and sweat glands. When the body is in emotionally excited states, under stress, in pain, or in other physiological conditions, the presence of electrolytes like sodium chloride on the skin increases along with sweat, leading to a rise in skin conductance. According to a study, the activity of sweat glands influences the conductance of an applied current. These influences result in electrodermal activity (EDA), which refers to the variations in the electrical conductance of the skin. The electrical conductance of the skin is enhanced by increased sweating. This is because, despite containing minerals, lactic acid, and urea, sweat is primarily composed of water. While thermoregulation is the main function of most sweat glands, those on the soles of the feet and palms of the hands are primarily associated with enhancing grasping performance rather than temperature control. These sweat glands are more sensitive to psychological stimuli than to thermal stimuli. This phenomenon is particularly noticeable in the hands and feet due to the high concentration of eccrine glands in these areas. However, emotionally induced sweating affects all eccrine sweat glands. Thus, EDA is considered a quantitative indicator of sudomotor activity and, by extension, an objective measure of arousal [10].

The EDA signals are usually divided into two parts. They are phasic components which are rapid transient change and tonic components which are the average conductance for a long period of time. However, before the signals are divided, they should be amplified and denoised. The noise is mainly constructed with power supply noise, electromagnetic interference and muscle electrical activity. As it is shown in a study, there is a way to denoise especially when there is a PPG sensor in the smart watch. This research introduces a denoising technique that simultaneously uses acquired photoplethysmography (PPG) as a reference signal correlated with respiratory noise, to reduce both respiratory and external noise interferences [11]. After denoise signals, now it comes to the process of emotional detection. As demonstrated in a study, electrodermal activity (EDA) serves as a psychophysiological marker of emotional arousal [12]. As it is discussed above, the phasic and tonic components are two essential aspects of EDA. These components can be extracted using time-domain analysis, frequency-domain analysis, mathematical model fitting, and the cvxEDA algorithm, providing valuable insights into the signal.

In the phasic component part, the number of peaks is of high importance, reflecting the frequency of emotional events in a certain period. The size of the peak shows the intensity of the emotion, and the rising time of the peak indicates the speed of emotion response, and the time to return to the baseline reflects the duration of this emotional event.

In the tonic component part, the average value shows the base level of the skin conductance, regarded as an individual's baseline physiological state. The dynamic changes of physiological state can be calculated through long-term trend of skin conductance. Also, its mean and variance reflects the stability and variability of the user's state.

4.3 Application

Due to its special function of monitoring mental state, the EDA sensors are favored by smart watches which take healthy or physiological detection importantly such as Fitbit sense, Neumitra, Spire health tag and Pip or devices with a high-performance health monitoring function such as Whoop 4.0.

5 Conclusion

In this study, several commonly used sensors on the smart watch are discussed, including PPG sensors, ECG sensors and EDA sensors. The study reviews the function of those sensors, then simply explains how they are constructed and the principles of their work. Sometimes, there are some methods to optimize sensors from various aspects such as changing more suitable materials, calculating specific parameters. Among the sensors employed on the smart watch, each type of sensor has different working principles, leading to different fields of functions. When they are integrated to a wearable device together, it will make the device multifunctional.

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