Multi-source Multi-frequency Bio-impedance Measurement Method for Localized Pulse Wave Monitoring

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***Abstract*—Continuous monitoring of cardiac parameters such as blood pressure (BP) and pulse transit time (PTT) from wearable devices can improve the diagnosis and management of the cardiovascular disease. Continuous monitoring of these parameters depends on monitoring arterial pulse wave based on the blood volume changes in the artery using non-invasive sensors such as bio-impedance (Bio-Z). PTT and BP monitoring require the measurement of multiple pulse signals along the artery through the placement of multiple sensors within a small distance. Conventionally, these Bio-Z sensors are excited by a single shared current source, which results in low directivity and distortion of pulse signal due to the interaction of the different sensors together. For a localized pulse sensing, each sensor should focus on a certain point on the artery to provide the most accurate arterial pulse wave, which improves PTT and BP readings. In this paper, we propose a multi-source multi-frequency method for multi-sensor Bio-Z measurement that relies on using separate current sources for each sensor with different frequencies to allow the separation of these signals in the frequency domain, which results in isolation in the spatial domain. The effectiveness of the new method was demonstrated by a reduction in the inter-beat-interval (IBI) root mean square error (RMSE) by 19% and an increase of average PTT by 15% compared to the conventional method.**

Keywords – Cuffless blood pressure (BP); pulse transit time (PTT); bio-impedance (Bio-Z).

I. Introduction

Cardiovascular disease (CVD) is the leading cause of death worldwide and its burden is estimated to be $200 billion per year [1]. Blood pressure (BP) is one of the major risk factors for CVD [2]. The current BP monitoring methods depend on a bulky and obtrusive cuff that only allows sporadic blood pressure readings. However, BP changes significantly throughout the day and high BP during sleeping is a critical risk for CVD [3]. Therefore, there is a crucial need to monitor BP continuously using cuffless methods based on non-invasive sensors that can be integrated into wearable devices such as smart watches to improve the diagnosis and management of CVD. Previous studies showed that cuffless BP can be estimated from features extracted from the arterial pulse signal at the wrist based on the morphology of the pulse signal and pulse transit time (PTT) which is the time delay between the pulse signal between two points along the artery [4-6]. The arterial pulse wave can be measured from blood volume changes in the arteries using non-invasive sensors

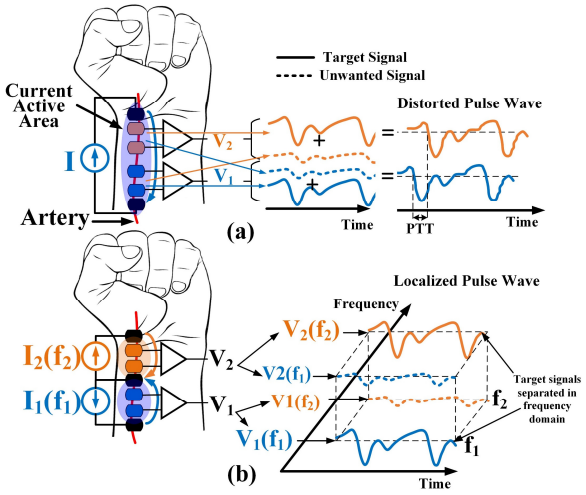

Fig. 1. (a) Conventional Bio-Z sensing for PTT using single current source. (b) Proposed multi-source multi-frequency bio-impedance sensing method for localized pulse wave monitoring.

such as bio-impedance [7, 8]. Bio-impedance (Bio-Z) can measure the fluids inside the body at a certain location by injecting AC current from a pair of electrodes and sensing voltage from a separate pair of electrodes placed in between the current electrodes. By placing the electrodes on the wrist arteries, the variations of Bio-Z signal represent the blood volume changes at the wrist, which can be used to estimate pulse arrival time and subsequently BP. The depth coverage of Bio-Z sensor has a longer range inside the tissue due to the deep penetration of the current signal inside the tissue that can reach deep arteries and provide accurate arterial pulse wave monitoring, in particular compared to optical modalities. For PTT and BP measurements from the wrist, we need to place multiple Bio-Z sensors at the wrist arteries within a small distance that focus on specific points on the artery to measure localized PTT and subsequently BP [9-11]. The conventional method of measuring PTT from multiple Bio-Z sensors is based on measuring multiple voltage signals excited by a single shared current source [12]. In this case, multiple Bio-Z voltage electrodes are placed in between a pair of current electrodes that are connected to a shared current source which results low directivity of the measured pulse signal. The measured voltage signal corresponds to the target pulse signal at the voltage sensing site, but distorted by unwanted signal

This work was supported in part by the National Institutes of Health, under grant 1R01EB028106-01 and National Science Foundation, under grant CNS-1738293.

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due to the impedance change within the tissue area of the other sensors as shown in Fig. 1 (a). Therefore, each measured pulse signal using a single current source will represent an average of the pulse activity over a wide area of the artery that results in low directivity and distortion of the pulse signal that reduces the accuracy of PTT and BP features, which cause higher error in BP estimation.

In this paper, we propose using a separate current source for each Bio-Z voltage channel with different current injection frequencies for each current source as shown in Fig. 1 (b). Each current source is responsible for injecting current signal in a certain location at each voltage sensor. Each voltage channel will combine the target signal from the corresponding current source in addition to other unwanted signals from all other current sources. If a single frequency used for all current sources, we will not be able to separate the target signal from the unwanted signals. In our method, we are using different frequencies for the current sources, in addition to bandpass filters at the voltage sensing side to pass only the target signal from the corresponding current source at the sensing location while removing all the other unwanted signals from the other locations activated by the other sources. Therefore, the separation of current signals in the frequency domain will result in spatial isolation between the different Bio-Z sensors. Consequently, this method measures localized pulse signal with more focus on a specific point on the artery, which leads to sharper Bio-Z pulse with improved BP features. The sharper Bio-Z pulse leads to lower IBI error compared to a reference pulse signal for each Bio-Z signal and higher PTT values between the Bio-Z sensors. Lower IBI error leads to an improvement in the detection of pulse characteristics, which improves the BP accuracy. In addition, larger PTT values result in BP estimation with less sensitivity to the PTT error and thus more accurate BP monitoring.

In this paper, Section II explains the hardware and signal processing methodology. Section III covers the reporting and discussion of the experimental results. The conclusion is presented in Section IV.

II. Methods

A. Bio-Z & PTT Measurement Hardware

We used our custom multi-source Bio-Z measurement system to monitor PTT by using two pairs of Bio-Z sensors to track the bio-impedance change along the radial artery and three electrodes had been used to inject multi-frequency AC currents. The system is based on an ARM Cortex M4 MCU that controls the generation of the AC currents with programmable amplitude and frequency by using two 16-bit DACs. Based on the experimental testing of the Bio-Z sensor on radial artery at 2 to 16 kHz, the frequencies were chosen to be 10.42 kHz and 11.72 kHz with frequency separation between them equal to 1.3 kHz, which is sufficient to use a bandpass filter to select the target carrier signal and filter out

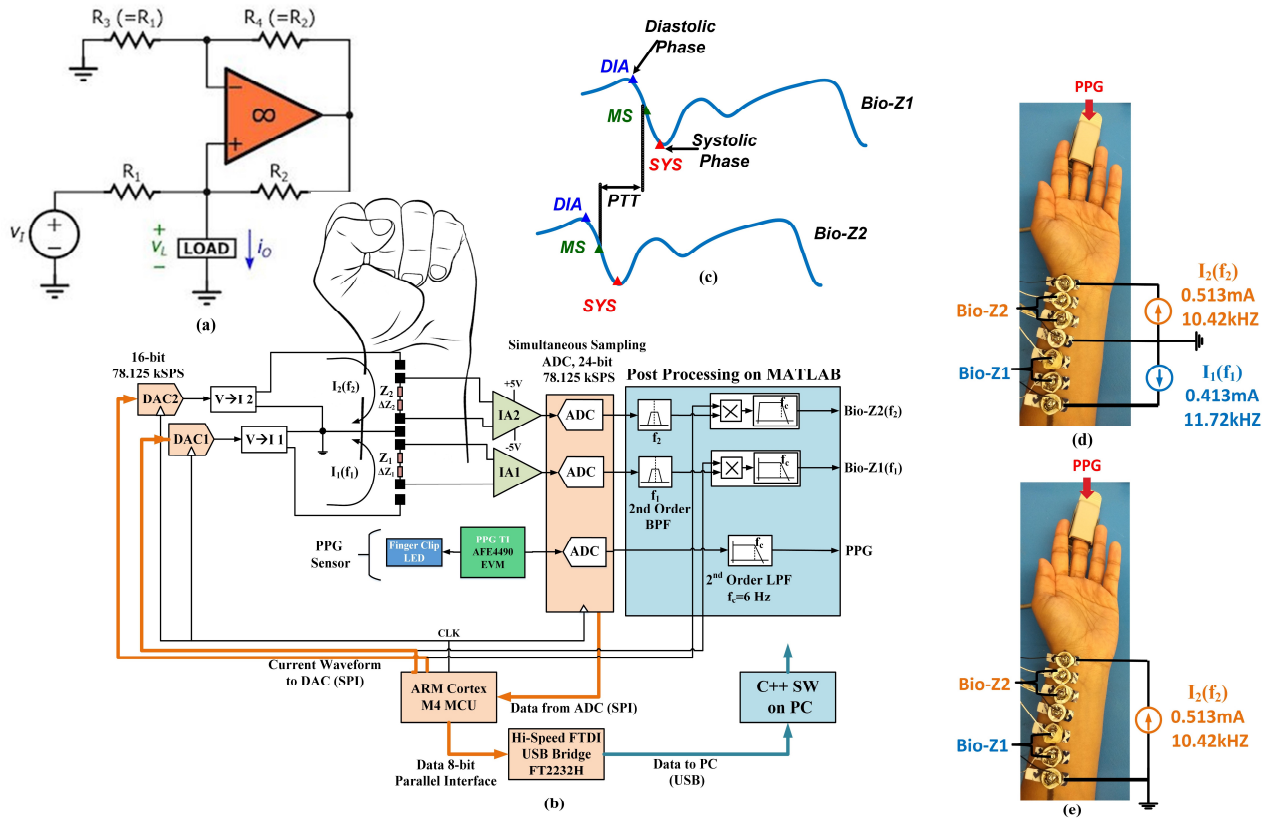

Fig. 2. (a)) Howland current source , (b) PTT measurement circuit schematic including PPG, (c) estimation of PTT form the time delay of two Bio-Z signals, (d) the placement of Bio-Z electrodes on the wrist for multi-source current injection, (e) the placement of Bio-Z electrodes on the wrist for single current source injection.

the other carrier with high attenuation. Two identical Howland current sources with similar schematics as shown in Fig. 2 (a) worked as V-to-I converter to transform each DAC voltage waveform into the current signal. Howland current source is a unity gain difference amplifier based on LT6375 chip from Analog Devices which produces a current dividing the input voltage by a load resistance. The GND terminal of the load of the Howland current source is shared between the two sources and connected to an additional electrode placed between two pairs of Bio-Z sensors. The sensing path for each Bio-Z sensor included instrumentation amplifier (IA) which is AD8421 from Analog Devices with a low noise spectral density of 3.5 nV/√Hz at 1 kHz to obtain RMS error in Bio-Z measurements less than 1mΩ. The IAs are followed by an ADC that samples the Bio-Z signals at a sampling rate of 78.125 ksps as shown in Fig. 2 (b). All the channels of the ADC were sent to the MCU, then stored in the PC as binary files through a USB bridge from FTDI. The carrier from the DAC output was used to demodulate the ADC signals using MATLAB code. The signals were followed by a low-pass filter with a cut-off frequency of 6.0 Hz to remove high-frequency noises. A PPG signal from the finger was used as a reference pulse signal which was measured using a finger clip device connected with AFE4490 EVM by Texas Instruments. To analyze the improvement of the method a single frequency current injection circuit has been used. Through MCU, an AC current at 10.42 kHz has been injected using a DAC and a V-to-I board. Two pairs of Bio-Z sensors were used to estimate PTT.

B. Bio-Z Features

The Bio-Z sensors are placed on a wrist to extract certain features and points from each pulse signal. When the heart pumps blood into the arteries, the Bio-Z signal falls from the peak point (DIA) which represents the diastolic phase to the foot point (SYS) which represents the systolic phase passing a maximum slope point (MS) as shown in Fig. 2 (c). As a new pulse arrives, there may be some smaller peaks and foots showing the reflection of blood through the wrist arteries.

PTT is the time difference that pulse needs to reach one point from another, thus PTT can be measured directly from the delay between the two Bio-Z signals on the wrist. As the distance between the electrodes is very small and the circuit is highly sensitive, a slight variation of movement can cause different delays in their peak and foot points. In order to ensure the highest accuracy, PTT has been estimated from the differences of the maximum slope points (MS) between two Bio-Z signals.

Root mean square error (RMSE) of inter beat interval (IBI) was also extracted from the pulse signals to monitor the quality of the signal. IBI is estimated as the difference between two consecutive MS. The IBI of Bio-Z has been compared with the IBI of the reference PPG to get the RMSE error as follows:

$$\text{IBI RMSE Error} = \sqrt{\frac{\sum_{i=1}^{n}(|IBI\ Bioz_i - IBI\ PPG_i|)^2}{n}}$$

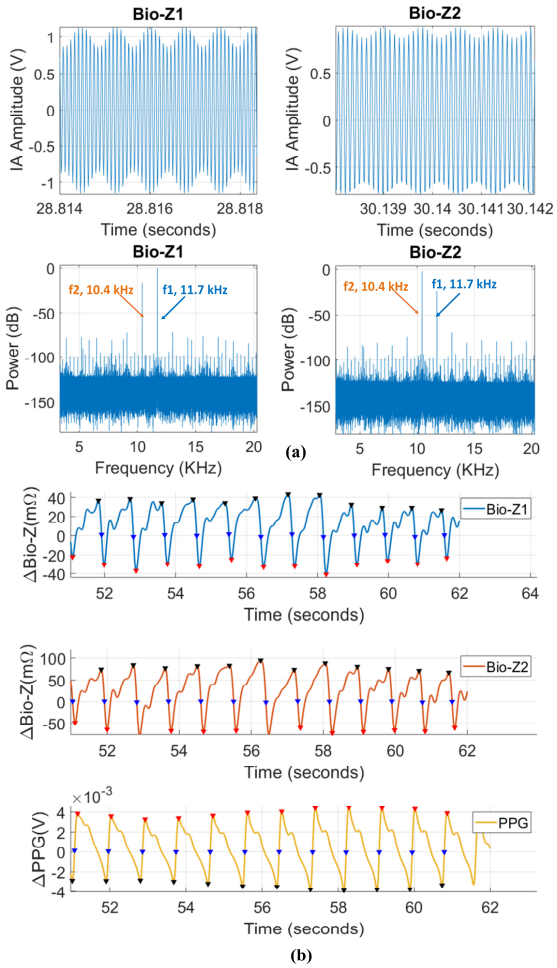

Fig. 3. (a) The IA voltage output in time domain and its power spectral density showing the 2 frequency components, (b) The pulse signal from Bio-Z1, Bio-Z2 and PPG in time domain .

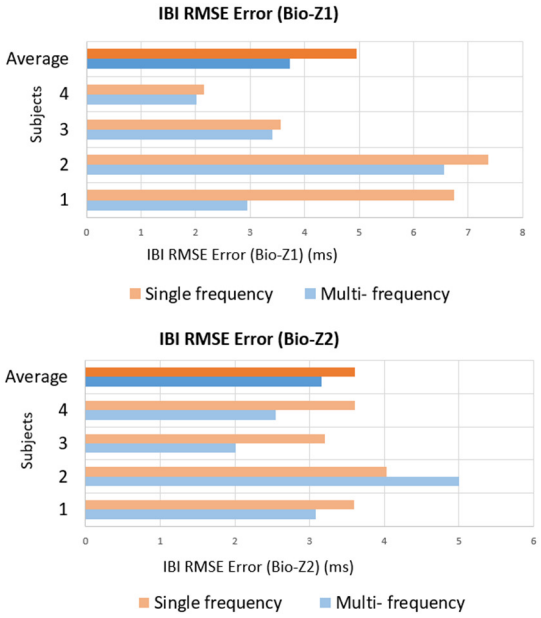

Fig. 4. Average IBI RMSE of Bio-Z1 and Bio-Z2 along with individual subject values.

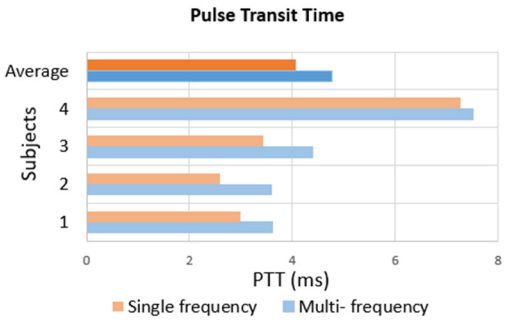

Fig. 5. The average PTT with individual subject values.

III. Experimental Results

The Bio-Z sensor was first calibrated using reference resistors that simulate the body to form a relation between the measured voltage and the reference resistance. The wrist tissue resistance and skin resistance were considered as 55.6 Ω and 2.1 kΩ respectively based on our measurements using wet ECG electrodes that have been used to inject current and to receive signals from the wrist. Each DAC and current source was calibrated at each current injection frequency. The radial artery has been detected using Huntleigh Dopplex MD2 Doppler, which measures blood flow in the arteries. The electrodes were placed with 15mm distance between each other. The data was collected under IRB approval IRB20170086D using gel electrodes with size of 0.8x1.5 cm from four participants with five trials while seated on a chair at rest; each trial was one minute to provide an average of 345 heart beats per subject. The multi-frequency current was injected with an amplitude of 413µA at frequency 11.72 kHz at Bio-Z1 sensor and 513µA at frequency 10.42 at Bio-Z2 sensor. The injected current amplitudes were selected to be compliant with safety standards [13]. For comparison, the same procedure has been repeated with the same placement of electrodes for all four subjects using single frequency AC current with an amplitude of 513µA at frequency 10.42 kHz. The data for multi-frequency current method and single frequency current collected sequentially after each other keeping the same electrode attachment to minimize any physical change over time. As expected the main frequency component of Bio-Z1 is 11.72 kHz but it also has a significant component of 10.4 kHz; Bio-Z2 also shows the opposite pattern in the frequency domain as shown in Fig.3 (a). In Fig. 3 (b), the pulse signal of Bio-Z1 and Bio-Z2 are shown with the PPG signal over time. The average IBI RMSE error for all subjects was less in the case of multi-frequency current injection for both Bio-Z as shown in Fig. 4. In the case of Bio-Z1, the average IBI RMSE error decreased by 25% from 4.96 ms to 3.73 ms and for Bio-Z2, it decreased by 12% from 3.61 ms to 3.16 ms as shown in Table I. According to the blood flow direction towards the hand, Bio-Z1 showed the decreasing slope indicating blood arrival before Bio-Z2. The average PTT for multi-frequency current method is 4.78 ms which is 15% higher than the single frequency current injection which is 4.07 ms as shown in Fig. 5. The proposed method requires an additional electrode, which can fit in the original form-factor through using slightly smaller electrodes.

TABLE I. Average IBI RMSE Error and average PTT

Method	Average IBI RMSE Error		Average PTT
	Bio-Z1	Bio-Z2	
Multi-frequency	3.73 ms	3.16 ms	4.78 ms
Single-frequency	4.96 ms	3.61 ms	4.07 ms

IV. Conclusion

In this paper, we introduced the multi-source multi-frequency bio-impedance measurement method that provides localized pulse signal sensing. The results showed the effectiveness of the multi-frequency Bio-Z measurement method compared to the single-frequency method by measuring pulse signals with lower IBI error and larger PTT values. The proposed method of localized current injection for each sensing location improves the accuracy of BP feature extraction and estimation results.

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