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Noninvasive Cuffless Blood Pressure Measurement by Vascular Transit Time

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Abstract **- Blood pressure (BP) is one of the most important physiological parameters that can provide valuable information for personal health care. There are two ways to measure human blood pressure viz. invasive and noninvasive methods. Though invasive methods have been known to measure BP continuously and accurately but they are extremely inconvenient to use and might cause infection. The widely used cuff-based noninvasive methods are also not very convenient to use especially for injured or obese people and infants. Thus, there has been an unmet need for a convenient noninvasive cuffless BP measurement technique. While cuffless methods to measure BP have been previously studied, most of them were limited to offline processing of captured signals and none have presented an end-to-end prototype. Therefore, in this paper, we present a simple and low-cost fully realized implementation that can measure Blood Pressure immediately after capturing heart activity signals from a user namely PPG (Photoplethysmograph) and PCG (Phonocardiogram). The data is transmitted through a Bluetooth module in the system and results are displayed in a user interactive android application. We compared our results with those measured using a commercial cuff-based digital blood pressure measuring device and obtained encouraging results of about 95% accuracy.**

Index Terms – Cuffless, Blood Pressure, PPG, PCG, Vascular Transit Time (VTT)

I. INTRODUCTION

In today's fast life, personal healthcare is given a lot of importance. Technological advancements necessitate the availability of portable and wearable devices for monitoring vital physiological parameters like Blood Pressure during unexpected conditions. Conventionally, there are two ways to measure human blood pressure viz. invasive and noninvasive methods. Though invasive methods have been known to measure BP continuously and accurately but they are extremely inconvenient to use and might cause infection. The widely used noninvasive methods are based on cuff technology and also not very convenient to use especially for injured or obese people and infants. The occlusion of blood flow in the arteries during BP measurement causes an unpleasant feeling and discomfort for users. Moreover, these devices are bulky and inconvenient to carry and a complete BP measurement takes about one minute due to the long period of inflation and deflation. Therefore, a convenient noninvasive cuffless method for measuring BP is much more desirable. This becomes even more vital especially for patients with expected fluctuation in BP, e.g. undergoing Cesarean Section.

We hereby present a noninvasive cuffless blood pressure measurement technique. In other words, we replace the conventional cuff based methods to measure blood pressure by capturing heart activity signals namely PPG and PCG. Our system primarily consists modules for signal acquisition, signal processing, data transmission and estimation of blood pressure. The PPG and PCG signals, which are captured simultaneously, are processed on an LPC1768 Processor Kit. Then the Vascular Transit Time (VTT), which is defined as the time taken by the blood to travel from the heart to an extremity of the body for one stroke of the heart, is extracted and transmitted via Bluetooth to an android smartphone. The user interactive android application, after reading user's personal information such as age, weight and height, estimates and displays the Blood Pressure and Heart Rate (HR) of the user. [1]

II. IMPLEMENTATION OF THE SYSTEM

A. *Overview of the System*

The aim of this paper is to design and implement a cuffless noninvasive BP measurement system for users during day to day life. Fig. 1 shows the architecture of our designed system. The raw signals obtained from the sensors are first amplified and filtered through anti-aliasing filters and then converted into digital form using ADC of the LPC1768 processor kit. Both the signals are further processed with appropriate digital filtering for the purpose of correct identification of peaks of two signals. Then, VTT is calculated from the time difference between the corresponding systolic peaks of PPG and PCG signals. Afterwards, the Bluetooth module transmits the data to the android application developed by us to calculate the value of Blood Pressure from VTT and user fed information such as age, weight and height. Our system can measure the blood pressure of a user in about 8-10 seconds. In this way, our system is able to support frequent BP monitoring.

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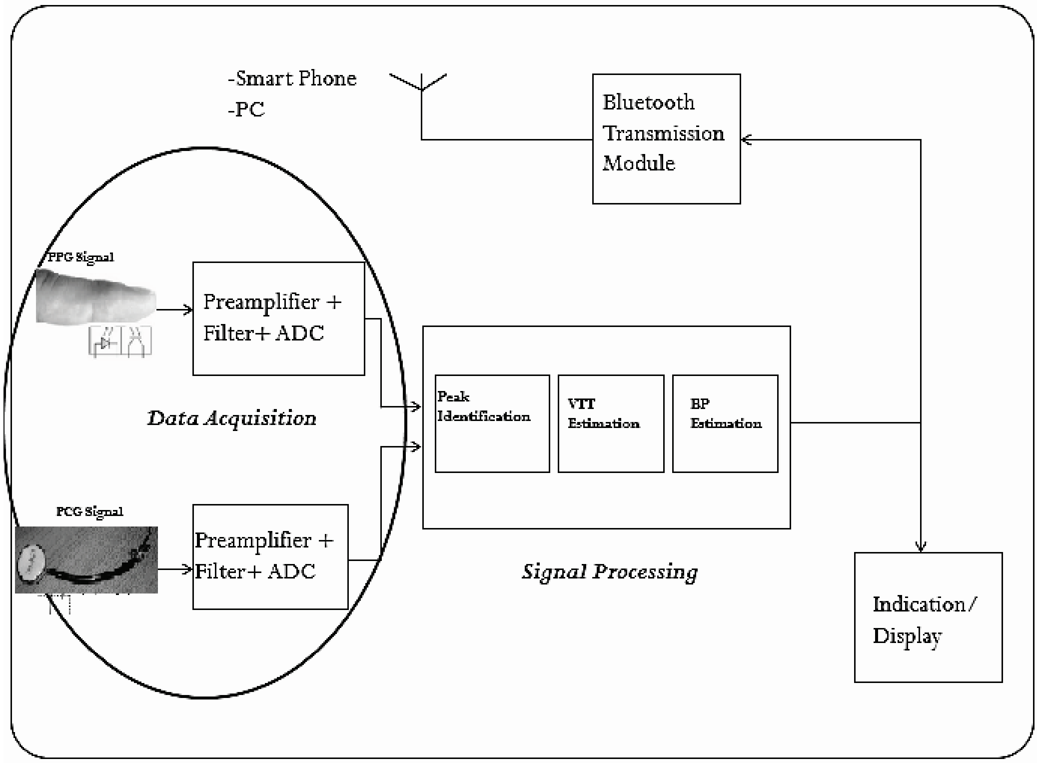

Fig. 1. Architecture of our designed system

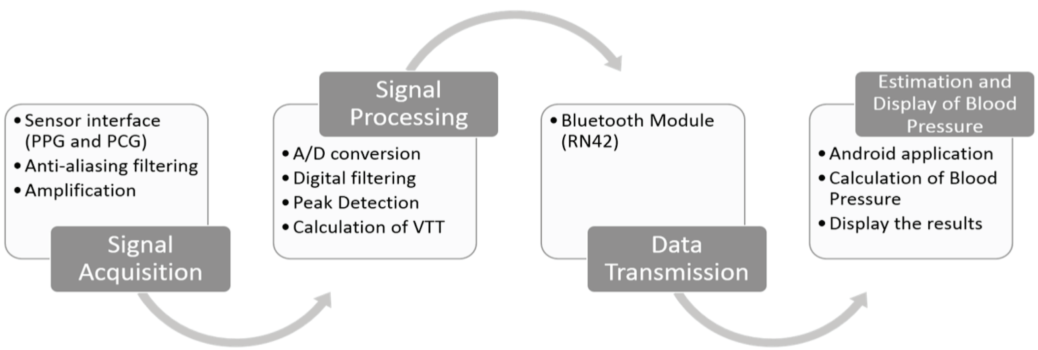

Fig. 2. Design Flow of our system

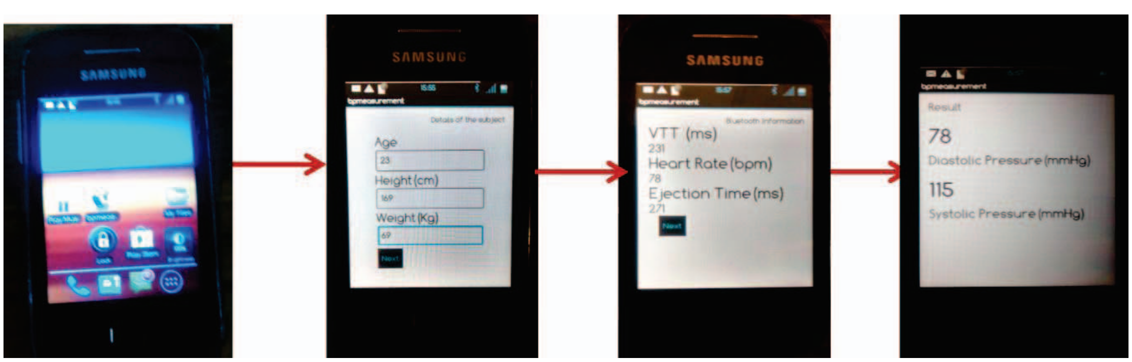

Fig. 3. Android App GUI (gets Bluetooth information and calculates BP & HR)

B. Methodology

Our system comprises of specifically designed sensor modules for effectively capturing PPG and PCG signals. For PPG signal capturing, we have used a commercial reflectance type optical sensor TCRT1000 [2]. When the user places fingertip over the PPG sensor, finger pulse is recorded as an AC signal [3]. While for PCG signal, we have used a custom made stethoscope-microphone assembly (shown in Fig. 4) enabled by a power circuit for the microphone. When the stethoscope diaphragm is placed on subject's chest, heart sounds vibrate the diaphragm creating acoustic pressure waves which travel through the hollow tube and the microphone, which is fixed in between the hollow tube, captures the acoustic waves.

The captured PPG and PCG signals are then passed through Anti-aliasing filters with cut-off frequencies specific to both the signals. The boosted and filtered signals are then transferred to the signal processing module.

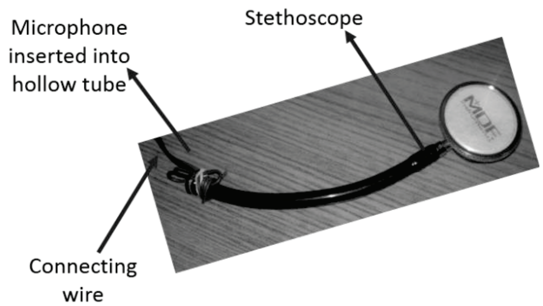

Fig. 4. Custom made PCG sensor

The specifications for PPG signal AAF filter are f_c (high pass) = 0.5 Hz, f_c (low pass) = 22.6 Hz and Gain = 150. Similarly the corresponding values for PCG AAF filter are f_c (low pass) = 284 Hz, since most heart sounds recorded are in this range, and Gain = 15.

These signals are then digitized using the inbuilt ADC of the LPC1768 Processor kit via simultaneous sampling with a sampling frequency 500 Hz. The channel switching time is of the order of 50 ns - 1 μs, thus it won't have any significant impact on the sampling. Since the spectrum of the sounds S1 and S2 have reasonable values well within the 300 Hz mark [10], choosing a sampling frequency of 500 Hz is a justified tradeoff against the available memory on the processor kit.

These signals are further filtered through digital filters; a 10^{th} order band-pass filter which allows frequencies only between 0.5-5 Hz for PPG and a 20^{th} order band-pass filter which allows frequencies within 40-250 Hz for PCG.

The next step is determination of peaks and identifying suitable peaks for calculating Vascular Transit Time, Heart Rate and Ejection Time (ET). With respect to PPG signal, HR is equal to number of systolic peaks per minute.

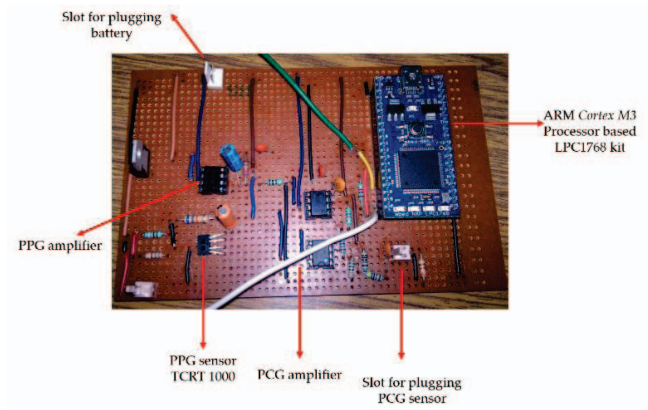

Fig. 5. Hardware implementation

Ejection time is defined as the time of ejection of blood from the left ventricle beginning with the opening of the aortic valve and ending with closing of the aortic valve. The ejection time was estimated graphically from the heart sound recorded as the time difference between S1 & S2 peak and not S2 & S1 peak. A peak detection algorithm [4] was applied on both the waveforms. In the algorithm, a peak function is used for each sample in the waveforms that computes the average of (i) the maximum among the signed distances of each sample from its k left neighbors and (ii) the maximum among the signed distances from its k right neighbors. We have chosen k = 10 for our system. Then the mean and standard deviation for each of the peak function values were calculated, based on which the local peaks were filtered. These local peaks, as seen in Fig. 6, are smaller in magnitude next to the systolic peaks. This resulted in identifying one prominent peak within a window clearly indicating the existence of a heartbeat.

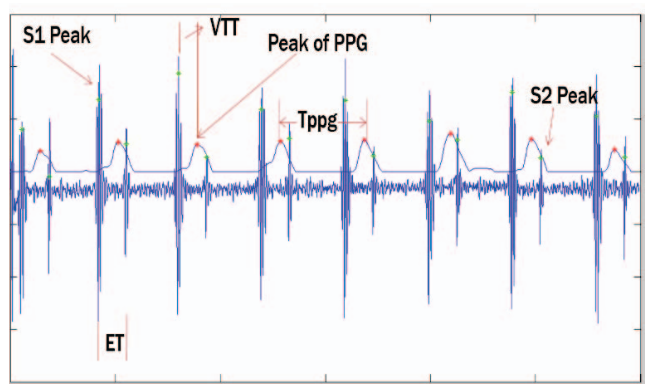

Fig. 6. Identification of Peaks: S1 and S2 are the first and second heart sounds, respectively. VTT is identified by time difference as shown in the figure

However, peak detection can sometimes lead to the detection of false peaks, due to noise and motion artefacts. Experimentally it has been observed that these false peaks generally lie between S2 peak of one systole and S1 peak of next systole in PCG signal. In PPG signal, no false peaks are found. These false peaks can be removed by further processing. Corresponding to each systolic peak of PPG signal, closest peak of PCG signal i.e. S2 peak is found, and then the previous adjacent peak i.e. S1 peak is stored with this S2 peak. In this way, all S1 and S2 peaks corresponding to each systolic peak are stored and rest of the peaks are removed. This method is employed only because erroneous peaks occurred between S2 of a systole and S1 of next systole. To further remove the erroneous readings, median filtering is employed with a window of 3 samples. But the median filter has no effect on the 1st and last entries of the data. So, sorting is done and then smallest and largest value of the data are removed. We used the Merge Sort algorithm. After detecting peaks in PPG and PCG signals, VTT, HR and ET are calculated and transferred wirelessly from the processor kit to smart phone using RN-42 Bluetooth Module. The advantage of having Bluetooth is that once the data is available in the smart phone, it can be sent via Internet/SMS to user's doctor in case of emergency situations.

C. Mathematical Equations

The change in systolic blood pressure can be derived from the change in VTT as described by Foo *et al.* [5].

$$\Delta P_s = -0.425 \times \text{VTT}$$

Based on above equation, Chandrasekaran *et al.* [1] derived an empirical relation between systolic blood pressure and VTT which is given as:-

$$P_s = -0.425 \times \text{VTT} + 214$$

The pulse pressure P_p and the stroke volume SV is computed as given in [4].

$$\text{SV(mL)} = -6.6 + 0.25 \times (\text{ET} - 35) - 0.62 \times \text{HR} + 40.4 \times \text{BSA} - 0.51 \times \text{Age}$$

where ET(ms) is the ejection time and BSA is the body surface area given by

$$\text{BSA} = 0.007184 \times \text{Weight}^{0.425} \times \text{Height}^{0.725}$$

With the computed stroke volume, the pulse pressure can be calculated in units of mmHg using [7].

$$\text{Pp} = \frac{\text{SV}}{(0.013 \times \text{WT} - 0.007 \times \text{Age} - 0.004 \times \text{HR}) + 1.307}$$

Having obtained the values of P_s and P_p, we can now compute the diastolic blood pressure as:-

$$P_d = P_s - P_p$$

Hence, using the captured PPG and PCG signals, systolic and diastolic blood pressure values were calculated using the equations stated above.

III. RESULTS

Here we present the experimental results of blood pressure measured for different subjects and the values are compared with a commercial cuff-based digital blood pressure measuring device. Fig. 7 shows the peak detection results on a set of typical PPG and PCG signals.

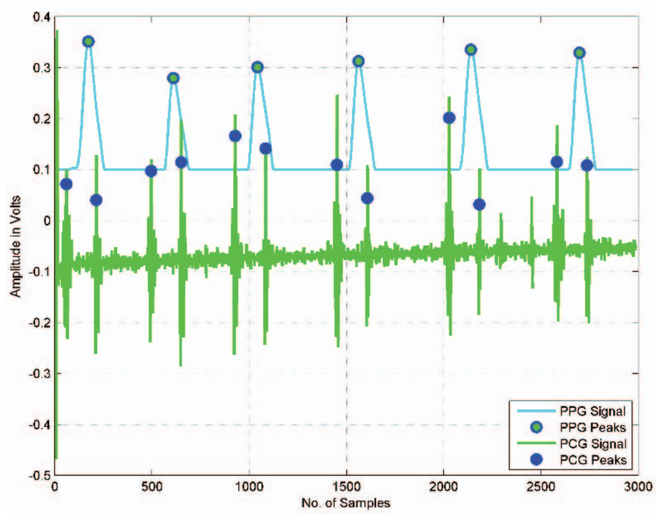

Fig. 7. Peak Detection on a set of typical PPG & PCG

A. Accuracy of our system

Table I provides the information of different subjects for whom the Blood Pressure values were measured using our system. Table II shows a comparison of average Blood Pressure values measured by our cuffless system and a commercial DBPM for different subjects from a data set comprising of over 100 measurements obtained from subjects in an age range of 21–55 years.

TABLE I. Subject Information

Subject	Age (in yrs)	Weight (in kgs)	Height (in cms)
1.	51	78	175
2.	33	65	160
3.	21	68	172
4.	21	64	168
5.	32	71	169
6.	23	73	174
7.	23	69	168

TABLE II. Accuracy of Blood Pressure measured using our method and a DBPM

Subject	Systolic Blood Pressure (mmHg)		Diastolic Blood Pressure (mmHg)		Heart Rate (bpm)		P_s Accuracy %	P_d Accuracy %	HR Accuracy %
	Measured	Actual	Measured	Actual	Measured	Actual			
1.	120	122	91	85	81	75	98.4	92.9	92.0
2.	115	116	75	79	61	61	99.2	94.9	100
3.	118	115	85	85	93	87	97.4	100	93.1
4.	107	118	62	63	62	65	91.7	98.4	95.4
5.	123	123	70	76	91	86	100	92.1	94.2
6.	103	110	72	67	63	67	93.6	92.5	94.1
7.	117	124	70	67	59	62	94.4	95.5	95.2

B. Performance Analysis

TABLE III. Multiple Readings for subjects

Systolic Blood Pressure (SBP) in mmHg	Subject 1	Subject 2	Subject 3
Observation 1	115	96	116
Observation 2	133	107	117
Observation 3	128	100	123
Observation 4	116	112	129
Average	123	104	123
Actual SBP	126	106	124

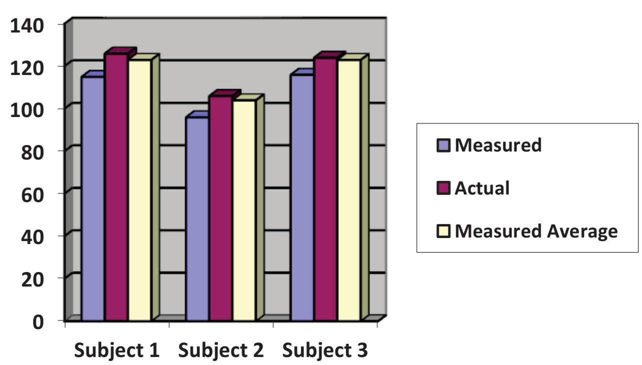

Fig. 8. Variation of measured SBP w.r.t. actual for Single Data Point (observation 1) and average of multiple data points

Table III (Fig. 8) clearly indicates that the number of data points can affect accuracy. Having more number of data points for a particular subject yields better accuracy than choosing a single data point. Since our system is quite convenient to be used frequently contrary to a cuff-based meter in which a gap of 40 minutes is recommended between consecutive readings, we have taken multiple readings for a subject resulting in improved accuracy. Here we have shown 4 observations; more data points are likely to improve accuracy further.

IV. Limitations and Future Work

The accuracy of the system largely depends on the estimation of VTT which can be affected by the way user handles the sensors. Currently, the user needs to sit upright and be quiet while capturing the signals. Errors may also creep in due to inappropriate pressure applied by the finger and/or misplacement of finger over the PPG sensor. For better recording of heart sounds, the sensor needs to be placed on bare chest making it inconvenient to use in public. Further, this method has not been tested on people with a history of cardiac disorders in which the same VTT-SBP relation might not hold.

Future works may include coming up with a more generalized empirical formula with more test subjects available. We can further improve the accuracy by reducing the motion artifacts in PPG signal [9]. Further, we plan to develop a System on Chip (SoC) to implement the full system.

V. Conclusion

This paper presents a noninvasive cuffless blood pressure measurement technique and addresses the lack of such a device which can potentially help in real time monitoring of Human Blood Pressure. The experiment evaluations with results of more than 90% accuracy clearly indicate that this technique is feasible, convenient, and portable and can be very well used for normal and non-pathological purposes especially for people with expected fluctuation in BP.

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