Model Design and System Implementation for the Study of Anti-motion Artifacts Detection in Pulse Wave Monitoring

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Abstract: Photoplethysmography (PPG) is a widely used technology for health monitor based on pulse wave measurement by monitoring the blood volume of blood vessels via electro-optic technique. As a kind of non-electrophysiological signal with low amplitude and low frequency, PPG signal may be easily disturbed by motion artifact. This paper proposes a simulation method based on a new reflection model which includes a skin-friendly flexible substrate with a narrow-band full-reflection film plating on it and an embedded system accordingly to study anti-motion artifacts detection in pulse wave monitoring. Monte-Carlo method is presented to simulate the dynamic human skin model and the results demonstrate the effectiveness of the proposed model. A wrist worn artifact-resistive pulse wave monitoring platform (PWMP) is presented accordingly, the measurement accuracy of pulse rate by the platform is within ±2 beats per minute(bpm) at the range of 30bpm to 240bpm compared with the output of Fluke Index2 (produced by Fluke Corp, USA) in stationary situation. Three kinds of typical postures are performed to verify the proposed model experimentally, results show that the proposed platform has good correlation as compared to PC-60B Medical Pulse Oximeter from Heal Force in the measurement of pulse rate, and the pearson correlation coefficient is 0.953($p<0.01$), which reveals that the proposed model has the potential to recover pulse wave signal for pulse rate monitoring.

1 INTRODUCTION

It is of great significance for the monitoring of pulse rate, blood oxygen saturation, blood pressure (Zhou et al.,2015). As one of the vital physiological parameters of human body, pulse can reflect many physiological and pathological features of the human respiratory system, cardiovascular system, etc (Nogami et al.,2018). Photoplethysmography (PPG) is a method that measures the blood volume of blood vessels via electro-optic technique. Accurate acquisition and processing of PPG signal play an important role in medical diagnosis, exercises and other fields(Davoudi et al.,2014). As this method is non-invasive, safe, reliable and adaptable, it is widely used in physiological signal monitoring equipment, especially wearable devices (Ra,2016; Zhou,2014), for the monitoring of pulse rate and blood oxygen.

Currently, there are many devices designed to detect the pulse rate, but not many of those have the ability to detect pulse rate precisely. PPG signal, which can be affected easily by motion artifact, is a kind of low- frequency and weak non-electrophysiological signal. Devices can perform well in static conditions, but the precision is challenged during movement due to the frequency overlapping between pulse wave and motion artifact. Motion artifact is mainly introduced in two kinds: one is the interference that human body's DC components (muscles, tissue fluid, capillaries, etc.) introduce during pulsation, such as capillary filling and tissue fluid increase caused by increased metabolism during exercise, etc. The other is the air gap generated by the relative displacement between the optical sensor and human body during exercise, which can be considered as additive noise, many works aimed to reduce this part as to enhance the anti-motion artifacts ability of the detection devices. For example, Fukushima et al., (2012) used an acceleration sensor to obtain the reference signal of motion artifact. Zhou et al.(2016) applied a differential channel following green and red light PPG channels to enhance the anti-

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motion artifacts ability of the device. Shimazaki et al. (2014) used another PPG sensor without contacting the skin to detect the reference signal. Their works showed that progresses had been made to the cancelation of motion artifact. And to the best of our knowledge, there is no similar research yet that combines the model design(simulation) and system implementation accordingly for anti-motion artifacts detection in pulse wave monitoring based on PPG, the systems mentioned usually based on priori knowledge or through a lot of experiments and measurements(Shimazaki et al.,2014).

This paper proposes a simulation method base on a skin-friendly flexible substrate with a narrow-band full-reflection film plating on it and an embedded system accordingly to study anti-motion artifacts detection in pulse wave monitoring based on PPG. We present a new reflection type sensor model by designing a narrow-band full-reflection film plating on a skin-friendly flexible substrate to extract the motion artifact separately, so as to achieve the relatively accurate reference signal for further signal processing. Meanwhile, this paper proposes a method for modeling PPG signal based on MC (Monte-Carlo) approach to obtain the simulation waveform from the model mentioned above. To verify the effectiveness of the proposed model, a wrist worn artifact-resistive pulse wave monitoring system (PWMP) is presented accordingly, three kinds of typical postures are performed and the results show that the proposed platform has good correlation as compared to the PC-60B in the measurement of pulse rate.

2 METHOD AND MATERIAL

2.1 A New Reflection Type Anti-motion Artifacts Model

In reflection type PPG detection, the Light Emitting Diode (LED) and the Photo-Diode (PD) are located on the same side of the tested part, and the change of the light absorption (PPG signal) is obtained by detecting the signal from PD. In the case of stationary state, it is generally considered that the probe composed of LED and PD is closely attached to the surface of the human skin, and the method can obtain accurate results. While in the case of motion, there will be a relative displacement between the probe and the measured part of the human body, which introduces a layer of air whose thickness changes with time. The air layer also absorbs and scatters the light emitted from LED, thus motion artifact is introduced into PD.

In this paper, an improved reflection type anti-motion artifacts PPG detection model is proposed based on electro-optic technique. Figure 1 shows the structure of this novel design, the pulse wave detection probe is constructed as two separate parts, one part is a reflection type pulse detection module, where two different wavelength LEDs and one PD together composed as a sensor module, and this module is electrically connected to the embedded system. The other part is a motion artifact detection module, where specifically a skin-friendly flexible substrate with a narrow-band full-reflection film plating on it is applied. Take a red light and green light LED-PD sensor module for example, a flexible substrate such as polydimethylsiloxane (PDMS) can firmly adhere to the surface of the human body, and the narrow-band full-reflection film is a red light full-reflection film. The red light is totally reflected on the surface of the film, and the green light can completely transmit into the tissue theoretically. In this model, the amount of red/green light received by PD can be expressed as

$$Q_R = Q_{\mathrm{r}\_normal} \tag{1}$$

$$Q_{\mathrm{G}} = Q_{\mathrm{g}\_normal} + Q_{g\_blood} \tag{2}$$

Equation (1) and (2) suppose that the red light absorption Q_R equals the amount of red light absorbed by air(simplified), and the green light absorption Q_G is composed of the green light absorbed by air(simplified) and human body AC components. The thickness of the air layer for red and green light is the same, that is, the optical path difference introduced by the relative displacement between the probe and the measured part is the same, thus Q_{r_normal} and $Q_{\mathrm{g\_normal}}$ are strongly correlated. The red light signal is regarded as a reference signal for noise, and the green light signal is regarded as a mixed signal of the noise signal and the real signal, so we can apply algorithms for motion artifact cancellation.

2.2 The Proposed Embedded System

In this section, we present a wrist worn artifact-resistive PWMP system, and the block diagram is shown in Figure 2. The PPG signal is acquired by an AFE (AFE4404 from Texas Instruments) after EMI filter, then the signal is amplified and 24bit-ADC sampled before sent to micro-controller through I^2C data communication protocol.

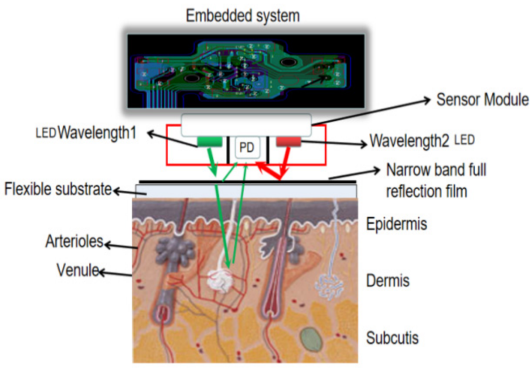


Figure 1: The structure of the improved anti-motion artifacts PPG detection model.

The MCU is an ultra low power, 2.4GHz RF device, it contains a 32bit ARM cortex-M3 processor. The standby current is 1uA, and the shutdown current of the MCU is 100nA, which makes it suitable for the design of wearable monitoring platform. An integrated high efficiency dc-dc converter BQ25015(from Texas Instruments) is designed to operate directly from a single cell lithium battery, the output voltage is adjustable from 0.7V to VBAT, this convert is highly integrated charge and power management device targeted at space-limited Bluetooth applications. In this design, PWMP can work almost 10 hours continuous even when powered by a 40mAh rechargeable lithium battery, which makes it suitable for long term health monitor. The pulse wave data is then transferred to PC through wireless module, and the data can be acquired in real time at the sample rate of 100Hz. The main board of the proposed PWMP system is in size of 20 *15mm^2, which is a miniaturized embedded system smaller in sized than previous work (Zhou et al.,2016). This kind of system has widely usage in physiological parameter monitoring area, and it is well established in other works (Zhang,2007).

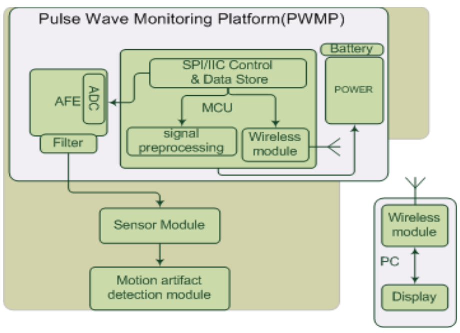


Figure 2: Block diagram of the Embedded system.

3 SOFTWARE AND ALGORITHM

We propose a simulation method to verify the model mentioned above. Light transport in optically dense random media is characterized by multiple scattering, but recent studies have demonstrated that the diffusion approximation fails to fully describe back-scattering/reflection and transmission characteristics. While Monte-Carlo simulation is an effective approach for modeling light transport in scattering and absorbing media such as tissue (Guo et al.,2002).

3.1 Monte-Carlo Approach

Monte Carlo approach (Monte-Carlo, MC) is a probabilistic statistical method widely used in the physical field to deal with particle transport problems. The basic idea is to first establish a probability model or a stochastic process corresponding to the physical process, and simulate the process through a series of random numbers, and then calculate the statistical characteristics of the parameters obtained by observing or sampling the model or process(Wang,Steven & Jacques,1992). In the simulation of light transport, the process can be described as: Firstly, describe the characteristics of tissue by the following parameters: the thickness d, the absorption coefficient ua the scattering coefficient us, the anisotropy factor g, and the refractive index n. ua is defined as the probability of photon absorption per unit infinitesimal path length, and us is defined as the probability of photon scattering per unit infinitesimal path length. Then the light beam is equivalent to a photon flow, in which each photon randomly interacts with the tissue during random walk, absorption and scattering, etc. The MC simulation is to generate a random number to sample these interactions (the walking step/the angle of scattering). Finally, by sequentially emitting photons and tracking the number of photons reflected, transmitted, and absorbed, the results of photon propagation in the tissue (reflectance, transmittance, etc.) are statistically represented.

There are many approaches for MC simulation, including analogue Monte-Carlo (AMC) and variance reduction Monte-Carlo (VRMC). AMC is the most direct description of real physical processes. The weight of the photon is always maintained at 1 until it is completely absorbed or leaves the area of interest and never returns. In order to get reliable results, it is necessary to simulate a large number of photons, which takes a long time to calculate. Therefore, VRMC is generally used to improve the AMC. In this method, the photon is given a certain initial weight. After each interaction with tissue, the weight of the photon is attenuated. When the weight of the photon is less than the given thresholds, we can believe that the transport of this photon has little contribution to the statistical results, and then use Russian roulette interrupt technology to give photons a certain chance of survival. If the photon survives, it continues to walk in tissue and if the photon dies, the next photon will be emitted.

In this paper, the MC simulation program is written based on the above process by MATLAB to simulate the basic frame of the proposed PPG module with the photon number set as 10^5.

3.2 Dynamic Optical Model of Human Skin Tissue

For a static optical model of skin tissue, the MC simulation can successfully track the interaction between photons and biological tissue at that moment. Since photon emission time is at a scale of ps, the photon emission process can be regarded as transient. Therefore, as long as we build a dynamic optical model of the skin tissue, that is, a model of the optical properties of the skin tissue changes with time, and use MC to simulate at an interval to model PPG signal in time domain. In actual physical process, the processor drives the LEDs to emit light at a certain frequency, and the PD receives the optical signal, which accords with the MC simulation process.

As the largest organ of human body, skin is a complex multi-layered structure. In short, skin can be divided into the epidermis layer, the dermis layer and the subcutaneous tissue (Cheong et al.,1990; Faber et al.,2004). The reflection type PPG detection is to detect the volume change of the blood in the blood-containing dermis layer. In this paper, the model of human skin is divided into six layers: the epidermis layer, the mastoid dermis layer, the upper layer of blood vessels, the reticular dermis layer, the deep blood vessels and the dermis layer. The upper layer of blood vessels and the deep blood vessels are made up of dermal tissue and blood in different proportions, and blood is evenly distributed. Most studies have shown that the upper blood vessels are composed of 90% dermal tissue and 10% blood, and the deep blood vessels are composed of 10% dermal tissue and 90% blood. The sixth layer of dermis is attached to the subcutaneous fat. The pumping action of the heart causes blood pressure to change periodically, and the optical properties of skin vary with the blood content of dermis. By establishing a relationship between blood pressure and skin optical properties, a dynamic optical model of human skin tissue can be established.

3.3 PPG Signal Modeling without Motion Artifact

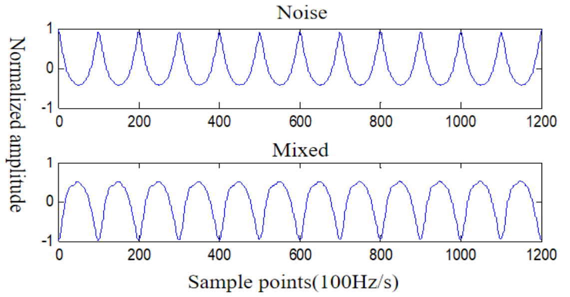
By combining the MC simulation with the skin tissue dynamic model, PPG signal modeling in time domain can be performed. First, Gaussian functions are used to fit the waveform of a standard pressure pulse wave with a period of 1s as the input of the model. The pressure value is used for calculating the skin optical model at that moment. The sampling is performed at a frequency of 100Hz, that is, 100 MC simulations are performed per second. Each simulation calculates the optical parameters of the skin tissue, and emits a photon packet of 10^5 photons with a wavelength of 540 nm green light. A detector is placed at a position of 0.2 to 0.3 cm from the incident position, which proves to be the best position for reflection detection, and the total weight of the photons emitted at the position is summed.

This process can be described as a simulation without motion artifact, that is, the probe and the measured part are closely attached without considering the motion artifact introduced by the movement of air layer.

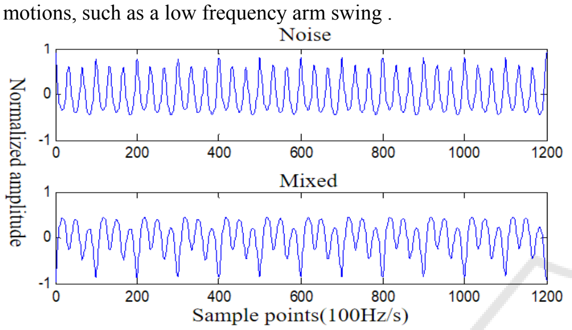
3.4 PG Signal Modeling with Motion Artifact

On the basis of the MC model above, it is easy to model the anti-motion artifacts probe proposed in Figure 1 by adding an air layer whose thickness changes with time for simulating the relative displacement between the probe and the measured part. Green light detects the mixed signal of the real pulse PPG signal and motion artifact, and interacts with a seven-layer MC model (one air layer, six skin layers). Red light only interacts with the air layer and detects only motion artifact. In the MC simulation, when the red light photon travels to the lower surface of the air layer, it will be reflected without using a random number to judge its path, so that the red light full-reflection film can be simulated. By changing the variation of the thickness of the air layer, different kinds of motion can be simulated.

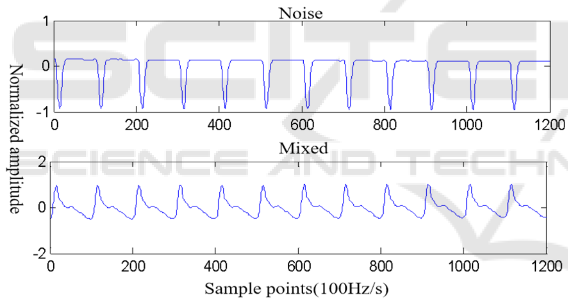
As shown in Figure 3, the noise signal can represent the variation of the thickness of the air layer, and the mixed signal is strongly disturbed by noise. It is hard to identify the typical dicrotic notch of the pulse wave signal in Figure 3(a), and it is almost impossible to distinguish the pulse wave in Figure 3(b) and Figure 3(c).



(a) The thickness of the air layer changes as a half sine curve that varies at a frequency of 1 Hz, simulating periodic low frequency motions, such as a low frequency arm swing .



(b) The thickness of the air layer changes as a half sine curve that varies at a frequency of 3 Hz, simulating periodic high frequency motions, such as a high frequency arm swing.



(c) The thickness of the air layer changes as a square wave with a 10% duty cycle, simulating a sudden shake, such as typing.

Figure 3: The result of PPG signal modeling with Motion artifact.

4 RESULTS AND DISCUSSIONS

4.1 Simulation Result

Adaptive filtering is a filtering method developed on the basis of Wiener filtering. Least Mean Square (LMS) adaptive algorithm is a method that continuously adjusts the parameters of the adaptive filter to minimize the mean square value of the error between the output signal and the expected response (Chan & Zhang,2002).

To meet the real world interference and sensor inputs, in this paper, the mixed signals and noise signals in Figure 3 are stretched and compressed in time domain by interpolation, then randomly combined as the input of the adaptive filter(mixed signals and noise signals are sampled at the same time). Figure 4 shows the simulation results.

In time domain, as the adaptive algorithm converges, the correlation with motion artifact can be removed and the PPG signal becomes distinguishable. From the results above, the motion artifact cancellation detection model proposed in this paper provides good reference signal for adaptive algorithm by extracting the motion artifact signal separate simutaneously, which shows that the proposed model has the potential to recover pulse wave signal for pulse rate monitoring for the proposed motion artifacts.

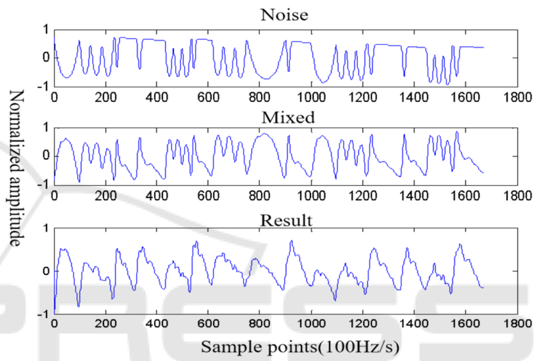


Figure 4: The result of adaptive algorithm.

4.2 PWMP System Test Result

The proposed platform PWMP was estimated by Fluke Index2 Vital Signs Simulators (produced by Fluke Corp.USA) at Zhejiang Institute of Medical Device Testing. The measurement accuracy of pulse rate by PWMP was within ±2 beats per minute(bpm) at the range of 30bpm to 240bpm compared with the output of Fluke Index2 in stationary situation.

To verify the model proposed, a 30*30*5mm^3 high reflection filter was customized, the filter showed high transmission to visible light bands and high reflection to other bands. Pulse signals acquired from wrist (left hand) were recorded by designed PWMP. Two young healthy subjects joined in this experiment for one week and performed the tests two times per day. For this type of study formal consent is not required. Measurements were carried out under certain temperature (20□~27□) and humidity conditions (50%~60%) compensated by air condition.

Three kinds of typical postures were performed, measurements began when the subject was in a seated

(a) (b) (c)

Figure 5: Experimental testing process, (a)stationary, (b)free arm swing, (c)typing.

position. Firstly, the subject was asked to sit in stationary situation mode, see in Figure 5(a); Then, free arm swing movement was applied, see in Figure 5(b); At last, typing for five characters was applied ,see in Figure 5(c).

During the experiment, a short break for sixty seconds was arranged between every two kinds of motions. At the mean time, the PC-60B medical Finger Clip Pulse Oximeter from Heal Force was worn at the index finger of the subject's right hand to work as criterion device. The right hand remained stationary during the experiment, and the pulse rate displayed on the pulse Oximeter was also recorded at an interval of 5s as the criteria data.

Three kinds of typical signals of two channel PPG lasted a period of 5s including green light PPG channel(signal with motion accordingly), infrared light PPG channel(motion accordingly) from wrist were captured. Figure 6 demonstrated the typical signal and signal process during free arm swing movement. The blue dotted waveform (in the bottom part of Figure 6, marked as noise) stood for noise was highly consistent with the motion disturbance waveform of infrared light(int the up part of Figure 6, marked as ir). The red waveform, from which pulse rate calculated and some maintain good morphological characteristics of pulse wave, stood for the result after signal process. In this case, the calculated pulse rate was 91bpm compared with 89bpm form PC-60B medical Finger Clip Pulse Oximeter.

Figure 7 demonstrated the typical signal and signal process of typing. As infra(ir) channel showed, the artifact during tying was random disturbance at high frequencies. The signal obtained by green channel was similar to the infra channel, the high intensity of motion artifact overwhelmed the original pulse wave shape. After signal process, the blue dotted waveform stood for noise was highly consistent with the motion disturbance waveform of infrared light, and the red waveform, from which pulse rate calculated, stood for the result after signal process. In this case, the calculated pulse rate was 77bpm compared with 78bpm form PC-60B .

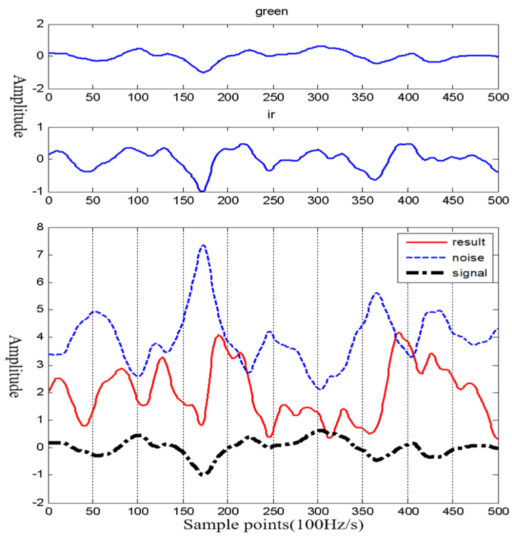


Figure 6: The typical signal and signal process of free arm swing movement.

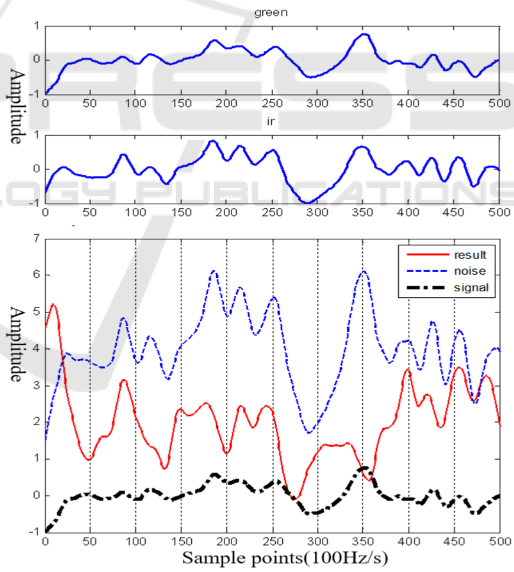


Figure 7: The typical signal and signal process of typing.

During the experiment, 1800 pieces of data were collected, LMS along with Independent Component Algorithm (ICA) was applied for signal processing. Using PASW Statistics 18.0(SPSS Statistics) software to analyze the data, we found that the average and standard deviation of the pulse rate obtained by proposed platform were 74.24 and 9.39 while they were 74.08 and 8.63 by using PC-60B. The Pearson correlation coefficient was 0.953($p<0.01$).

The average deviation and standard deviation was smaller than previous work as described (Zhou et al., 2014). Obviously, the proposed platform has good correlation as compared to the PC-60B in the measurement of pulse rate.

The Bland-Altman plot of the PWMP calculated in different postures and PC-60B in stationary situation obtained were given in Figure 8. The x-axis presented the average of the two methods, while the y-axis showed the difference between them. We observed that a total of 95.5% of the pulse rate measurements lay in the limits of agreement (1.96 × SD), which indicated that the pulse rate calculated by our proposed method was in close agreement with the PC-60B in stationary accordingly.

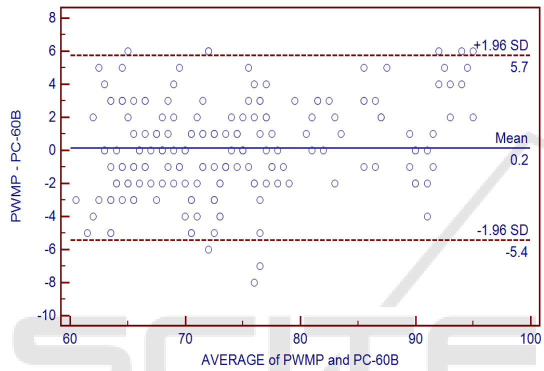


Figure 8: Bland-Altman analysis of PWMP calculated in different postures and PC-60B in stationary situation accordingly.

In Table 1, error analysis in different postures were presented. We could find that the mean square error (MSE) was lowest in stationary posture, that was mainly as in this posture, no movement was applied. In free arm swing MSE had the largest value, that was mainly because in this situation, pulse rate changed during arm swing and more artifact was applied into the platform. As typing last only a short time, the influence was not so strong as free arm swing.

By analyzing the waveform and comparing with the pulse rate data collected by Pulse Oximeter, the validity of the model was also verified from the perspective of experiment. Zhang et al., (2019) proposed a novel modular algorithm framework for motion artifacts removal based on different wavelengths for wrist-worn PPG sensors, and their framework was most effective in removing artifacts induced by micromotions from PPG signals using IR PPG as a motion reference. Our proposed module was tested under three kinds of typical postures(limited), more motion scenes should be designed for experimental verification in further works.

Table 1: Error analysis in different postures.

Typical postures	PWMP mean±SD /bpm	PC-60B mean±SD /bpm	MSE (Mean square error) /bpm
Stationary	73.00±3.16	72.33±2.50	2.00
Free arm swing	80.67±12.95	79.33±12.95	5.66
Typing	70.83±7.52	72.52±6.89	5.33

5 CONCLUSION

Unlike traditional pulse wave monitoring system designs based on priori knowledge or through a lot of experiments and measurements, this paper proposes a commonly used simulation method and an embedded system accordingly to study anti-motion artifacts detection in pulse wave monitoring based on PPG. In this model, a narrow-band full-reflection film plating on a skin-friendly flexible substrate is specially designed for extracting the motion artifact introduced by air. Compared to the conventional MC simulation for static skin model, a new method for PPG signal modeling is also proposed, that is based on Monte-Carlo approach to simulate the dynamic human skin model, so as to achieve the PPG signal. Both PPG signals with/without motion artifact are simulated and the simulation results show that the motion artifact cancellation detection model proposed in this paper provides good reference signal for adaptive algorithm by extracting the motion artifact signal separately. The measurement accuracy of pulse rate by PWMP meets the essential performance from the standard of “YY 0784-2010”. To verify the model proposed, three kinds of typical postures are performed and the results show that the proposed platform has good correlation as compared to the PC-60B in the measurement of pulse rate and the proposed model has the potential to recover pulse wave signal for pulse rate monitoring.

The modeling method for PPG signal proposed in this paper also can be used for further study. The model and embedded system proposed here are intended for continuous long-time, real-time pulse wave monitoring. It has the potential application in long-term human vital sign motoring, especially in blood oxygen, pulse rate and PPG based blood pressure monitoring. But there are still some problems that should be improved in future work, for example, more motion scenes should be designed for experimental verification (Hibbing,Mantis,2018), and in order to obtain more accurate morphological parameters from pulse wave, the signal processing algorithm should also be improved for different motion scenes.

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