A Novel Method for Pulse Transit Time Estimation Using Wrist Bio-Impedance Sensing Based on a Regression Model

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***Abstract*—Pulse transit time (PTT) is a promising method to estimate blood pressure using a wearable device. In this work, we explore the measurement of PTT using two bio-impedance (Bio-Z) sensors placed on the wrist 7.5 cm apart such that they can be integrated into a wrist watch. In order to take into account the different factors affecting blood flow in the wrist, a regression model is used based on multiple features extracted from the first and second derivative of Bio-Z. The estimated PTT is compared with a reference PTT measured from ECG and PPG sensors. Experimental measurements are conducted on three subjects and exhibited an average correlation coefficient of 0.77 for the PTT estimated from wrist Bio-Z compared to the reference PTT.**

Keywords— PTT; Bio-Z; regression model; Blood pressure

I. INTRODUCTION

Cardiovascular disease (CVD) is one of the most important ailments affecting a large number of people around the world. High blood pressure is a major factor that leads to CVD. Continuous monitoring of blood pressure (BP) is very important for early diagnosis and disease management. The most common method for BP monitoring is based on an inflatable cuff which is uncomfortable and not suitable for continuous BP monitoring during daily activities.

A prominent solution for continuous monitoring of BP in the literature is the measurement of pulse transit time (PTT), which does not require a cuff. Conventionally, PTT is measured based on the time delay between the R-peak of the electrocardiogram (ECG) and the point of maximum slope of the photoplethysmography (PPG) on the finger as shown in Fig. 1. It has been shown that PTT is correlated with BP, so PTT could be translated to BP in presence of suitable calibration techniques [1,2]. However, most existing solutions do not represent a single integrated PTT measurement device in a wearable form factor that is easy to use.

Bio-impedance (Bio-Z) is another signal that can be used to monitor PTT as shown in [3] which explored measuring PTT from ECG and a bio-impedance sensor on the wrist. Bio-Z is a non-invasive electrical method to measure blood volume change due to cardiac activity [4] without suffering from the optical issues of the PPG sensors such as ambient light effect and the isolation between the light source and the photodetector. In addition, Bio-Z is suitable for wearable devices because it is low cost, low power, and multiple sensors can be easily integrated into a watch.

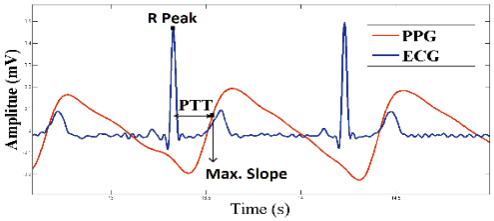

Fig. 1. PTT estimation using ECG and PPG waveforms.

Those PTT measurement methods depend on ECG, which has two issues. Firstly, there is a pre-ejection period (PEP) which is the time from the onset of the R-peak to the start of the actual pumping of blood out from the heart. So in effect, these methods are measuring PEP in addition to the actual PTT. This introduces challenges because the PEP can vary from beat to beat unpredictably, thus confounding the attempts to measure PTT [5]. Furthermore, most typical ECG lead configurations measure the potential between 2 electrodes on each side of the heart, which is challenging to realize in a device with a small form factor that must be easily wearable.

Other previous work explored the possibility of excluding ECG by using two different PPG sensors, one on the finger and the second on the wrist, to measure PTT [6] or using a pair of Bio-Z channels on the forearm [7]. However, their results were not validated with any existing established measures of PTT. To the best of our knowledge, there is no previous work that measured PTT from the wrist alone and compared it to a reference PTT. It is important to note that despite our investigation incorporates patch-based sensors, the extension of the proposed study will be applicable to dry-contact sensors that could be placed on the back of the smart watches. The contributions of this paper can be summarized as:

- A novel method to estimate PTT using a regression model based on multiple features extracted from two Bio-Z sensors placed on the wrist in a small area of 2.5x7.5 cm, which can be integrated into a wrist watch for continuous BP monitoring.
- The circuits and signal processing of the Bio-Z sensor are designed to measure the small variations and delays of the Bio-Z within a small area on the wrist.
- A set of features is extracted from the first and second derivative of the wrist Bio-Z to estimate PTT.
- Experimental results from three subjects show a high correlation between the estimated and reference PTT.

In this paper, Section II discusses the details of our method. The experimental results are presented in Section III and then, the conclusion in section IV.

II. METHODS

A. PTT Measurement Circuits

From our measurements, the average amplitude of Bio-Z variation is 100 mΩ due to blood volume change at the wrist and the maximum PTT through 7.5 cm is 10 ms. Therefore, a highly sensitive Bio-Z sensor was designed based on discrete components that include analog front-end circuits for current injection and voltage sensing, an analog-to-digital converter (ADC) for data sampling, and finally, signal processing algorithms for signal demodulation and filtering as shown in Fig. 2 (a). The Bio-Z was measured by generating an AC current signal from a DAC controlled by an MCU that generateed a voltage waveform followed by a V-to-I converter to convert the voltage to current. The current was applied to the wrist through 2 electrodes and in between, there were 2 pairs of sensing electrodes as shown in Fig. 2 (b). The sensing path for each Bio-Z sensor included instrumentation amplifier (IA) which is AD8421 from Analog Devices with low noise spectral density of 3.5 nV/√Hz at 1 kHz followed by an ADC. Then, the signal was demodulated in the digital domain by multiplying it by the carrier from the DAC output followed by a low-pass filter with a cut-off frequency of 4.4 Hz to remove the out of band noise, and to allow for measuring practical heart rates up to 180 beats per minute.

The reference PTT is the ECG-to-PPG PTT which was calculated from ECG and PPG on the finger. Although this reference PTT depends on ECG and suffers from the PEP problem, it was the only available standard method that could be used as our reference. The ECG was measured by the SparkFun Single Lead Heart Rate Monitor, which is based on the AD8232 analog front end developed by Analog Devices. The ECG electrodes were placed one on each arm to provide a single channel of ECG. The PPG was measured using the AFE4490 EVM by Texas Instruments. The sensor itself is a finger-clip based transmitting type PPG device attached to the index finger. All the signals were simultaneously sampled by the ADC ADS1274 from Texas Instruments at 64 kSPS to enable accurate measurement of PTT with an error less than 15.7μs, which is much smaller than the average PTT.

B. Bio-Z Features and Regression Model

The typical Bio-Z signal from a sensor placed on the wrist is shown in Fig. 3. When blood rushes to the artery at the sensor location, the Bio-Z signal falls from the maximum impedance (peak) to the maximum descending slope (MDS) point and then down to the minimum impedance (foot), followed by other smaller peaks and foots due to reflection pulses that decay with time till the arrival of the new pulse.

The PTT can be measured directly from the delay between the two Bio-Z signals on the wrist. Unfortunately, the delay across a small distance on the wrist is very small compared to the descending time from the peak to the foot. Therefore, small variations in the Bio-Z descending slopes between Bio-Z1 and Bio-Z2 causes different delays between their peak, MDS and foot points. In order to consider this effect, PTT was estimated using a regression model based on three different delays (T_n, T_m and T_p) at the start, middle and end of the descending slope as shown in Fig. 4. T_m is calculated as the delay from the MDS point of Bio-Z1 to Bio-Z2, while T_n and T_p are the delays between the negative and positive peaks of the second derivative of Bio-Z1 and Bio-Z2. The second derivative is used to calculate the start and end time of the descending slope instead of the peak and foot of the Bio-Z because they are affected by the reflection pulses that vary from beat to another.

To capture all the factors related to the slope, the maximum descending slope (MDS_1 and MDS_2) of Bio-Z signals were extracted from the amplitude of the negative peak of the first derivative. The descending time (DT_1 and DT_2) and the amplitude of the positive and negative peaks of the second derivative (A_{n1}, A_{p1}, A_{n2}, A_{p2}) are useful features that are correlated to the slope. The heart rate (HR) is also an important feature that affects PTT especially during fast changes of HR.

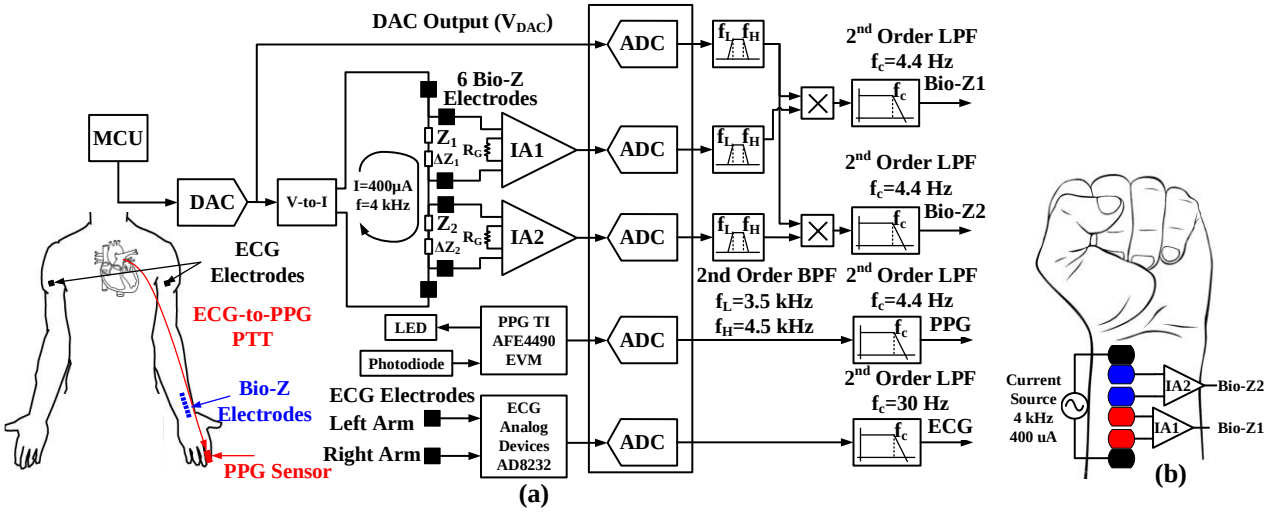

Fig. 2. (a) Overall measurement circuit schematic and the placement of Bio-Z, ECG and PPG sensors, (b) The placement of the current injection electrodes, Bio-Z1 and Bio-Z2 sensing electrodes

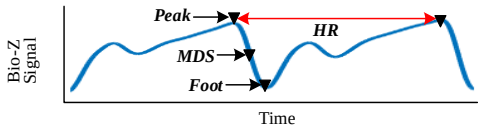

Fig. 3. Bio-Z signal showing HR and, peak, foot and MDS points.

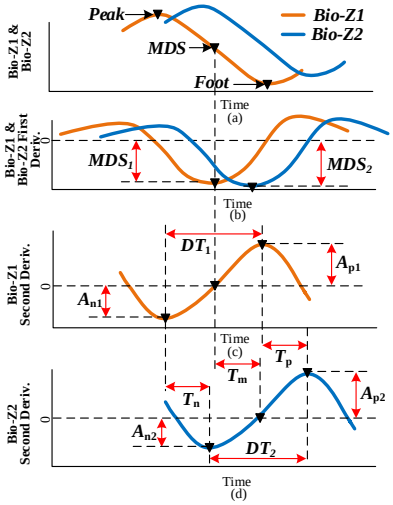

Fig. 4. (a) Bio-Z descending slope and the features as extracted from (b) Bio-Z first derivatives, (c) and (d) Bio-Z1 and BioZ2 second derivatives.

All these features were used by a regular linear regression model to estimate the PTT (PTT_{est}). This simple model is attractive for wearable devices because of its low computational cost while it shows reasonable results in estimating the PTT based on the features extracted from the Bio-Z signal. The model took the aforementioned features as the input and estimated the PTT_{est} in the output as shown in (1). The reference PTT (ECG-to-PPG PTT) was used to train the model and find the coefficients of this model:

$$PTT_{est} = b_0 + b_1T_n + b_2T_m + b_3T_p + b_4DT_1 + b_5DT_2 + b_6A_{n1} + b_7A_{p1} + b_8A_{n2} + b_9A_{p2} + b_{10}MDS_1 + b_{11}MDS_2 + b_{12}HR \quad (1)$$

Where b_i's are the coefficients that were calculated in the linear regression model for each subject. The data set was divided into 60% for training and 40% for testing.

III. Experimental Results

The Bio-Z sensor was first calibrated leveraging a known fixed resistor to convert voltage to resistance. The RMS error of the Bio-Z sensor was measured to be less than 1mΩ, which is much lower than the target Bio-Z variations. The delay between the two Bio-Z channels was confirmed to be within ±1 ADC time step, which is not significant in measuring PTT.

Covidien gel ECG patches were used for the Bio-Z and ECG electrodes. The two Bio-Z sensors were placed along the radial artery within 5 cm distance of each other to potentially fit in a wrist watch as shown in Fig. 5. Based on experimental testing of the Bio-Z sensor on radial and ulnar arteries at different frequencies from 2 to 16 kHz, the radial artery and the frequency of 4 kHz were the best configuration to detect the variations of Bio-Z due to blood flow. The current amplitude was also adjusted to 400µA to be compliant with safety standards [8].

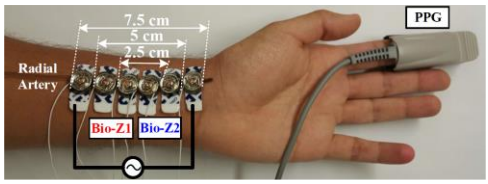

Fig. 5. The placement of electrodes on the wrist for the Bio-Z1 and Bio-Z2 sensors and the PPG finger clip.

The data was collected from 3 subjects with 10 trials each while seated on a chair; each trial was 8 seconds, limited by the maximum number of points that can be acquired by the ADC software provided with the EVM. The trials were evenly divided to represent 3 different states: normal condition, Valsalva breathing maneuver [9], and immediately after preforming push-ups for 30 seconds. These actions introduced temporary changes in BP, and thus PTT, to train and test our model. The data was collected from human subjects under IRB approval IRB2017-0086D. Fig. 6 shows an example of the four simultaneous physiological signals as measured by our circuits and after filtering and signal processing. The average Bio-Z was 132.8 Ω and 129.1 Ω with variations of 85 mΩ and 102 mΩ for Bio-Z1 and Bio-Z2, respectively.

The time delay from ECG R-peak to the MDS point of Bio-Z1, Bio-Z2 and PPG were compared beat-to-beat as shown in Fig. 7. The time delay of the PPG signal was larger than those of Bio-Z1 and Bio-Z2, since it represents the maximum distance traveled by the pulse wave till reaches the finger. The figure also shows that all delays are correlated together from beat to beat.

We observe that Bio-Z1, which is nearer to the heart, has an unexpected higher delay compared to Bio-Z2. This can be explained by the observation of the descending edges of both Bio-Z1 and Bio-Z2 as shown in Fig. 8.

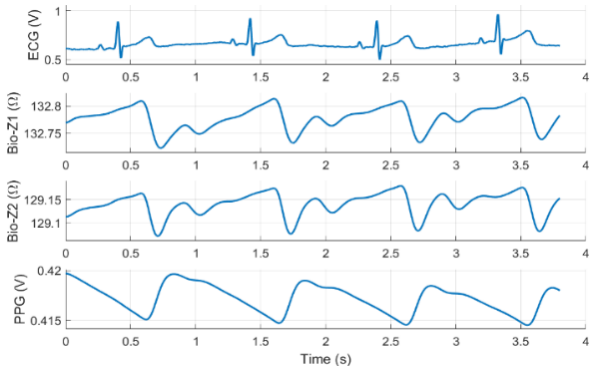

Fig. 6. ECG, Bio-Z1, Bio-Z2 and PPG signals as measured by our circuit

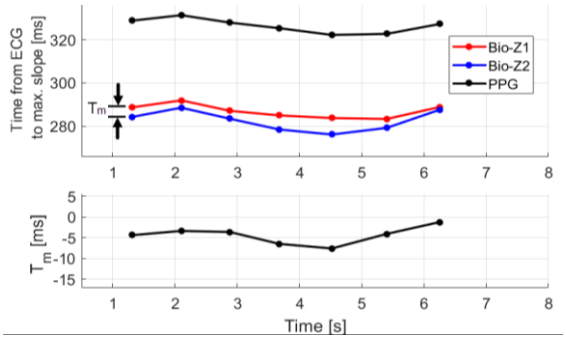

Fig. 7. The beat-to-beat time delay from ECG R-peak to the MDS point of Bio-Z and PPG (above), the time delay (T_m) between two Bio-Z (below).

Bio-Z1 starts falling before Bio-Z2, which shows the arrival of the blood pulse at Bio-Z1 before Bio-Z2. On the other hand, Bio-Z2 has faster descending slope than Bio-Z1, which results in the leading of Bio-Z2 MDS and foot points relative to Bio-Z1 and thus, negative T_m and T_p delays. The delays between Bio-Z1 and Bio-Z2 are different at peak, MDS and foot points because of different slopes. This shows the importance of estimating PTT over such small distances on the wrist using multiple features based on the delays and slopes of Bio-Z1 and Bio-Z2.

The beat-to-beat correlation between PTT measured from the wrist Bio-Z and the reference PTT for subject #3 was 0.35, as shown in Fig. 9, in the case of considering only the delay between MDS points of the two Bio-Z (T_m). However, using the regression model based on the proposed features, the correlation between the PTT_{est} and the reference PTT was increased to 0.78 as shown in Fig. 10. The data of estimated PTT from Bio-Z was aggregated for all the subjects and the average correlation coefficient was 0.86 for the training data set and 0.77 for the testing data set as shown in Fig. 11 and Fig. 12. The correlation coefficient could be higher if the actual PTT is used as the reference, without the PEP that accompanies ECG and introduces error in the measured PTT. According to these results, BP can be estimated from wrist Bio-Z using the proposed features that can model PTT with high correlation.

IV. Conclusion

In this paper, PTT was estimated from two Bio-Z sensors placed on the wrist. Multiple features were proposed based on time delays and slopes of the two Bio-Z signals. Experimental results exhibited a high correlation between the estimated PTT from wrist Bio-Z and the reference PTT. This work would enable the development of a continuous BP monitoring wearable device in the form of a wrist watch.

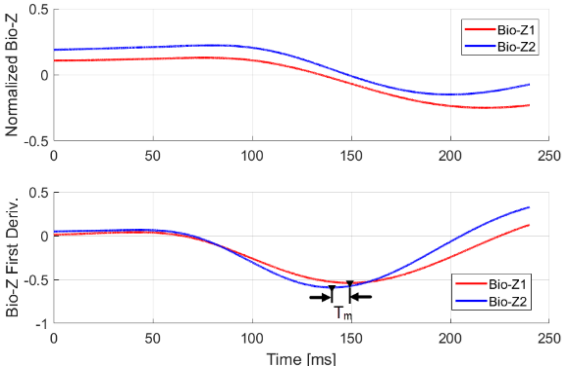

Fig. 8. An example of measured Bio-Z signals and their first derivative

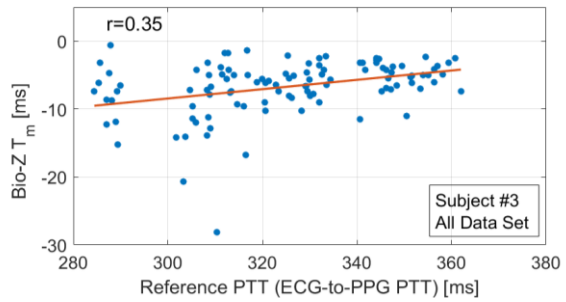

Fig. 9. The correlation between the T_m and reference PTT for subject #3

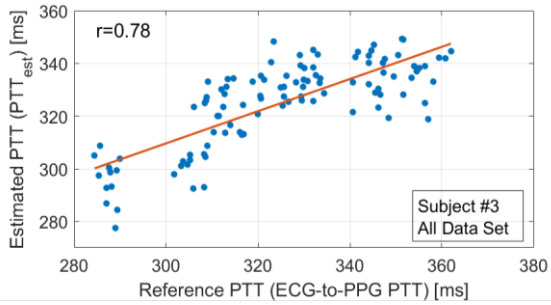

Fig. 10. PTT estimated for subject#3 after using the regression model.

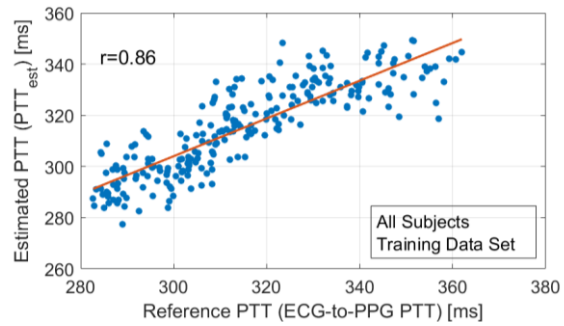

Fig. 11. PTT estimated from Bio-Z for training data set of all subjects.

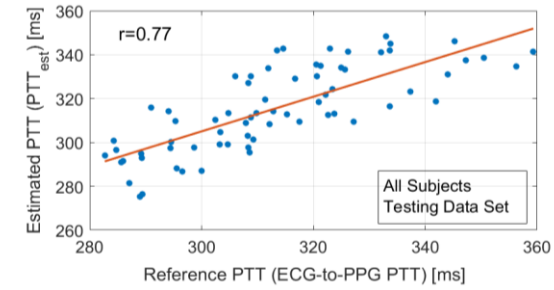

Fig. 12. PTT estimated from Bio-Z for testing data set of all subjects.

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