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Development of Non-occlusive blood pressure monitor with height correction for home used application

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ABSTRACT

Non-occlusive blood pressure measurement method is developed to avoid the use of discontinuous and uncomfortable cuff-based methods. In this research, Pulse Transit Time (PTT) and Photoplethysmogram Intensity Ratio (PIR) is used to measure blood pressure. Two photoplethysmogram (PPG) sensors that are placed on the wrist and one of the finger joints both on the left hand is used to get the PTT and PIR. The name of the device is ARTSEN. During measurement, there is a measurement error caused by the hydrostatic effect when the device position is not inline with the heart. To minimize this error, this research proposes an automatic continuous blood pressure monitor. The device will conduct measurement only when the height of the device is inline with the heart. Accelerometer and gyroscope are used to detect the height of the device. There are 30 subjects that are involved in this research. To evaluate the performance of the device, there are two measurement conditions, during lying in the bed and sit down position. The blood pressure measurement is conducted using ARTSEN and sphygmomanometer (as the gold standard). The average error of systolic blood pressure is 8 mmHg with standard deviation 5 mmHg, and average error of diastolic blood pressure is 8 mmHg with standard deviation 4 mmHg.

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1. INTRODUCTION

Blood pressure monitor has been widely developed for home-used healthcare devices. The common methods to measure the blood pressure oscillometry, tonometry, and volume-clamp. These methods require blood vessel blockage and only produce one measurement result (non-continuous). In global, hypertension is major cause of cardiovascular disease and chronic kidney disease [1]. Self-monitoring tool to measure blood pressure is recommended to be used by people with hypertension [2-3]. Continuous blood pressure monitoring is needed to obtain the trend of the blood pressure's values, especially for people with hypertension or hypotension.

Non-occlusive blood pressure monitor device using Pulse Transit Time (PTT) and Photoplethysmogram Intensity Ratio (PIR) has been developed in this research. This device named ARTSEN. The main objective of the research is to develop non-occlusive blood pressure monitor that has meet the standard blood pressure error tolerance. The reference is based on Association for the Advancement of Medical Instrumentation (AAMI) standard, it is stated that the error tolerance of the blood pressure measurement is 8 mmHg [4].

Two photoplethysmogram (PPG) sensors are used on the wrist and the finger joints, as shown in Figure 1. This device has some advantages, the size are smaller than arm monitoring device and can be used by obese people. However, the device prone to have systematic errors caused by the hydrostatic effect due to the different (height) position of the wrist device relative to the heart. This error can be avoided if the wrist is positioned at heart-level during measurement [5].

2. IMPLEMENTATION

2.1. Specifications

The measurements range are from 0 - 250 mmHg. The measurement resolution is 1 mmHg, and error toleranceis 8 mmHg based on AAMI standard. The device use two PPG sensors that have 1 KHz sampling rate and ARM based microcontroller. The height of the device relative to the heart is measured using accelerometer and gyroscope.

2.2. Filtering PPG using EMA

The first step is to filter the PPG signal. In this research, the Exponential Moving Average (EMA) method is used to remove the noise. Here is the equation to calculate the value of EMA.

$$EMA_t = EMA_s + k(X_t - EMA_s) \quad (1)$$

$$k = 2N + 1 \quad (2)$$

EMA_t = Last EMA (now)
EMA_s = Previous EMA
X_t = Last closing rate
k = Smoothing factor
N = Period

The first EMA value (EMA_{s1}) is the value of the Simple Moving Average (SMA) of the first N data:

$$EMA_{s1} = SMA = (data_1 + data_2 + \cdots + data_N)/N \quad (3)$$

2.3. Peak Time Detection

The next step is to detect the peak time of the PPG signals on the wrist and the finger joint. The shape of the PPG signals differ from person to person, and vary depending on the location and the placement of the sensors [6]. Based on the empirical experiment and the reference [7], there are generally four possible PPG curve forms as in Figure 1. There are three parameters to detect the peak time of PPG signals, that are the shape; amplitude; and period. In this paper, only four types of these signals that can be processed with the peak time detection algorithm. So, it’s important to place the PPG sensors correctly.

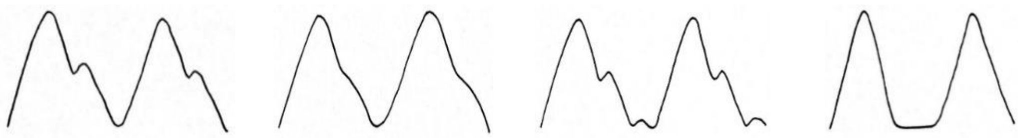
(a) (b) (c) (d)

Figure 1. The shape of PPG curve

The first detected peak is not always the systolic peak, it can be diastolic peak or other peak, peak with very small amplitude, Figure 1(c). To solve this problem, this research propose a simple solution, set a threshold value of the amplitude. Based on the references and the data that is obtained from the preliminary research, the threshold value is defined as follows. The distance between two peaks of the systolic pressure is at least 300 ms. This threshold value is based on the maximum heart rate (MHR) for the human:

$$MHR=208-0.7*age \text{ (bpm)} \quad (4)$$

Assuming the device can only be used by teenager and adult, according to WHO) and Ministry of Health of Republic of Indonesia (MOHRI), adolescence begin at age 12 years, so the threshold limit is set as follows:

$$\text{MHR} = 208 - 0.7(12) \cong 200 \text{ bpm} = \frac{60}{200} \text{ bps} \quad (5)$$

Minimum distance of the two peaks is:

$$\frac{1}{MHR} = \frac{60*1000}{200} ms = 300 \text{ ms} \quad (6)$$

The value of systolic peak is set at least 90 % of the previous systolic peak value, this apply to both PPG signals, on the wrists and the fingers. This value is intended to prevent another local peak (diastolic peak and another peak) undetected. Based on the preliminary research, the diastolic peak and other peak values are below 80 % of the systolic peak.

The peak time detection algorithm will record the first three peak values detected, then calculate the maximum value of this three peaks. The maximum value is used as the starting point to determine the peak time of PPG signals. The systolic peak of PPG signal is determined by tracing the ten data (offset). The program will check the value from the i-th to the (i+9)-th data. When the curve is increase, then the value of its state variable is 1, whereas if it decrease the state variable value is -1. Peak will be detected if the state value changes from 1 to -1. The function of offset use is to ignore any detected noise, even if only one. The next process is to detect the peak time of the second systolic peak, the scenarios are:

a) If the peak time interval is less than the specified threshold value, 300 ms, then the value will be discarded.
b) If the peak time interval is more than or equal to the specified threshold value, 300 ms, then this value will be stored and used for the next step.

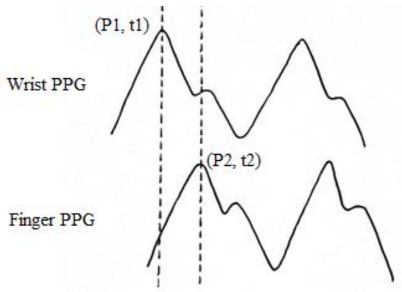

Figure 2. PTT calculation using wrist and finger PPG curves

The next process is to detect the peak amplitude, if the amplitude has more than 90% of the previous peak amplitude, then the peak is designated as systolic peak. This values will be stored. The next process is systolic peak verification. The purpose of this stage is to ignore locally detected peaks, which are not represent the systole and diastole. This process is important, due to the fact that the local peak(s) often passes the peak time detection process. The peak time detection process is applied to PPG in finger joint. The final process is to get the PTT value that is obtained from peak time from PPG signals in wrist and finger joint.

2.4. PTT and PIR Measurement

The first step in PIR measurement is to find the PTT value, that is obtained from the time interval between systolic peak from two PPG curves, the finger joint and wrist PPG. PTT can be calculated easily because it only requires simultaneous recording of PPG signals at two different points [8]. Figure 2 illustrate the PTT calculation.

$$\text{PTT} = t_2 - t_1 \quad (7)$$

P_1 = Wrist PPG peak.
P_2 = Finger joint PPG peak.
t_1 = Peak time of wrist PPG.
t_2 = Peak time of finger joint PPG.

In this process, there are two cases are found. First, wrist PPG peak occur simultaneously with finger joint PPG peak, so the PTT will be zero. Then, finger joint peak is leading, so the PTT value will negative. The ideal condition is wrist PPG peak occur in advance than finger joint PPG peak. Although very rare, both cases should still be avoided. This research propose a simple solution, if one of the two cases occur, the PTT will be set the same value as the previous PTT. The first step in PIR detection is obtain the peak and valley of PPG signal in every cardiac cycle. Then, compare the previous PPG signal with the current signal.

2.5. Relative Height

There is a measurement error caused by the hydrostatic effect when the device position is not in line with the heart. To minimize this error, this research propose an automatic continuous blood pressure monitor. The device will conduct measurement only when the height of the device is in line with the heart. Accelerometer and gyroscope are used to detect the height of the device. One way to obtain the height is by using dual Micro Electro Mechanical Systems (MEMS) accelerometer [9]. Several advantages of the MEMS are has small size, light, low power consumption and start-up time. However, it lack in accuracy compared to traditionally made sensors [10].

Angular displacement of accelerometer and gyroscope sensors are the key to measure the relative height. This research use an inertial measurement unit, MPU6050 that consists of accelerometer and gyroscope. The outputs from accelerometer and gyroscope are combined using complementary filter to get the angular displacement. The basic idea of complementary filter is to use accelerometer output to correct the gyroscope output. The combination formula can be written as:

$$\text{Angle}_{\text{accurate}} = (\text{GyroPercentage}) * \text{Angle}_{\text{gyro}} + (1 - \text{GyroPercentage}) * \text{Angle}_{\text{accel}} \quad (8)$$

GyroPercentage is a factor with a value ranging from 0 to 1, usually 0.9 depending on the sensor that are used [11]. In this research, GyroPercentage value is 0.98, so the accelerometer weight value is 0.02. The next step is to determine the estimation of human arm length. The relative height to the heart can be obtained using simple trigonometry as illustrated in Figure 3.

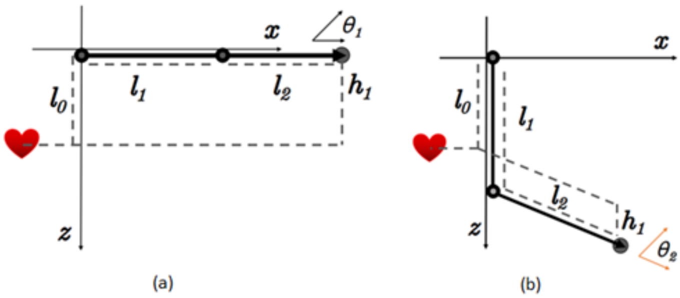

Figure 3. Height measurement conditions: (a) outstretched arm and (b) lower arm perpendicular to upper arm

l_0 = Length of the heart to shoulder.
l_1 = Upper arm.
l_2 = Lower arm.
h = Relative height of the device to the heart.
θ = Angular displacement to transversal axis

The device is placed on the wrist, which is represented as a black dot in the Figure 3. The relative height can be measured under two scenarios illustrated in Figure 3. In this research, the second scenario is chosen (the bottom one). So, the height can be measured as:

$$h_1 = (l_1 - l_0) + l_2 \sin\theta_2 \quad (9)$$

2.6. Blood Pressure Estimation

Blood pressure is mainly influenced by four factors: arterial compliance, cardiac output, peripheral resistance, and blood volume. Arterial compliance can be evaluated using PTT, due to PTT is an index of arterial stiffness. Cardiac output can also be related to PTT through heart rate. PTT is a key parameter in the calculation of continuous blood pressure, the value is inversely proportional to the value of blood pressure (with increasing blood pressure value, PTT value will decrease) [12-14]. Peripheral resistance and blood volume are affected by arterial diameter which can be seen through changes in PIR [15]. So, PTT and PIR can be used to estimate the value of blood pressure as they represent changes in blood pressure indirectly [16]. Blood pressure will only be measured if the device is at heart level. In the preliminary research, PTT is used to measure the blood pressure. The result from this method are not systolic and diastolic pressure, but Mean Arterial Pressure (MAP). The relationship between MAP to systolic and diastolic pressure is:

$$MAP = [\text{systole} + (2 \times \text{diastole})]/3 \tag{10}$$

From the previous research, there is a correlation between PTT and MAP, using this equation:

$$\ln\left(\frac{1}{ptt^2}\right) = kP_{tm} \tag{11}$$

Transmural pressure (P_{tm}) is the pressure between vessel walls and can be written as:

$$P_{tm} = P_{MAP} + \rho g h(t) - P_{ext} \tag{12}$$

If device is positioned at heart level, hydrostatic pressure can be assumed neglected and under this assumption, no external pressure is working, (11) become:

$$\ln\left(\frac{1}{ptt^2}\right) = kP_{MAP} \tag{13}$$

Blood pressure is estimated using (13) with constant k depending on the value of PTT. Since this is not a standard method, this research also uses PIR to estimate the blood pressure. If the initial calibration is performed to obtain systolic and diastolic pressure reference values, from (6) and (10) systolic and diastolic pressures can then be expressed as:

$$DBP = DBP_0 . \frac{PIR_0}{PIR} \tag{14}$$

$$SBP = DBP + PP_0 . \left(\frac{PTT_0}{PTT}\right)^2 \tag{15}$$

Variables with subscripts "*o*" are obtained from the initial calibration [16].

3. RESULTS AND ANALYSIS

3.1. Height Correction Test

To test and benchmark the height correction module, IMU sensor is placed on a plane. Then, the plane height is changed every 1cm. The measured height is compared to a ruler (as standard) to get the accuracy. Test result of this measurement is shown in Figure 4.

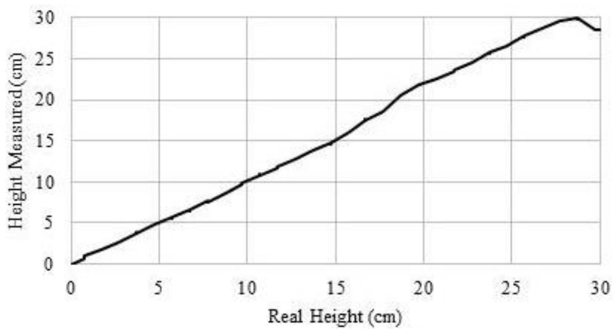

Figure 4. Height test results

3.2. Blood Pressure Measurement Result

There are 30 subjects that are involved in this research. To evaluate the performance of the device, there are two measurement conditions, during lying in the bed and sit down position. The first blood pressure measurement is conducted using sphygmomanometer (as the gold standard and for benchmarking). Then, blood pressure is measured using the device developed (ARTSEN), for around two minutes for each subject.

Table 1 show the measurement result from 30 subjects. The maximum error for both systolic and diastolic pressures is 18 mmHg. The minimum error for systolic pressure is 0 mmHg, and for diastolic pressure is 2 mmHg. The average error for systolic pressure is 8 mmHg, with standard deviation 5 mmHg. The average error for systolic pressure is 8 mmHg, with standard deviation 4 mmHg.

Table 1. Blood Pressure Estimation Results

Subject #	Calibration		Absolute Error	
	Systolic (mmHg)	Diastolic (mmHg)	Systolic (mmHg)	Diastolic (mmHg)
1	120	80	18	18
2	100	70	12	6
3	100	80	8	8
4	100	75	14	14
5	90	70	9	9
6	110	75	4	4
7	125	70	12	12
8	110	80	2	2
9	120	70	18	18
10	110	70	18	13
11	120	70	14	14
12	115	60	3	3
13	100	70	6	6
14	125	70	4	5
15	90	60	7	7
16	90	70	8	8
17	120	70	10	5
18	100	75	10	10
19	100	70	10	10
20	110	70	6	6
21	120	80	7	10
22	100	70	6	6
23	90	60	0	4
24	100	80	5	5
25	120	80	8	8
26	120	80	4	6
27	120	70	6	6
28	110	70	9	9
29	110	80	7	7
30	110	75	8	8

3.3. Development of ARTSEN apps

There are two authentication modes: offline and online (using internet connection). In the login menu, the user will be asked to fill in the registered email along with the password made. There is a register menu for new user. One feature of the ARTSEN Apps is that the measurement data can be sent to the user's email. The data communication between the device and smartphone is transmitted using Bluetooth module.

Figure 5 show the user interface of the ARTSEN Apps. One main feature of the apps is the realtime PPG signal display during the measurement. There are two PPG signal graphs, PPG1 at the top of the display is a PPG signal from the wrist and PPG2 at the bottom of the display is a PPG signal from the finger joint. The measurement result of blood pressure value is shown on the tab “measure” that’s equipped with start and stop measurement button. Blood pressure values will be displayed every 10 seconds.

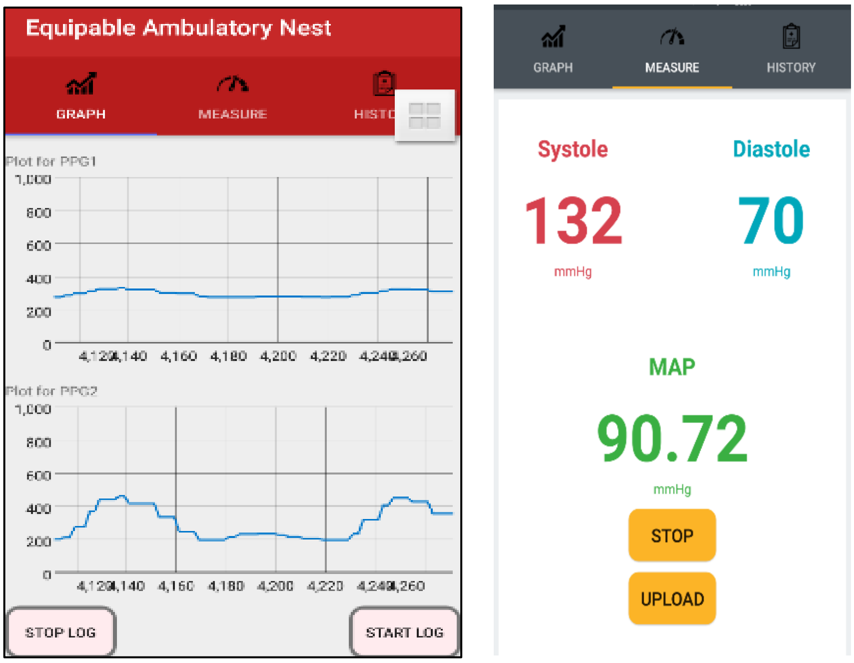

Figure 5. User interface of the ARTSEN apps

4. CONCLUSION

In this research, the photoplethysmogram intensity ratio (PIR) and pulse transit time (PTT) are used to estimate blood pressure. Using this method, this research develop a non-occlusive blood pressure monitor that can be used to measure blood pressure continuously. From 30 subjects, the results of this research can be summarized as follow: The maximum error for both systolic and diastolic pressures is 18 mmHg. The minimum error for systolic pressure is 0 mmHg, and for diastolic pressure is 2 mmHg. The average error for systolic pressure is 8 mmHg, with standard deviation 5 mmHg. The average error for systolic pressure is 8 mmHg, with standard deviation 4 mmHg.

For further development, the research will focus on decreasing the maximum error, < 8 mmHg. So, the next research will use PPG and ECG to determine PTT and PIR. Also, this device can be implemented for wearable device that is used as homecare device monitor or in sport application.

REFERENCES

[1] A.V. Chobanian, *et al.*, "National heart, lung, and blood institute joint national committee on prevention, detection, evaluation, and treatment of high blood pressure; national high blood pressure education program coordinating committee: the seventh report of the joint national committee on prevention, detection, evaluation, and treatment of high blood pressure: the JNC 7 report," *Jama* 289, pp. 2560-2572, 2003.

[2] J. George and T. MacDonald, "Home Blood Pressure Monitoring," *European cardiology*, vol. 10, no. 2, pp. 95-101, 2015.

[3] V.N. Panicker and A.K. Sukesh, "Development of a blood pressure monitoring system for home health application." *In 2015 IEEE International Conference on Circuit, Power and Computing Technologies*, pp. 1-4, 2015.

[4] Association for the Advancement of Medical Instrumentation. American national standard. Electronic or automated sphygmomanometers. *ANSI/AAMI SP 10-1992*. Arlington, VA: AAMI, pp. 40, 1993.

[5] T.G. Pickering, *et al.*, "Recommendations for Blood Pressure Measurement in Humans and Experimental Animals. Part 1: Blood Pressure Measurement in Humans: A Statement for Professionals From the Subcommittee of Professional and Public Education of the American Heart Association Council on High Blood Pressure Research," *Circulation*, vol. 111, no. 5, pp. 697-716, Feb 2015.

[6] S. Millasseau, *et al.*, "Determination of age-related increases in large artery stiffness by digital pulse contour analysis", *Clinical Science*, vol. 103, no. 4, pp. 371-377, 2002.

[7] N. Westerhof, *et al.*, "The arterial Windkessel," *Medical & Biology Engineering & Computing*, vol. 47, no. 2, pp. 131–141, Feb 2009.

[8] T. Tamura, *et al.*, "Wearable Photoplethysmographic Sensors—Past and Present", *Electronics*, vol. 3, no. 2, pp. 282-302, 2014.

[9] P. Shaltis, *et al.*, "Wearable, Cuff-less PPG-Based Blood Pressure Monitor with Novel Height Sensor," *in 2006 Proc. of the 28th IEEE International Engineering in Medicine and Biology Conference*, pp. 908-911, 2006.

[10] O.J. Woodman, "An introduction to inertial navigation", *Technical Report. UCAM-CLTR-696*, University of Cambridge, Computer Laboratory, Aug 2007.

[11] "Reading a IMU Without Kalman: The Complementary Filter", pieter-jan.com, 2017. [Online]. Available: http://www.pieter-jan.com/node/11. [Accessed: 09- May- 2017].

[12] R. Smith, *et al.*, "Pulse transit time: an appraisal of potential clinical applications", *Thorax*, vol. 54, no. 5, pp. 452-457, 1999.

[13] J.M. Padilla J, *et al*., "Assessment of relationships between blood pressure, pulse wave velocity and digital volume pulse", *2006 Computers in Cardiology*, vol. 33, pp. 893–896, 2006.

[14] M. Wong, *et al.*, "An Evaluation of the Cuffless Blood Pressure Estimation Based on Pulse Transit Time Technique: A Half Year Study on Normotensive Subjects", *Cardiovascular Engineering*, vol. 9, no. 1, pp. 32-38, 2009.

[15] N. Westerhof, *et al.*, "The arterial Windkessel," *Medical & Biology Engineering & Computing*, vol. 47, no. 2, pp. 131–141, Feb 2009.

[16] X. Ding, *et al.*, "Continuous Cuffless Blood Pressure Estimation Using Pulse Transit Time and Photoplethysmogram Intensity Ratio", *IEEE Transactions on Biomedical Engineering*, vol. 63, no. 5, pp. 964–972, 2016