Extracting Motional Information from the PhotoPlethysmography Using Reconstruction of the Wavelet Transforms Modulus Maxima

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Abstract— **A movement during measurements can generate motion artifacts in photoplethysmography(PPG) signals. The motion artifacts reflect some information of tester's motion. If we can extract the relevant information from these interferences, it probable will be a new information collection method for portable physiological monitor. This paper first analyzes the relationship between the motion artifact and the PPG signals form the Beer-Lambert law. Then, compare the influence of PPG signals by different direction of movement. Finally, extract the information of motion through the reconstruction of wavelet transforms modulus maxima. Through compares the extracted signal and the real motional signals collected by accelerometer (ACC), two signals have certain relativity. The extracted signal can basically reflect the tester's movement. It will be a new way of community and athletes medical care.**

Key Words—**Wavelet, Modulus maxim, PPG, Motion Artifact.**

I. Introduction

Pulse oximeter has been widely used in clinical applications, but accurate and reliable measurements of blood oxygen saturation are primarily achieved only in static environments [1]. As the PPG signals' measurement and calculation are easy and mature, at the same time oxygen saturation can better reflect the physiological state of tester, the reflectance-mode pulse oximeter are widely used in mobile physiological monitoring devices. However, with the demands of community's physiological monitoring devices, such as wearable, portable monitor equipment, continually increasing, in order to reflect more comprehensive current physical state of tester, people want to get more information, such as motional information, from the PPG signals. The PPG signals are vulnerable to interference, so it can reflect some tester's movement.

Traditional motional information collection method is using the acceleration sensor, which will increase in hardware costs while increasing the size and weight of the portable equipment. This paper will use the digital signal processing methods to extract the motional information form the corrupted PPG signals. Since the frequency spectrum of this noise overlays frequency spectrum of the desired signal traditional filtering methods fail to separate the signals [1]. This paper attempts to use the method of reconstructing the wavelet transform modulus maxima based on the Lipschitz exponent as a judgment to achieve the signals separation.

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II. Motion Artifact in PPG

A. Oxygen saturation measurement

A typical commercial pulse oximeter uses light at two different wavelengths in the red (660nm) and infrared (940nm) regime. The ac component of the light absorbance at each wavelength is obtained from the pulse oximeter and divided by the corresponding dc component. The resulting absorbance is relatively independent of the light intensity at the two wavelengths [2]. Equation 1 denotes the measurement method of the oxygen saturation [3].

$$SpO_2 = \frac{\varepsilon_{Hb}^{\lambda_1}}{\varepsilon_{Hb}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1}} - \frac{\varepsilon_{Hb}^{\lambda_2}}{\varepsilon_{Hb}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1}} \cdot \frac{I_{AC}^{\lambda_1} / I_{DC}^{\lambda_1}}{I_{AC}^{\lambda_2} / I_{DC}^{\lambda_2}} \qquad (1)$$

Where $I_{DC}^{\lambda_1}$ and $I_{DC}^{\lambda_2}$ are the red and infrared light intensity of dc component detected by the photodiode; $I_{AC}^{\lambda_1}$ and $I_{AC}^{\lambda_2}$ are the red and infrared light intensity of ac component; $\varepsilon_{Hb}^{\lambda_1}$ 、 $\varepsilon_{HbO_2}^{\lambda_1}$ and $\varepsilon_{Hb}^{\lambda_2}$ are the red light absorption coefficient of the hemoglobin, the red light absorption coefficient of the oxyhemoglobin ,and the infrared light absorption coefficient of hemoglobin, in arterial blood respectively. These three coefficients are constant.

B. Motion Artifact

As the body's motion, the blood forms the filling state in the blood vessel. It changes the optical path of measurement, which conduct to the motion artifact. A reflectance-mode pulse oximeter on the finger is assumed for this model, where the geometry structure and tissue properties are borrowed from [4] – A finger tip is considered a hemispherical volume that is a homogenous mixture of blood and tissue. The pigmented epidermis and embedded bone are neglected.Light intensity in tissue is described by the Beer-Lambert law[5][1].

$$I_t = I_0 (e^{-\mu_{aT} T})(e^{-\mu_{aV} V})(e^{-\mu_{aA} A}) \qquad (2)$$

Where I_0 is the incident light intensity; I_t is the light intensity detected by the photodiode; at μ_{aT}、 μ_{aV} and μ_{aA} are the absorption coefficient of the bloodless tissue layer, the venous blood layer, and the arterial blood layer, respectively, in units of cm-1; and A and V denote the volume fraction of arterial and venous blood[1].

We divided the A and V into AC and DC components. The heart's pumping action generates arterial pulsation and relative changes in arterial blood volume [1], represented by $\Delta A'$. The body's motion produce relative changes in volume of arterial blood and venous blood, represented by ΔA and ΔV.

$$I_t = I_0(e^{-\mu_{aT}T})(e^{-\mu_{aV}V+\Delta V})(e^{-\mu_{aA}A+\Delta A+\Delta A'}) \quad (3)$$

An arterial blood pressure (e.g.>60mmHg) is much higher than venous pressure (e.g. <10mmHg), so the blood volume in veins is much more susceptible to motion artifacts [6]. We assume that motion primarily affects venous blood volume and therefore neglect arterial volume changes. Equation 3 as:

$$I_t = I_0(e^{-\mu_{aT}T})(e^{-\mu_{aV}V+\Delta V})(e^{-\mu_{aA}A+\Delta A'}) \quad (4)$$

The ac component of the I_t is

$$\Delta I = I_0(e^{-\mu_{aT}T})(e^{-\mu_{aV}V})(e^{-\mu_{aA}A})(e^{-\mu_{aV}\Delta V}e^{-\mu_{aA}\Delta A'}-1) \quad (5)$$

The $I_0(e^{-\mu_{aT}T})(e^{-\mu_{aV}V})(e^{-\mu_{aA}A})$ is the component without the impact of heart's pumping action and body's motion. So the equation 5 can be transformed into equation 6.

$$\frac{\Delta I}{I_{DC}} + 1 = e^{-\mu_{aV}\Delta V}e^{-\mu_{aA}\Delta A'} \quad (6)$$

As $\Delta I << I_{DC}$,

$$\ln\left(\frac{\Delta I}{I_{DC}}+1\right) \approx \frac{\Delta I}{I_{DC}} \quad (7)$$

So equation 7 can be transformed into equation 8

$$\Delta I \approx (-\mu_{aV}\Delta V - \mu_{aA}\Delta A') \cdot I_{DC} \quad (8)$$

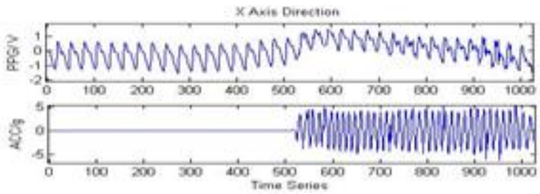
In equation 8, the pervious part caused by the body's movement, the latter weight caused by the heart's pumping action. equation 8 show that the corrupted PPG ac signals are sum of the normal PPG ac signals and the mutative signals caused by the movement of tester.

Relationship between motion Artifact and motion direction

The distribution of fingertip blood vessels makes the different movement orientation produces different influence on PPG signal. For the convenience purpose of researching, the normal movement is divided to three direction's basic movement - X axis, Y axis and Z axis for analysis. Experiment picture shows in fig1. For examine the relationship between interferences and movement, a 3D acceleration sensor was added to blood oxygen probe to collect PPG signal and acceleration signal at the same time. At the meanwhile, minimize the interferences caused by the other factor. During the period of experiment, keep the probe exposing from light. Fig 1(a) is the picture of experiment. The finger maintains stable in the previous half stage of experimentation, the normal signal was gathered, and later half stage the finger moves back-and-forth in three directions separately. Fig 1 (b), (c) and (d) shows the collection of PPG signal and movement acceleration signal when finger moves along the three directions. As can be seen from fig, the PPG signals heavier interfered by movement along Y axis, real signals were almost totally submerged by the movement interference, and the movement along X axis and Z axis contributes less to the interference of PPG signal.

General movement can be decomposed into movement along these three mutually vertical directions, so we analyses on, individually, the movement interfere along three directions, it provides foundation for analysis on more complex movement form.

(a)



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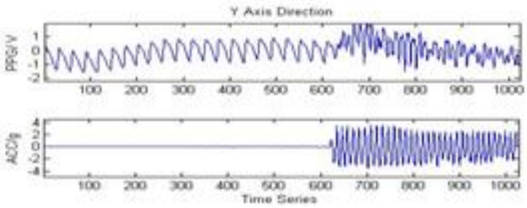

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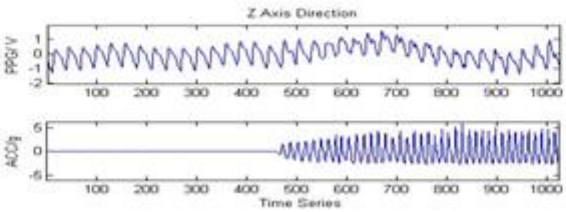

(d)

Figure 1. The Relationship between motion artifact and motion direction

III. MATH WAVELET ANALYSE

For the movement along Y axis heavily interfere the PPG signals, so we will focus on researching the movement info which is extracted from the interference caused by the movement along Y axis. On this thesis we will divide the signal by utilizing the differences Lipschitz exponent of the normal signals and interferences.

A. *Singularities and Lipschitz exponents*

Singularities and irregular structures often carry the most important information in signals. So we will analyze the PPG signal through the singularities and irregular structures. A remarkable property of the wavelet transform is its ability to characterize the local regularity of function. In mathematics, this local regularity is often measured with Lipschitz exponents.

Definition:

Let n be a positive integer and $n \le \alpha \le n+1$ .A function $f(x)$ is said to be Lipschitz α at x_0, if and only if there exists two constants A and $h_0 > 0$, and a polynomial of order n, $P_n(x)$,such that for $h < h_0$

$$|f(x_0+h) - P_n(h)| \le A|h|^{\alpha} \quad (9)$$

The function $f(x)$ is uniformly Lipschitz α over the interval $]a,b[$, if and only if there exists a constant A and for any $x_0 \in]a,b[$ there exits a polynomial of order n, $P_n(x)$,such that equation 9 is satisfied if $x_0 + h \in]a,b[$ [7] .

The Lipschitz exponent is a measurement of the strength of a singularity.

B. Lipschitz exponents and wavelet modules maxima

Theorem:

Let n be a positive integer and $\alpha < n$, let $f(x) \in L^2(R)$. if $f(x)$ is Lipschitz α at x_0 ,then there exists a constant A such that for all point x in a neighborhood of x_0 and any scale s [7].

$$|Wf(s,x)| \le A(s^{\alpha} + |x - x_0|^{\alpha}) \quad (10)$$

When the $s = 2^j$, $x = x_0$,the equation 10 into equation 11

$$|Wf(j,x)| \le A(2^{j*\alpha}) \quad (11)$$

This equation put the wavelet transform scale s, modules maxima and Lipschitz exponent linked. For example, we use symmetric wavelet, the wavelet transform $Wf(j,x)$ will be maximum value when $x = x_0$. Then the two adjacent-scale wavelet transforms modules maxima respectively are:

$$|W_j f(t)| = A2^{j*\alpha}$$

$$|W_{j-1} f(t)| = A2^{(j-1)*\alpha}$$

The ratio of two equations above is:

$$\frac{W_{j-1} f(t)}{W_j f(t)} = 2^{\alpha} \quad (12)$$

This equation shows that the relationship of the wavelet transforms modulus maxima and the Lipschitz exponent.

C. Wavelet transform

In this study, the symlet-4 wavelet with 4 vanishing moments was used to characterize the PPG signals. The symlet-4 wavelet was chosen because of its near symmetric properties which are optimum for quasi-sinusoidal signals such as a PPG signal [8] [9].

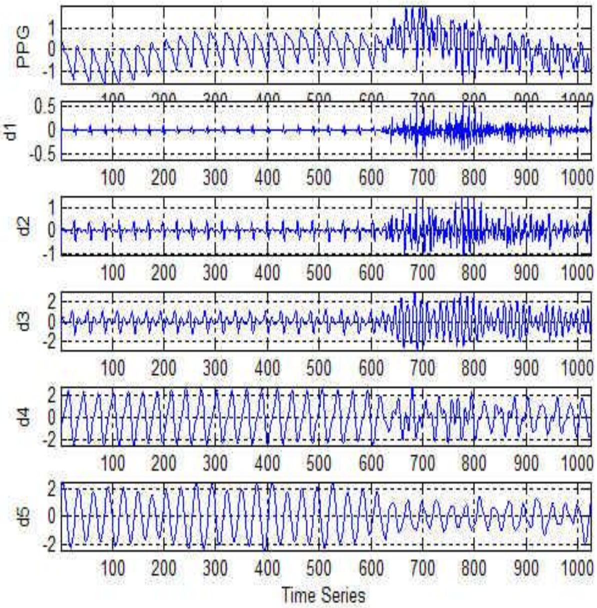

Figure 2. The wavelet transform of PPG signal

As shown in Fig.2, the wavelet decomposition was performed up to level 5 because the d_5 signal contained the cardiac frequency. We can see from Fig.2 the normal signal and the corrupted signal's modulus maxima are thinning with the scale fining. All these indicate that the normal signals and corrupted signal Lipschitz exponents $\alpha > 0$. As the scale constantly fining, the decay rate of the normal signal is faster than the corrupted signal. This indicated that the Lipschitz exponents of normal signal is bigger than the corrupted signal's one.

D. Some Common Mistakes

In this thesis we will separate the normal signal and interference signal by the method which is based on Lipschitz exponents, as it is shown in equation 10, we will using the ratio of d1 and d2 to reflect the Lipschitz exponent. We chose the fine scale level of wavelet modulus maximum value to calculate Lipschitz exponents, because we want only one singularity in the wavelet support at the fine scales. Only like this the Lipschitz exponents can be estimated more accurately and stably.

Figure 3 point out that the normal signal's ratio of two scale level is bigger than the corrupted signal's. According to this we assume that the Lipschitz exponents of normal PPG signals caused by the beating of heart are bigger than the interference signals caused by body's motion. If we can separate the interference signals from the corrupted PPG signals, we will know the tester's related physical movement. Based on the above analysis, we separated modulus maximum caused by body's motion from the corrupted signal modulus maximum by Lipschitz exponents in d1 and d2. And then find out the corresponding transfer modulus maximum in other scale level of wavelet transform. Finally, reconstruct the separated signal through the Mallat alternative projection algorithm. Figure 4 show that the comparison of the reconstructed signal and the signal from the acceleration sensors. Two signals have certain relativity.

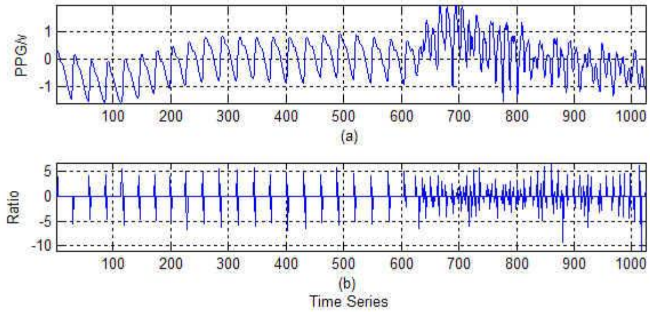

Figure 3. Ratio of two scale level

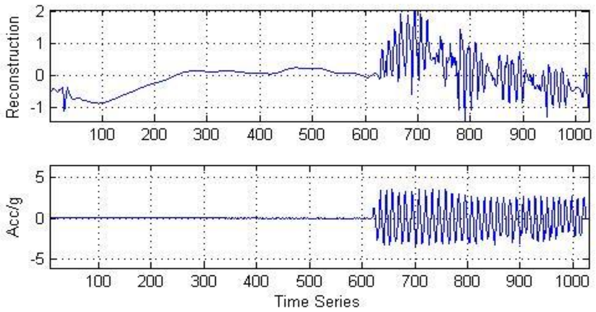

Figure 4. The reconstructed signal and the ACC signal

IV. DISCUSSION

In this article, first we made the conclusion of the relationship between normal PPG ac signals and the movement interference signals. At the same time we divide the movement to 3 directions: x axis, y axis and z axis, also analyzed the interferences status of the PPG and movement signals from all movement directions by comparing analysis. We get the result that the movement along y axis has the biggest force on corrupted PPG signals, while the movement of x axis and z axis only has the minor force, which can be omitted in practical using. At last we used the separate method of wavelet Modulus Maxima and the Mallat alternative projection algorithm to extract the interference signals caused by movement.

Since the effect of the movement interferences on PPG signals is complex, lots of detail is still unknown. We can find that the movement interferences info extracted from the corrupted signal is not enough. From the figure we can see that the reconstructed signal only approximate reflect the situation of motion, still can’t reflect the detailed info about the movement accurately.

The motion information which extracted from the PPG signal , can convenience monitor patient's current activity status by the systems which suing real-time physiological monitoring and community monitoring in patients' home and community where the long-distance medical care and community ,without increasing any hardware or equipment ,we can monitor patients' all the movement status or the activity info of a specific period of time in real-time ,thus we can provide more info for monitoring and doctor’s diagnosis.

As the improvement of the technology about digital signals processing , the continuous refinement improvement will be make for extracting the movement info from interfered PPG signal ,we by this thesis made some useful exploration in this area.

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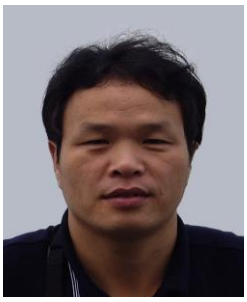

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