Wrist Photo-Plethysmography and Bio-Impedance Sensor for Cuff-less Blood Pressure Monitoring

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***Abstract*— A multimodal wrist sensor system is proposed in this paper for a wearable reflectance photo-plethysmography (PPG) and impedance-plethysmography (IPG) biomedical data sensing. A near Infrared (NIR) optical wavelength has been used to extract PPG signal from subject's wrist, while tetra-polar configuration based IPG sensor using two pairs of electrodes for current injection and voltage detection are used to acquire IPG signal. Furthermore, the signal arrival time delay between the IPG and PPG signal in two different but closed arterial sites (wrist area) known as pulse transit time (PTT) is used to estimate subject's blood pressure cufflessly. As an initial study, two clinical points have been extracted from both IPG and PPG signal, such as B-point, and Maximum of 2nd derivative of the signal, respectively. Therefore, a predicted systolic blood pressure (SBP) and diastolic blood pressure (DBP) achieved a mean absolute deviation of 4.16 ± 5.23 and 2.44 ± 3.12, respectively.**

Keywords—PPG; Bio-Impedance; Cuff-less; Blood Pressure; Wearable, Wrist.

I. INTRODUCTION

Blood pressure (BP) is an important, critical person's healthcare parameter which needs to be monitored and controlled regularly. Uncontrolled hypertension may lead to the complication including stroke, heart failure, chronic kidney disease, and aneurysm [1]. Conventionally, BP measured by a cuff-based inflatable oscillometry, these method considered to be an unreliable device for a long-term BP monitoring due to non-continuous measurement and it's uncomfortable for the users. Therefore, a ubiquitous BP monitoring was proposed to overcome this problem. The key technology of this ubiquitous BP monitoring is cuff-less, wearable, and for continuous measurement. The most common method that been proposed for cuff-less continuous BP monitoring system is based on the pulse transit time (PTT) method [2]. PTT is the time taken by the blood to travel between the proximal and distal arterial sites. It is inversely proportional to the BP and is a distance between two arterial sites (D) divided by pulse wave velocity (PWV). Therefore, the relationship between BP and PTT is given as the Moens-Korteweg equation, shown as follow:

$$PWV = \frac{D}{PTT} = \sqrt{\frac{E_0 e^{\alpha p} h}{\rho d}} \qquad (1)$$

Where E_0 and α are subject-specific parameters, and ρ, h, d are the blood density, arteries wall thickness, and arteries diameter, respectively. Although PTT considered being a promising approach for cuff-less BP monitoring, there are some limitation and problems for the implementation of the PTT-based cuff-less BP monitoring. One of the most significant problems is that PTT requires two pulse waveforms measured in two different measured sites. As an example, typically ECG measured from subject's chest is used as a proximal waveform, and PPG the signal measured from the subject's finger or ear used for distal waveform [2]. To overcome these problems, researcher started to develop the system that significantly reliable and convenient for users with also high performance. Some notable results focus on implementing these cuff-less continuous monitoring system into the wearable single-measurement sites devices, such as a wearable glasses Glabella [3], a seismocardiogram and PPG based wearable wristwatch [4], and an armband [5]. This paper proposed a novel multimodal sensors that measured IPG and reflectance PPG signals from a single-sites of subject's wrist. The developed system is proposed to overcome the inconvenient problem of the conventional cuff-based BP monitoring, while still propose a reliable accurate performance. The significance of our proposed system is related to the reliable sensor placement. The difference with [4], our proposed wrist-based wearable sensors system did not require subject's to put their hand on their chest. In addition, a wrist-based PPG and IPG signals are weaker compared to the other sites, such as PPG from subject's finger, therefore to overcome this problem we proposed several steps of analog filtering that are going to discuss deeply in the next section. Finally, we compare two types of PTT extracted features from different point of PPG and IPG signals, to find the best model for the cuff-less BP prediction.

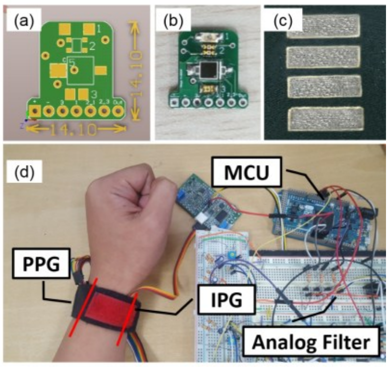

Fig. 1. Proposed multimodal wrist sensor prototype.

II. MATERIAL AND METHODS

A. *Multimodal PPG and IPG wrist sensor system*

As seen in Fig.1, our proposed sensor system includes tetra-polar configuration-IPG sensors and multi-optical wavelength PPG sensors. Both sensor were integrated inside the wristband and had a direct contact with the subject's skin. PPG sensors located in the area of interosseous arteries, while

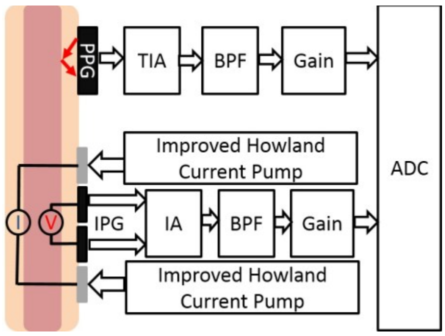

Fig. 2. Block diagram of analog signal filtering for both PPG and IPG sensors.

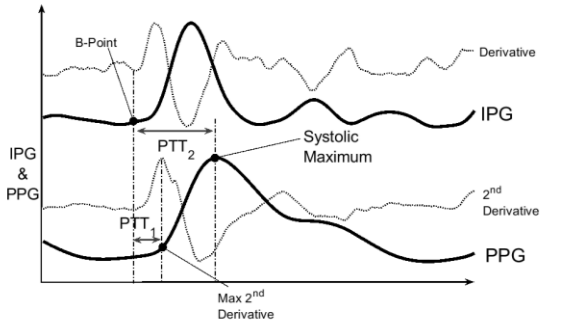

Fig. 3. PTT estimation using extracted features from IPG and PPG signal.

IPG sensors are measuring signal under the radial arteries. Our proposed prototyped multi-optical wavelength PPG sensors is 15 x 15 mm^2 size, with the photodiode BPW 34 (OSRAM Semiconductor Inc.) located in the middle area of the sensor package. Moreover, four LED representing different optical wavelength in both visible and near-infrared optical wavelength are used in 660, 770, 850, 940 nm, respectively (Vishay Semiconductors and Marktech Optoelectronics). The overall design and fabricated prototype might be seen in Fig. 1(a) and Fig. 1 (b).

The proposed IPG electrodes are based on the conductive-Ag-plated fabric electrodes. It is stretchable and soft electrodes which suitable for a long-term contact with the subject's skin. Four electrodes are used as two input electrodes for voltage detection and two output electrodes for current injector, where the voltage detection electrodes located in the middle of the sensor packaging [6, 7], as seen in Fig. 1(c). In this study, the Wien-bridge oscillator and a monopolar improved Howland current pump are utilized to generate high-frequency sine waves and high-impedance constant 500 µA at 100 kHz current source, respectively. Finally, our overall proposed system is shown in the Fig. 1(d).

Fig. 2 shows our analog signal filtering for both PPG and IPG sensors. In PPG, a trans-impedance amplifier (TIA) is used as a current-to-voltage converter using TL082 (Texas Instruments). Moreover, a 2nd order active low pass filter (LPF) and high pass filter (HPF) used to form a bandpass filter (BPF) with a range of 0.3 - 10 Hz. Finally, a programmable-gain amplifier is used before an analog I/O port of microcontroller for an analog to digital converter (ADC). In IPG, AD8421 (Analog Devices) is used as a high-speed, low noise instrumentation amplifier (IA) with high common-mode rejection ratio (CMRR) of 110 dB, and a gain of 60 dB at 100 kHz. Therefore, the active BPF with the 0.1 – 3 Hz working range is designed using 2nd order active LPF, and 3rd order HPF.

B. *Extracted features and Cuff-less Blood Pressure Prediction Model*

Raw reflectance PPG and IPG signals are recorded under the sampling frequency of 500 Hz, therefore a down-sampling is used to reduce the data sampling rate to 250 Hz for a convenient signal pre-processing. In addition, a 1st order derivative of IPG and a 2nd order derivative of PPG also derived from the raw PPG signal for further feature extraction. Wavelet decomposition and moving average is used for a baseline wander removal and signal to smooth, respectively. Finally, a local maxima is utilized for peak detection for further signal segmentation.

In this paper, a consecutive ten periodic PPG and IPG signals were segmented and averaged using ensemble average algorithm. Where the segmented signals were gathered from the information of the peak from each signal. Finally, this ensemble averaged PPG and IPG signal is used for feature extraction. Since there is no standard for the determination of PTT, several studies employ a different method to determine PTT such as peak to peak [8], valley to valley, peak to the max of 1st derivative [9]. Therefore, the PTT information from B point of IPG signal to the max of 2nd derivative of PPG and the systolic maximum/peak of the PPG are collected as PTT_1 and PTT_2, respectively. For this particular experiments, only a PPG signals from 940 nm used for analysis. The detail position of each extracted point from PPG and IPG signal may be seen in Fig. 3. Finally, a linear regression prediction model from each PTT is used and compared to find the best parameter to determine and predict subject's BP cufflessly.

III. Experimental Results

The subject specific PPT-based SBP and DBP prediction model have been established. Our study computed the estimated BP correlation coefficient (r) and the mean absolute deviation (MAD) ± standard deviation (SD) compare to the gold standard in 24-hour ambulatory blood pressure monitoring (ABPM) of Oscar 2™ system from SunTech Medical®. This system is certified to meet the requirement of British Hypertension Society (BHS), and the AAMI-SP10

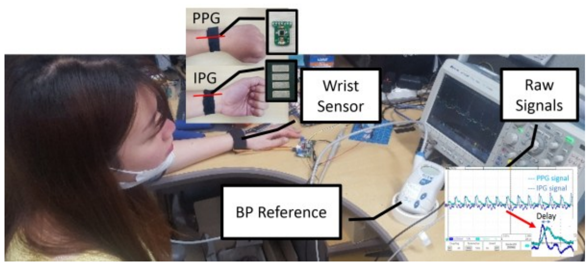

Fig. 4. Measurement Setup with proposed sensor (on subject wrist) and BP reference (on subject arm).

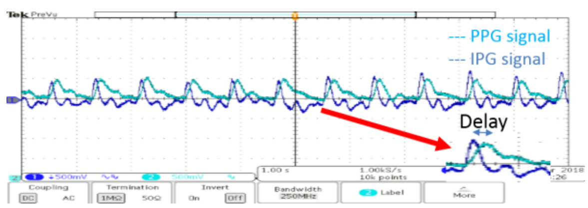

Fig. 5. Raw Signal recorded from Tektronix AFG3102C, the delay of PPG signals also shown here.

TABLE I. TOTAL DATABASE VALUE (N=10)

Index	Total Database	
	SBP (mmHg)	***DBP (mmHg)***
Mean	*121.3 ± 16*	*72 ± 9*
SD	*10 ± 2.1*	*5 ± 2*

TABLE II. PROPOSED SYSTEM PERFORMANCE

Index	Predicted Blood Pressure			
	SBP (mmHg)		***DBP (mmHg)***	
	r	MAD ± SD	r	MAD ± SD
PTT_1	0.51 ± 0.05	4.16 ± 5.23	0.42 ± 0.19	2.44 ± 3.12
PTT_2	0.42 ± 0.17	4.29 ± 5.40	0.36 ± 0.17	2.45 ± 3.19

standards. The total database that discussed here were performed on 10 young adults without any history of cardiovascular diseases (age: 25 ± 4 with 6 males and 4 females), thus the whole range of the gathered SBP and DBP mentioned in Table 1. The proposed multimodal sensors are located in subject's left wrist while the reference Oscar 2^{TM} system is wrapped around subject's left arm. In this experiment, a recorded signal is started 5 seconds before the Oscar 2^{TM} reference measurement and finished after 60 seconds after the reference data recording. The recorded signals are sampled and digitized by Arduino Due, 32-bit ARM core microcontroller and analyzed using MATLAB R2017b.

Our proposed measurement scenario is mentioned as follow, first, each subject was instructed to sit and stay still in a comfortable office chair. Then, there are a total of 8 pairs of data collected in each experiment. Which related to the data during the rest condition and after a 10-minute arm exercise, repeated for 4 sessions. Each subjects were tested two times, thus a total of 160 data pairs were collected from 10 subjects, and 150 of them are analyzed. Moreover, the overall measurement setup and sensor placement may be seen in the Fig. 4. As shown in Fig. 5, the PPG signal lags behind the IPG signal. This is due to the different measurement location of the sensors in the arterial sites of the subject's wrist. As mentioned, our PPG sensor is placed in the area of anterior interosseous arteries which is the branch of ulnar arteries, on the other hand, IPG sensors are placed in the area of the radial arteries. Since the origin of the signal is the same (Subject's heart), thus the signal that recorded by the PPG sensor took a longer path through ulnar arteries and its branch which makes it is lag behind the IPG signals.

The overall system performance is shown in Table 2. Our proposed system show the results of 4.16 ± 5.23 for SBP value prediction and 2.44 ± 3.12 for DBP value prediction from PTT_1. While 4.29 ± 5.40 and 2.45 ± 3.19 for SBP and DBP from PTT_2. Our results shows that the prediction BP value that extracted features from the PTT_1 is slightly better to compare to the PTT_2. This result is also proved that the extracted feature from foot/valley of PPG, in our case the max value of the 2nd derivative, has the best PTT-BP correlation and robustness to artifact [2, 10]. Moreover, a reasonable r-value of SBP 0.51 ± 0.05 has been achieved compared to the reference gold standard Oscar 2^{TM} system from PTT_1 feature. This is comparable to the other researcher results which varied from 0.30 to 0.90, where the high correlation usually achieved by utilizing a multivariate regression with multiple PTT

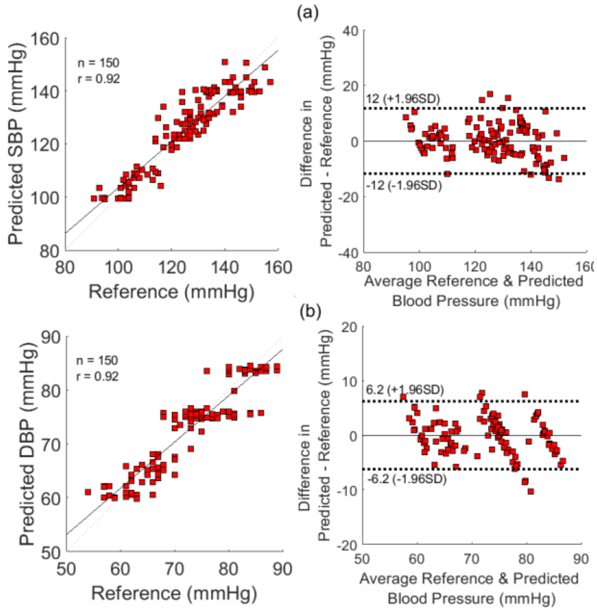

Fig. 6. Estimated vs Reference from PTT_1-based prediction model, with correlation and Bland Altmant plot analysis from all subjects using proposed system.

feature extracted [11]. Finally, the Bland-Altman plots of all predicted BP versus reference device gathered from all subjects is shown in Fig. 6. The average BP of reference and predicted BP is plotted on the x-axis with the difference between the two plotted on the y-axis. The mean bias of differences between our prediction and a reference value of SBP and DBP are both 0, with the upper limit and the lower limit of 2 times standard deviations around mean bias difference is plotted as a dashed line on the figure.

IV. CONCLUSIONS

A multimodal-IPG and PPG sensors presented in this paper. Our novel prototype wrist-based wearable sensor was developed as an unconstructive, seamless, and continuous cuff-less BP monitoring system. The proposed PPG sensor were consists of four LED measuring reflectance PPG signal in four different visible and near-infrared optical wavelength. Moreover, a tetra-polar based IPG sensors also developed for bio-impedance detection under the skin tissue. A cuff-less BP monitoring system was performed under the extracted feature between B point of IPG signal to the max of 2nd derivative of PPG and the systolic maximum/peak of the PPG, defined as PTT_1 and PTT_2. Furthermore, experimental results show that the prediction model trained by PTT_1 featured are more robust and has a slightly better performance compared to the PTT_2-based model. An overall performance of our proposed prediction model is 4.16 ± 5.23 and 2.44 ± 3.12 for SBP and DBP value prediction, respectively. In the future, a machine learning based multi-variable prediction model will be considered to achieve a better prediction performance, moreover a different kind PTT features also going to be investigated with a different reference point extracted from the wrist-based PPG and IPG signal.

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