SpO2 and Heart Rate Measurement with Wearable Watch Based on PPG

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Abstract

This paper is based on the Photoplethysmography technology to measure the arterial blood oxygen saturation (SpO2) and Heart rate which are people's vital sign. In the system we design a non-invasive continuous and portable wearable watch to measure human SpO2 and Heart rate. The wearable watch uses the micro-optoelectronic sensors to get PPG signal and utilizes wireless Bluetooth 4.0 to communicate with PC or mobile phone.

The principle of Photoplethysmography is that reflection or transmission light changes with blood volume in the microvascular of tissue. So the PPG signal contains much valuable information about cardiovascular system such as SpO2, heart rate, blood pressure, and respiratory rate. The most advantages of PPG is non-invasive and low-cost, however the transmitting and receiving channel of PPG is easily disturbed by outside light and motion.

In this Paper, to minimize the PPG channel noise and motion artifacts, we build the PPG signal channel model and use sensor to measure the outside light to cancel the distance disturbance between micro-optoelectronic sensors and skin. Because of the motion noises falls within the same frequency band as the physiological signal, we use MEMS approach to measure the motion information and cancel the disturbance. Disease about cardiovascular will be monitored and predicted in future work.

1 Introduction

Cardiopathy has become a serious disease in modern society, because of many people with high pressure from study and work [1]. They don't have enough time to take care of health, so convenient and non-invasive approach is improved to measure heart fatal sign in home. Photoplethysmography which was proposed firstly by Hertzman is very convenient for us to measure the fatal sign, such as heart rate and SpO2 [2].

Heart rate is the number of beats per minute, which is the most important characteristics and related to the safety and death of Human beings. Heart rate reflects the pulse of Human ventricular and atrium cycle of contraction and diastole [3]. Blood with oxygen began to spread along the whole arterial system, So many parameter of the tissue is related to the form of pulse wave from the aortic root. The comprehensive information of the shape, intensity, speed and rhythm of the pulse wave is a large part of the physiological and pathological characteristics of human cardiovascular system.

Oxygen saturation (SpO2) is the percentage of oxygen-saturated hemoglobin (HBO2) relative to total hemoglobin in the blood, which indicates the capacity of blood carrying oxygen [4]. It is an important physiological parameter of respiration and circulation, therefore, monitoring arterial oxygen that is calculated by oxygen hemoglobin and oxygen saturation can be estimated the capacity of the lung.

Nowadays, wearable mobile medical equipment has become very important and popular. Intelligent wearable watch times is coming, so we grasp the opportunity and challenge to design the wearable watch providing a continuous and non-invasive measurement device [5]. The wearable watch designs for people to monitor heart rate and SpO2, it can calculate the heart and SpO2 in real-time, and use Bluetooth wireless protocol to connect PC and mobile phone.

2 Principle

2.1 PPG

The principle of Photoplethysmography is reflective or refraction light changing with blood volume in the microvascular of tissue [3, 6]. Based on the different sensor sample style, there are two approaches to measure the PPG signal: reflective and transmission.

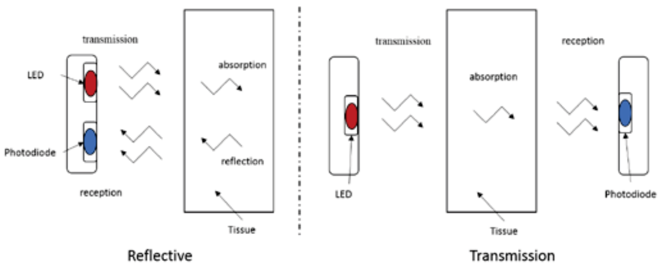

Fig 1: the structure of the PPG signal obtain

We can use the source LED emits light and use the photodiode to receive the light which is transmitted or reflected from the body tissue. As the heart beats, the photodiode value is changed with the blood volume.

Photoplethysmography utilizes Beer-Lambert's law, which states that the absorption of light to the properties of the material through which the light is traveling. By definition, the absorbance of material as Equation (1):

$$A = \varepsilon c L \tag{1}$$

Where A is the absorbance, a dimensionless quantity, normally termed the optical density (OD). ε is the wavelength dependent extinction coefficient, c is the concentration of the absorber and L is the optical path length.
The transmittance of material sample is related to its absorbance A and given by Equation (2):

$$T = \frac{I_t}{I_0} = e^{-A} \tag{2}$$

Where T is the transmittance of material, I_0 is the source light intensity and I_t is the transmitted light intensity.

2.2 Heart rate

When using red light or infrared light to measure heart rate on a finger or earlobe with a considerable number of arterial blood can get the a better result [7]. Because of wrist with few arteries, wrist wearable devices must be through the skin's surface below the veins and capillaries to detect the heart pulse. The green light is based on the changes of the light absorbance along with the pulse of blood density in the arm. It can measure the heart rate continually and movement. However, the red light utilises the change of absorbance of blood hemoglobin in blood vessels to measure pulse, the signal is relatively weak and susceptible to outside. Measuring heart rate by red light need a quiet state. So we use green LED to measure the heart rate in order to obtain more accuracy.

The PPG pulse signal is synchronous with the beating heart and cycle of arterial contraction and diastole, therefore we can extract the information of heart rate with peak detection [8]. The measurements of Heart rate is shown in Fig 2:

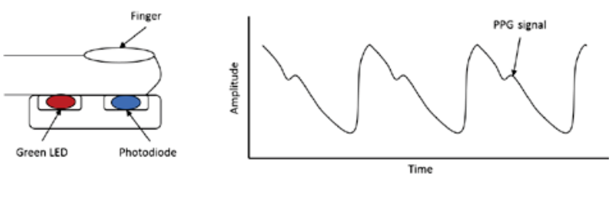

Fig 2: the PPG signal of Green LED

So we can obtain the relationship between the incident light intensity (I_o) and the transmitted light intensity (I_t) by Equation (1), (2):

$$I_t = I_0 e^{-\varepsilon c L} \tag{3}$$

Usually the dissipation of light in the air is very few. It mainly decided by the distance between LED and skin. When people stay in calm the dissipation can be neglected. Light arrives the skin, some of will be reflected by the skin surface directly, and another transmitted light will be reflected by the tissue and blood. So we can separate the Is into two part, one is reflected light I_r, and another is transmitted light I_t. Following is the relation between I_s, I_r and I_t:

$$I_s = I_r + I_t \tag{4}$$

Where: Is is the light intensity of skin surface, I_r is the directly reflected light and I_t is the transmitted light. Furthermore, the receiver of light sensor get many part of light I_r, I_t and outside disturbance I_d.

$$I_a = I_r e^{-\varepsilon_1 c_1 L_1} + I_t e^{-\varepsilon_2 c_2 L_2} + I_d \tag{5}$$

Where: I_a is the all light intensity of receiver sensor; I_d is the outside disturbance light intensity. So we can conclude from the equation: To measure the heart rate with the green light mainly determined by the absorbance of tissue and blood which is changing with the heart pulse. PPG signal can be disturbed by distance and outside light, so we should avoid this kinds of noise in system design.

2.3 SpO2

Light transmit through tissue and blood vessels will be divided into DC component ((such as skin, muscle, bone, etc.) and AC component (such as arterial blood) [9]. Based on the Beer-Lambert's law, when the pulse is calm and the wavelength of λ emit to the tissue, the DC component (I_{DC}) can be calculated by the following Equation (6):

$$I_{DC} = I_0 e^{-\varepsilon_0 c_0 L} \cdot e^{-\varepsilon_{HbO2} c_{HbO2} L} \cdot e^{-\varepsilon_{Hb} c_{Hb} L} \tag{6}$$

Where ε_0 , c_0 is the non-pulsation component of extinction coefficient and concentration; ε_{HbO_2}, c_{HbO_2},ε_{Hb}, c_{Hb} are the HbO2 and Hb of extinction coefficient and concentration.

When heart beats and arterial vasodilation, the optical path length of arterial vascular added ΔL, so the light intensity added I_{AC}:

$$I_{AC} = I_{DC} - I_{DC} e^{-(\varepsilon_{HbO2} c_{HbO2} + \varepsilon_{Hb} c_{Hb})\Delta L} \tag{7}$$

Transforming the Equation (7) and calculating the natural Logarithmic of that:

$$\ln[(I_{DC} - I_{AC})/I_{DC}] = -(\varepsilon_{HbO_2} c_{HbO_2} + \varepsilon_{Hb} c_{Hb})\Delta L \tag{8}$$

Considering the AC component ratio to the DC component is much less than 1, so we can obtain the following equation:

$$\ln[(I_{DC} - I_{AC})/I_{DC}] \approx I_{AC}/I_{DC} \tag{9}$$

$$I_{AC}/I_{DC} = -(\varepsilon_{HbO_2} c_{HbO_2} + \varepsilon_{Hb} c_{Hb})\Delta L \tag{10}$$

Because of unknowing the optical path length, we use two different wave as incident light to measure the SpO2. Two wavelength are λ_1 and λ_2. Assuming $R_{\lambda_1} = I_{AC}^{\lambda_1}/I_{DC}^{\lambda_1}$, $R_{\lambda_2} = I_{AC}^{\lambda_2}/I_{DC}^{\lambda_2}$, and combining Equation (10):

$$\frac{R_{\lambda_1}}{R_{\lambda_2}} = \frac{I_{AC}^{\lambda_1}/I_{DC}^{\lambda_1}}{I_{AC}^{\lambda_2}/I_{DC}^{\lambda_2}} = \frac{\varepsilon_{HbO_2}^{\lambda_1} c_{HbO_2} + \varepsilon_{Hb}^{\lambda_1} c_{Hb}}{\varepsilon_{HbO_2}^{\lambda_2} c_{HbO_2} + \varepsilon_{Hb}^{\lambda_1} c_{Hb}} \tag{11}$$

Based on the definition of oxygen saturation, just as:

$$SpO_2 = \frac{c_{HbO_2}}{c_{HbO_2} + c_{Hb}} \times 100\% \tag{12}$$

So combined Equation (11) (12):

$$SpO_2 = \frac{\varepsilon_{Hb}^{\lambda_2}(R_{\lambda_1}/R_{\lambda_2}) - \varepsilon_{Hb}^{\lambda_2}}{(\varepsilon_{HbO_2}^{\lambda_1} - \varepsilon_{Hb}^{\lambda_1}) + (\varepsilon_{HbO_2}^{\lambda_2} - \varepsilon_{Hb}^{\lambda_2}) \cdot (R_{\lambda_1}/R_{\lambda_2})} \tag{13}$$

When we choose λ_2 which leads to $\varepsilon_{HbO_2}^{\lambda_2} = \varepsilon_{Hb}^{\lambda_2}$, we have:

$$\mathrm{SpO_2} = \frac{\varepsilon_{Hb}^{\lambda_1}}{(\varepsilon_{Hb}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1})} - \frac{\varepsilon_{Hb}^{\lambda_2}}{(\varepsilon_{Hb}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1})} \frac{R_{\lambda_1}}{R_{\lambda_2}} \tag{14}$$

Where $\varepsilon_{Hb}^{\lambda_1}$, $\varepsilon_{HbO_2}^{\lambda_1}$, $\varepsilon_{Hb}^{\lambda_2}$ are constant parameters which can be measured by spectral analysis in time domain and frequency domain. If we assume $A = \varepsilon_{Hb}^{\lambda_1} / (\varepsilon_{Hb}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1})$, $B = \varepsilon_{Hb}^{\lambda_2} / (\varepsilon_{Hb}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1})$

$$\mathrm{SpO_2} = A - B \cdot \frac{R_{\lambda_1}}{R_{\lambda_2}} \tag{15}$$

$$\mathrm{SpO_2} = A - B \cdot \frac{I_{AC}^{\lambda_1} / I_{DC}^{\lambda_1}}{I_{AC}^{\lambda_2} / I_{DC}^{\lambda_2}} \tag{16}$$

Where A and B can be calculate by experiment.

HbO2 and Hb absorb light at different wavelengths. In order to choose a better light wavelength to obtain PPG signal [10], the graphs of haemoglobin with and without light absorption are shown in Fig. 3.

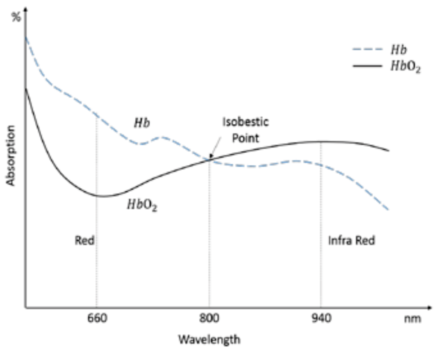

Fig. 3: Absorption of HbO2 and Hb at Different Wavelengths.

We can conclude that absorption of HBO2 and Hb were significantly different from the spectral curve. In order to reduce the tissue impact on the measurement accuracy, HBO2 and Hb of light absorption coefficient should be greater than the absorption coefficient of non-pulsation component, so the 650 nm is selected, and the difference of the absorption coefficient between Hb and HbO2 is the largest. The equation (11) requires HBO2 and Hb absorption coefficient should be equal, we select wavelength of 800 nm from Fig 2. But the absorption coefficient with the wavelength is sensitive, wavelength of 940 nm is selected from Fig 2.

The schematic of SpO2 is a little difference from the heart rate, there are two selected LED with Red (650nm) and infra-Red (940) to generate different wavelength for HbO2 and Hb with different absorption coefficient. The SpO2 measurement schematic is shown as Fig 4:

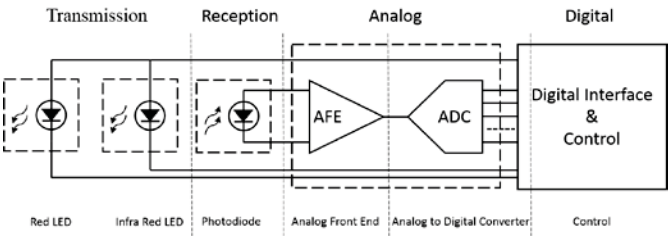

Fig 4: SpO2 measurement schematic

In the picture, the Red and Infra Red LEDs alternate to emit light and photodiode obtain corresponding PPG signal. AFE deal with the analog signal and ADC convert the analog to digital. The digital Interface & Control calculates SpO2 value and communicate with CPU through I2C bus.

3 System Design

3.1 Hardware

In order to measure PPG signal and analysis heart rate and SpO2, we design the wearable watch with necessary sensor and chip. The hardware of system consist of the four parts as following:

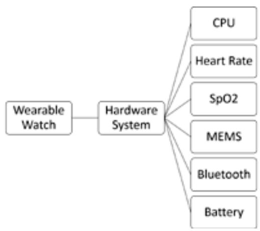

Fig 5: Hardware System Structure

Heart rate mainly use PAH8001EI-2G which is produced by PixArt Imaging Inc. The PAH8001EI-2 is a high performance and low power CMOS-process optical sensor of Green LED with 525nm and DSP integrated serving as a Heart Rate Detection (HRD) sensor. It is based on optical technology which measures the variation of human blood movement in the vessel. Ultra-low power consumption, power saving mode during time of no touch movement.

The measurement of SpO2 need two LEDs with Red (650nm) and infra-Red (940). We choose the ADPD142RI produced by Analog Device Company is the most suitable solution for wearable watch. ADPD142RI has the small footprint. The analog front end uses two structures to reject interferers from dc to 100 kHz. After the analog signal conditioning, a 14-bit, successive-approximation analog-to-digital converter (ADC) digitizes the signal, which is transmitted via an I2C interface to a microcontroller for final post processing. A synchronized transmit path is integrated in parallel with the optical receiver. Its independent current sources can drive two separate LEDs with current levels programmable up to 250 mA. The LED currents are pulsed, with pulse lengths in the microsecond range, so the average power dissipation is kept low to maximize battery lifetime.

In the System, The microchip CC2541 is a system-on-chip solution for Bluetooth low energy in wireless data exchange. The CC2541 combines the excellent performance of a leading RF transceiver with an industry-standard enhanced 8051 MCU, in-system Software Stack programmable flash memory, 8-KB RAM. The CC2541 is highly suited for systems where ultralow power consumption is required. This is specified by various operating modes. Short transition times between operating modes further enable low power consumption.
The hardware of the system takes into a full account of low power consumption, we choose a battery as big as possible in wearable watch and every chip perform very well in power consumption.

3.2 Software

For the system, the software is very important to the wearable watch. When we start the system, the soft will get the state by key and judge the state, if the system judge there is no measurement duty, it will go into power down mode, Else it will measure the PPG signal and calculate the heart rate and SpO2 value. The Program flow diagram is shown as Fig 6:

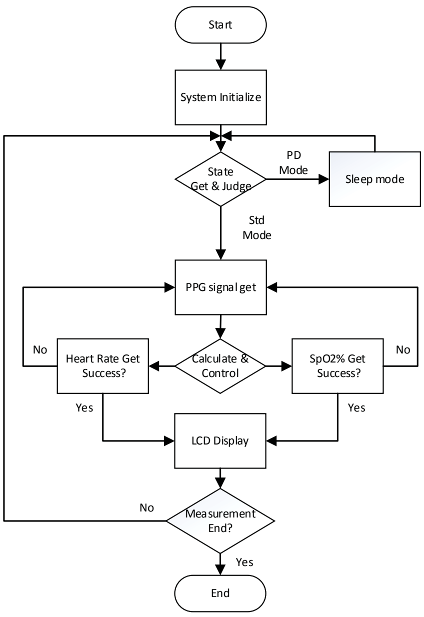

Fig 6: Software flow diagram of system

4 Conclusion

The Wearable Watch is based on the Photoplethysmography theory, it can measure the heart rate and SpO2 of human beings and keep a good accuracy compared with medical oxymeter. The basic version circuit of the system is shown as Fig 7:

Fig 7: the test circuit of the syetem

In the system, we use adaptive peak detection to measure heart rate, but there are still shortages that the heart rate disturbed by the distance between sensor and wrist skin when people is moving and sporting. Ambient light and motion-generated artifacts are the challenges for the SpO2, we set up the basic model of the light transmission absorption and reception and optimize the structure to cancel the outside disturbance.
The wearable watch basic realised the measurement of heart and SpO2, there are some problems need to further study, and Doing more experiment to make the algorithm robust and reliable.

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