31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Pulse Transit Time-based Blood Pressure Estimation Using Hilbert-Huang Transform

Qiao Zhang, Yang Shi, Daniel Teng, Anh Dinh, Seok-Bum Ko,
Li Chen, Jenny Basran, Vanina Dal Bello-Haas, Younhee Choi

Abstract— **The pulse transit time (PTT) based method has been suggested as a continuous, cuffless and non-invasive approach to estimate blood pressure. It is of paramount importance to accurately determine the pulse transit time from the measured electrocardiogram (ECG) and photoplethysmogram (PPG) signals. We apply the celebrated Hilbert-Huang Transform (HHT) to process both the ECG and PPG signals, and improve the accuracy of the PTT estimation. Further, the blood pressure variation is obtained by using a well-established formula reflecting the relationship between the blood pressure and the estimated PTT. Simulation results are provided to illustrate the effectiveness of the proposed method.**

I. INTRODUCTION

The continuous, cuffless and non-invasive measurement/estimation of blood pressure is more desirable for people who need regularly monitoring of their blood pressure. In recent years, the estimation of blood pressure using related physiological parameters has been studied extensively. It is commonly accepted that pulse transit time (PTT) can be regarded as an index of arterial stiffness, and has been employed as an indirect estimation of blood pressure [1]. PTT can be measured as the time interval between the peak of R wave of the electrocardiogram (ECG) and a characteristic point at predetermined thresholds of the photoplethysmogram (PPG) in the same cardiac cycle, which is the blood propagation period from the aortic valve to a peripheral site. The starting point of PTT is the R wave peak of ECG, and mainly there are three different choices of the ending point: (1) the foot of the PPG signal, (2) the peak of the PPG signal, and (3) the maximum inclination of the PPG signal [2].

Different expressions have been derived to characterize the relationship between the blood pressure and the PTT. Most effective ones are Moens-Korteweg's [3] and Bramwell-Hill's [4], which have been widely used. Essentially, the elasticity of an artery was early recognized to be related to the velocity of the volume pulses propagating through it [5].

The pulse wave velocity (PWV) is defined by Moens and Korteweg as a function of such factors as the thickness of vessel wall (t), the elasticity of the arterial wall, the density of blood (ρ) and the interior diameter of the vessel (d). The equation is shown as follows [3]:

$$PWV = \sqrt{\frac{tE}{\rho d}}, \tag{1}$$

where E stands for the Young's modulus describing the elasticity of the arterial wall, and generally it is not a constant. Further, the Young's modulus E was described by Geddes as $E = E_0 e^{\alpha P}$ [3], where E_0 is the modulus of the zero pressure, α is a constant that depends on the vessel, varying from 0.016 mmHg^{-1} to 0.018 mmHg^{-1}, P is the blood pressure, and e is 2.71828. Then we have

$$PWV = \sqrt{\frac{tE_0 e^{\alpha P}}{\rho d}}. \tag{2}$$

In this work, we will apply the relationship formula developed in [6] based on the above Moens-Korteweg formula.

Bramwell and Hill have found that the propagation velocity of the pulse wave in the artery filled with blood is related to the volume-pressure relationship of the artery, with the assumption that the artery is an elastic tube filled with an incompressible and invisible liquid, which can be written as [4]:

$$PWV = \sqrt{\frac{V}{\rho}\frac{\Delta P}{\Delta V}}, \tag{3}$$

where PWV is the velocity of pressure wave, V is the volume of the tube, ρ is the density of the blood, ΔV is the volume change, and ΔP is the change in the distending pressure. The velocity of pressure wave can also be described as $PWV = \frac{L}{T}$, where L is the length of the pulse wave propagation along the artery, and T represents the pulse transit time. Therefore, the velocity of local pressure wave can be readily estimated by using this equation. It requires no knowledge of the thickness and diameter of the vessel, or of the elasticity of the arterial wall, but only the rate of increase of volume with pressure, which is simple and directly observable. The compliance, C, which represents how much the change in the volume is in response to a given change in the distending pressure:

$$C = \frac{\Delta V}{\Delta P}. \tag{4}$$

This research was supported by the Natural Sciences and Engineering Research Council of Canada.

Q. Zhang is with the Division of Biomedical Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9.

Y. Shi (Corresponding Author) is with the Department of Mechanical Engineering and also with the Division of Biomedical Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9. `yang.shi@usask.ca`

D. Teng, A. Dinh, S. B. Ko, L. Chen, and Y. Choi are with the Department of Electrical and Computer Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9.

J. Basran is with the Department of Medicine, University of Saskatchewan, Saskatoon, SK, Canada S7N 5E5.

V. D. Bello-Haas is with the School of Physical Therapy, College of Medicine, University of Saskatchewan, Saskatoon, SK, Canada S7N 5E5.

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

Thus, PTT can be written in terms of compliance and volume [7]:

$$(\frac{L}{T})^2 = \frac{V}{\rho C}. \tag{5}$$

According the above discussion, the blood pressure is inversely proportional to pulse transit time, and the relationship between them is individual-dependent, thus, many authors apply the linear regression in estimating the blood pressure [8]: First, the coefficients of the model are identified based on the experimental data; second, the model is used for blood pressure estimation.

PTT-based blood pressure estimation has received considerable attention. The PPG sensor was developed in [9]. In [10], some important factors that could affect the accuracy of the estimation method were explored. A Butterworth band pass filter was applied to denoise the signals and estimated the PTT [1]. The wavelet transform was employed to detect the peak value of the signals and then calculated the PTT [11]. However, most of the existing methods in the literature have not fully considered the inherent nature of the nonlinear and non-stationary properties of the measured ECG and PPG signals when applying different kinds of signal processing techniques. In this paper, we aim to process the measured signals by using the Hilbert-Huang Transform (HHT) that can effectively process the nonlinear and non-stationary signals.

The remainder of the paper is organized as follows. Section II briefly introduces and reviews the Hilbert-Huang Transform. Section III presents the algorithm that is used to calculate the PTT and estimate the blood pressure. In Section IV, the results are presented to illustrate the effectiveness of the method. Concluding remarks are addressed in Section V.

II. HILBERT-HUANG TRANSFORM

To provide a more efficient method of filtering of a signal from noise for nonlinear, non-stationary data, Huang, et.al. [12] introduced a new approach called the Hilbert-Huang Transform (HHT). Other methods have some inherent shortcomings. Fourier spectral analysis requires the stationarity and linearity. Spectrogram, a limited time window-width Fourier spectral analysis, has to assume the data to be piecewise stationary. Moreover, wavelet analysis has the non-adaptive nature, and the leakage generated by the limited length of the basic wavelet function makes the quantitative definition of the energy-frequency-time distribution. HHT can overcome the limitations of the above mentioned methods. It allows first-time-ever analysis of nonlinear and non-stationary data. HHT is the first adaptive method for measuring things that does not stay still and does not follow regular patterns. The result is a more precise definition of particular events in time-frequency space, and a more meaningful interpretation of underlying dynamic processes that can be obtained by historical methods [13].

HHT consists of two steps. First, the empirical mode decomposition (EMD) method is used to obtain finite intrinsic mode functions (IMF). Second, with the Hilbert transform, the IMFs yield instantaneous frequencies as functions of time. Finally, the Hilbert Spectrum can be obtained, which is an energy-frequency-time distribution. Since the decomposition is based on the local characteristic time scale of the data, it is applicable to nonlinear and non-stationary processes. The detailed dynamics characteristic of a nonlinear system through the instantaneous frequency can be examined using this technique.

With the attractive advantages, HHT has successfully found a wide variety of applications: Basic nonlinear mechanics, climate studies, earthquake engineering, geophysical exploration, submarine design, structural damage detection in bridges and buildings, speech signal processing, satellite data analysis, and so on.

ECG and PPG signals are inherently nonlinear and non-stationary due to lots of interference. Therefore, we apply the HHT to process the ECG and PPG signals to estimate the PTT.

III. ALGORITHM DESCRIPTION

A. *PTT estimation*

HHT is applied to process the ECG and PPG signals, respectively, to obtain the intrinsic mode functions. To achieve so, we need to accurately determine the time instance of the R wave peak in the ECG signal, and recognize several related characteristic points in the PPG signal. First, the IMFs are obtained using the EMD procedure. Second, we reconstruct the signal without noise by ignoring the IMFs corresponding to noise part. Third, each interested IMF is compared with the rebuilt signal to see which one shows better performance on the time instance. The logic flowchart is illustrated in Figure 1.

Generally, PTT is defined as the time interval between the R wave peak of ECG and the peak of PPG in the same cardiac cycle [14].

B. *The estimation of blood pressure*

The mathematical expressions that describe the relationship between the blood pressure and the PTT are given in (1). According to the derived results of [6], substituting the pulse wave velocity $PWV = \frac{L}{T}$ and the elastic modulus $E = E_0 e^{\alpha P}$ into (1), we have

$$\frac{L}{T} = \sqrt{\frac{tE_0 e^{\alpha P}}{\rho d}}, \tag{6}$$

then it follows that

$$P = \frac{1}{\alpha}[\ln \frac{L^2 \rho d}{tE_0} - 2\ln T]. \tag{7}$$

If the changes in the wall thickness and the diameter of the vessel with respect to the change in blood pressure are negligible, and the change in the modulus E_0 is slow enough, the change of blood pressure can be described as:

$$\triangle P = -\frac{2}{\alpha T} dT. \tag{8}$$

Remark 1: It can be seen that the change of blood pressure is related to the PTT. After accurately estimate the PTT, the variation of blood pressure can be readily calculated using (8).

IV. RESULTS

In this section, for the measured ECG and PPG signals, we apply the HHT method to estimate the PTT, and further calculate the change of blood pressure.

The original signals and the empirical mode decomposition components are listed in Figure 2 and Figure 3, respectively.

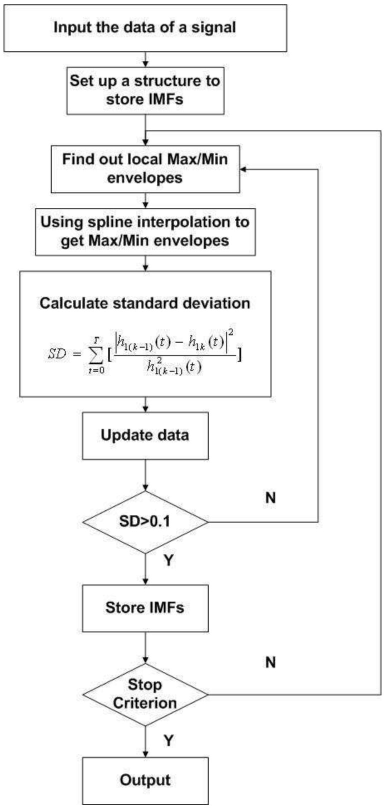

Fig. 1. The logic flowchart to decompose the input signal into successive IMFs.

The peak detection of ECG is performed on the rebuilt signal without noise, as shown in Figure 4. For the PPG, it is noticed that the third IMF of PPG shows better performance in the peak detection comparing with other functions and the rebuilt PPG signal. After detecting the peak of the signals, the time interval between ECG and PPG in the same cardiac cycle can be determined, which will be used to estimate the blood pressure. Compared with the intrinsic model functions of ECG, the rebuilt signal clearly shows better performance to determine the R wave peak information.

The ECG and PPG are collected at 256 Hz and the constant parameter α is fixed as 0.017 mmHg^{-1}. The change of blood pressure can be readily calculated: Some of the

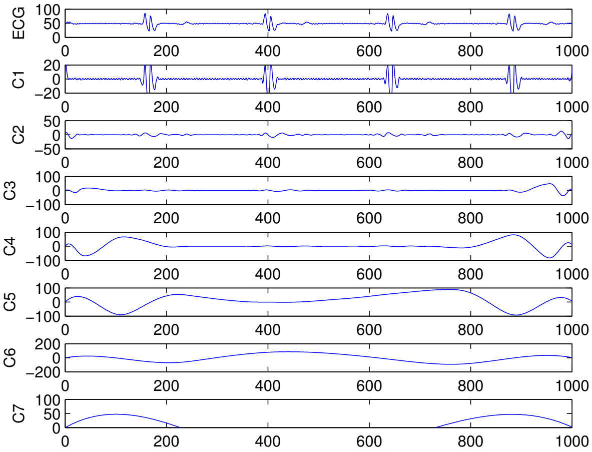

Fig. 2. The original ECG and the empirical mode decomposition components C1-C7.

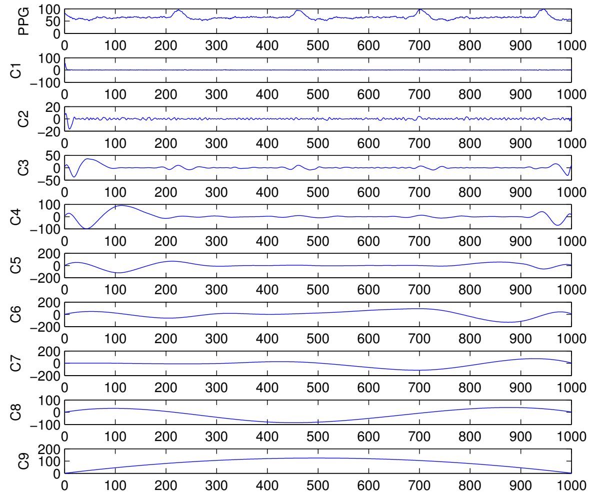

Fig. 3. The original PPG and the empirical mode decomposition components C1-C9.

TABLE I

THE PULSE TRANSIT TIME AND THE CHANGE OF BLOOD PRESSURE

Peak of ECG	Peak of PPG	PTT (s)	Change of BP (mmHg)
157	223	0.2578	
395	460	0.2539	1.8100
636	700	0.2500	1.8382
876	942	0.2578	-3.5651
1116	1183	0.2617	-1.7559

estimated data are shown in Table I.

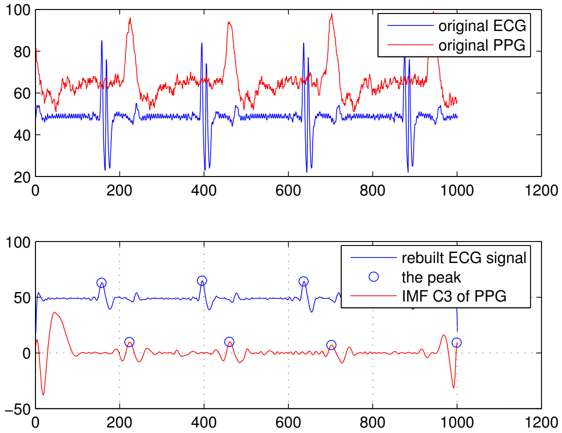

Fig. 4. The original signals and the detection of the peak based on the rebuilt ECG and IMF C3 of PPG.

Remark 2: A good estimation of the blood pressure variation is very useful in monitoring patients' health status, and it can be potentially applied to the fall and near-fall detection system, developed by our research team. If the base blood pressure level is known, then we can obtain the estimated blood pressure.

V. CONCLUSION

In this paper, we apply the HHT to process the measured ECG and PPG signals, and further estimate the PTT, and finally calculate the variation of blood pressure. Simulation results for the measured ECG and PPG signals illustrate the effectiveness of the proposed method. It is worthwhile noting that to further explore the more accurate relationship between the PTT and the blood pressure will be of importance for applications, which is our future work.

REFERENCES

[1] C. Ahlstrom, A. Johansson, F. Uhlin, T. Lanne, and P. Ask, Noninvasive Investigation of Blood Pressure Changes Using the Pulse Wave Transit Time: a Novel Approach in the Monitoring of Hemodialysis Patients, *The Japanese Society for Artificial Organs*, vol. 8, 2005, pp. 192-197.

[2] T. Ma and Y. T. Zhang, "A Correlation Study on the Variabilities in Pulse Transit Time, Blood Pressure, and Heart Rate Recorded Simultaneously from Healthy Subjects", *Proceeding of the 27th Annual Conference of the IEEE Engineering in Medicine and Biology*, Shanghai, China, September 1-4, 2005, pp. 996-999.

[3] S. H. Shin, Y. B. Park, H. W. Rhim, W. S. Yoo, Y. J. Park, and D. H. Park, Multibody Dynamics in Arterial System, *Journal of Mechanical Science and Technology*, vol. 19, no. 1, 2005, pp. 343-349.

[4] M. Nitzan, B. Khanokh, and Y. Slovik, The Difference in Pulse Transit Time to the Toe and Finger Measured by Photoplethysmography, *Physiological Measurement*, vol. 23, 2002, pp. 85-93.

[5] X. F. Teng and Y. T. Zhang, "Theoretical Study on the Effect of Sensor Contact Force on Pulse Transit Time", *IEEE Transactions on Biomedical Engineering*, vol. 54, no. 8, August, 2007, pp. 1490-1498.

[6] W. Chen, T. Kobayashi, S. Lchikawa, Y. Takeuchi, and T. Togawa, Continuous Estimation of Systolic Blood Pressure Using the Pulse Arrival Time and Intermittent Calibration, *Medical and Biological Engineering and Computing*, vol. 38, 2000, pp. 569-574.

[7] F. J. Callaghan, C. F. Babbs, J. D. Bourland, and L. A. Geddes, The Relationship between Arterial Pulse-wave Velocity and Pulse Frequency at Different Pressures, *Journal of Medical Engineering and Technology*, vol. 8, no. 1, 1984, pp. 15-18.

[8] Y. Yoon, J. H. Cho, and G. Yoon, Non-constrained Blood Pressure Monitoring Using ECG and PPG for Personal Healthcare, *Journal Medicine System*, 2008, DOI 10.1007/s10916-008-9186-0.

[9] P. Shaltis, A. Reisner, and H. Asada, "Calibration of the Photoplethysmogram to Arterial Blood Pressure: Capabilities and Limitations for Continuous Pressure Monitoring", *Proceeding of the 27th Annual Conference of the IEEE Engineering in Medicine and Biology*, Shanghai, China, September 1-4, 2005, pp. 3970-3974.

[10] C. C. Y. Poon, Y. T. Zhang, and Y. Liu, "Modeling of Pulse Transit Time Under the Effects of Hydrostatic Pressure for Cuffless Blood Pressure Measurements", *Proceeding of the 3rd IEEE EMBS*, MIT, Boston, USA, September 4-6, 2006, pp. 65-68.

[11] D. L. Li, Y. Pan, H. Chen, S. M. Ye, and H. Yan, "The Establishment of a Non-invasive Continuous Blood Pressure Measure System based on Pulse Transit Time", *The 2nd International Conference on Bioinformatics and Biomedical Engineering*, Shanghai, China, May 16-18, 2008, pp. 1624-1627.

[12] N. E. Huang, Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung, and H. H. Liu, "The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Nonstationary Time Series Analysis", *Proceedings of Royal Society of Lond A*, vol. 454, 1998, pp. 903-995.

[13] N. E. Huang, Z. Shen, and S. R. Long, A New View of Nonlinear Water Waves: the Hilbert Spectrum, *Annual Review of Fluid Mechanics*, vol. 31, 1999, pp. 417-457.

[14] E. K. Park, B. H. Cho, S. H. Park, J. Y. Lee, I. Y. Kim, and S. I. Kim, "Continuous Measurement of Systolic Blood Pressure Using the PTT and Other Parameters", *Proceeding of the 27th Annual Conference of the IEEE Engineering in Medicine and Biology*, Shanghai, China, September 1-4, 2005, pp. 3555-3558.