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ONLINE MICRO-CONTROLLER NON-INVASIVE BLOOD PRESSURE MONITORING SYSTEM (E-BPM)

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Abstract. Measurements of blood pressure have been part of the basic clinical examination since the earliest days of modern medicine. Two of the most commonly used methods in performing the non-invasive blood pressure measurement are the auscultatory method and the oscillometric method. However, the conventional auscultatory method using sphygmomanometer and stethoscope is still widely used by doctors. The main problem in implementing this conventional method is the inaccuracy in readings due to the different abilities among doctors in sensing their patients' blood pressure. On the other hand, the usage of oscillometric electronic blood pressure monitors has provided a good solution to the problem but the limitation is that they do not indicate the patient's heartbeat condition. As a solution, the online micro-controller based non-invasive blood pressure monitoring system (e-BPM) is developed in this study to provide a more convenient and accurate measurement of blood pressure using the principles of the oscillometric method. In performing the blood pressure measurement, the medical hardware delivers the pressure inside arm cuff to the pressure sensor port. The e-BPM is developed to display the measurement results with oscillation signal waveform (which indicates the patient's heartbeat condition) on the computer screen where the results can be printed out for reference. The simulation results show the oscillation signal waveform, giving a comprehensive exposure in the application of non-invasive blood pressure measurement. The developed *e-BPM* is accurate in giving the measurement of pulse rate. In addition, for blood pressure measurements, the accuracy of the system is still acceptable by referring to the obtained mean values. However, some applied coefficients should be reviewed in order to improve the accuracy in performing the blood pressure measurement.

Keywords: Blood pressure; pressure sensor

Abstrak. Pengukuran tekanan darah telahpun merupakan sebahagian daripada pemeriksaan klinikal pada zaman perubatan moden ini. Dua daripada kaedah yang sering diaplikasi dalam mengukur tekanan darah secara tidak langsung ialah kaedah *auskultatori* dan kaedah *osilometrik*. Namun, kaedah konvensional *auskultatori* dengan menggunakan tolok tekanan dan stetoskop masih diguna secara meluas oleh doktor. Masalah utama dalam mengaplikasi cara konvensional ini ialah berlakunya ketidaktepatan bacaan akibat daripada kepekaan di kalangan doktor yang berlainan dalam menentukan tekanan darah bagi pesakit mereka. Sebaliknya, penggunaan mesin pengukur tekanan darah elektronik telah memberi penyelesaian bagi mengatasi masalah tersebut, tetapi ia masih tidak mampu menunjukkan keadaan denyutan jantung pesakit. Sebagai langkah

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untuk mengatasi masalah ini, sistem pengukur tekanan darah tidak langsung berdasarkan mikro-pengawal (e-BPM) telah direka bentuk dalam kajian ini bagi memberi pengukuran tekanan darah yang lebih mudah dan tepat melalui kaedah osilometrik. Untuk mengukur tekanan darah, tekanan yang di dapati di lengan akan dihantar ke *port* pengesan tekanan. e-BPM ini direka bagi memaparkan hasil pengukuran bersama-sama dengan isyarat ayunan (di mana ia mewakili keadaan denyupan jantung pesakit) pada skrin komputer. Selain itu, hasil pengukuran juga boleh dicetak bagi tujuan rujukan. Kajian ini, memaparkan hasil simulasi bersama-sama dengan isyarat ayunan, iaitu pendedahan kepada applikasi pengukuran tekanan darah secara tidak langsung. Ia juga boleh memberikan bacaan kadar denyutan dengan tepat. Sebagai tambahan, bagi ukuran tekanan darah, ketepatan sistem tersebut boleh diterima dengan merujuk depada nilai *mean* yang dihasilkan. Bagaimanapun, terdapat *coefficients* yang perlu dikaji semula untuk menambahbaik ketepatan dalam menjalankan ukuran tekanan darah.

Kata kunci: Tekanan darah; pengesan tekanan

1.0 INTRODUCTION

Blood pressure measurements have been part of the basic clinical examination since the earliest days of modern medicine. The determination of human blood pressure has proven essential to clinical studies of certain illnesses, to control blood hypertension and to evaluate the condition of patients within the intensive care units and emergency rooms. In general, measurements of blood pressure can be performed either invasively or non-invasively.

The invasive measurement method is generally accepted as being the gold standard method of recording blood pressure. However, this method introduces risks to the patient and increases workload for physicians, as it involves the rather complex setup procedures for arterial catheter insertion. Therefore, this method is only available at special medical sites and is used almost exclusively in diagnostic procedures such as heart catheterization [1].

The complexity and inconvenience in the application of the invasive method has made the non-invasive method the most extensive in use. In fact, non-invasive devices are usually well tolerated by patients, safer, have rare clinical problems and can be utilized in most situations. Thus, they are generally suitable for routine clinical use and can be used in normal subjects, leaving the invasive methods to be used only when absolutely necessary [2].As technology in the world of healthcare grows, the quality and cost of healthcare have been improving in step with the rising standards of living. Till today, different non-invasive techniques and measurement methods have been developed to provide more convenient and reliable measurement of arterial blood pressure, either for clinical use or home use.

However, the conventional auscultatory method using sphygmomanometer and stethoscope is still widely used by doctors in performing the blood pressure measurement. In fact, the main problem in implementing this conventional method is the inaccuracy in readings due to the different abilities among doctors in sensing their patients' blood pressure, while the reliability of arterial blood pressure measurement is very important for medical purposes [3].

In addition, regular inspection is necessary in using the traditional mercury sphygmomanometer to eliminate conditions that could cause the blood pressure measurement to be read as erroneously high or low. Care must also be taken in handling and storing the mercury sphygmomanometer in order to prevent the glass tube from breaking. Hence, it is essential to find an alternative method to replace the traditional mercury sphygmomanometer due to the toxicity of mercury [4].

As a solution of the problem, this study aims to develop a more convenient and accurate non-invasive blood pressure monitoring system that uses the principles of oscillometric method to determine the blood pressure and pulse rate. As an enhancement, the system is developed to display the measurement results, including the values of systolic pressure, diastolic pressure, mean arterial pressure, maximum oscillation amplitude and pulse rate with the captured oscillation signal waveform on the computer screen since the captured oscillation signal waveform is important in giving doctors information on the patient's heartbeat conditions. In addition to that, the measurement results can be printed on a paper for reference.

In this study, a non-invasive blood pressure monitoring system that uses the oscillometric method in determining blood pressure and pulse rate is developed. The system displays the measurement results with oscillation signal waveform on the computer screen. For safety purposes, the system is developed to be semi-automated, where the pressure cuff needs to be manually inflated by using inflation bulb. Therefore, the system will indeed give doctors a safer and more convenient way to record patients' blood pressure, as the measurement results are shown clearly on the computer screen. It is suitable for routine clinical use solely for blood pressure measurement, as it provides more accurate measurements compared to the conventional method.

On the other hand, the system can also be used for educational purposes in colleges and universities, especially in the fields of medicine and bioinstrumentation. The system shows the simulated measurement results with the oscillation signal waveform, giving the students a comprehensive exposure in the application of non-invasive blood pressure measurement.

2.0 BLOOD PRESSURE MEASUREMENT TECHNIQUES

Blood pressure can be measured either invasively or non-invasively. The term invasively refers to the direct way of measurement which the instrument directly infers the blood pressure from the cannulated artery. On the other hand, non-invasive technique is the indirect way of measuring the blood pressure which the body is not entered in the measurement process [3]

2.1 Invasive Technique

The measurement of blood pressure invasively is actually a continuous method which provides punctual values in every heartbeat and the blood pressure continuous waveform directly from the coronary system. Figure 1 shows the waveform of the invasively measured blood pressure. In order to obtain the blood pressure values invasively, a catheter (sterile and flexible tube) must be inserted into an artery. This procedure is performed under local anesthetic using aseptic methods, as in an operation [5]. Besides that, the direct measurement of blood pressure with indwelling arterial lines is technically difficult, which existing standards must be followed [6]. The equipment and procedure require proper setup, calibration, operation, as well as maintenance to make the pressure reliable [7]. This gold standard of blood pressure measurement is used almost exclusively in diagnostic procedures such as heart catheterization, or for monitoring patients during operations and in critical care. Therefore, the invasive blood pressure measurement is only available at special medical sites or during certain diagnostic procedures.

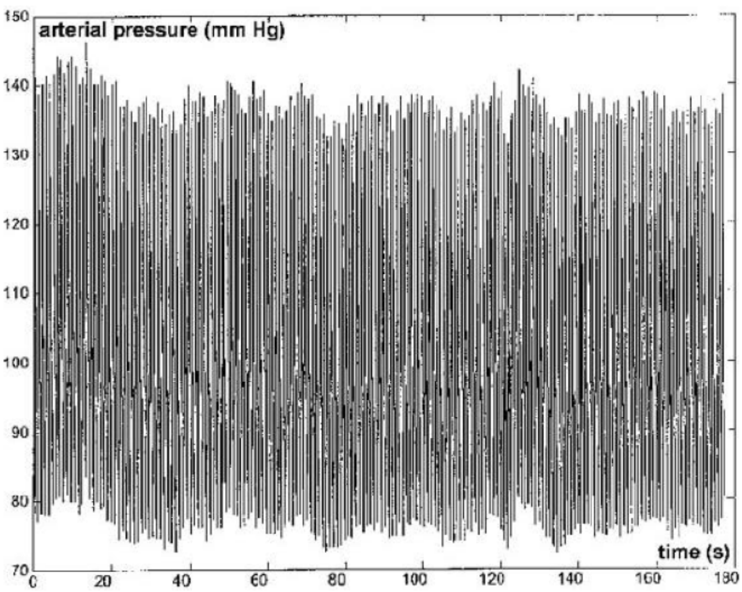

Figure 1 Invasively measured blood pressure [5]

Even today, the invasive technique is seldom used solely for blood pressure measurement and it presents the only satisfactory alternative when non-invasive techniques are not successful [3].

2.2 Non-invasive Technique

Non-invasive blood pressure measurements involve the use of an air bladder occlusion cuff and pressure gauge to indirectly infer and measure the blood pressure without needing the body to enter in the measurement process [8]. There are several methods used in determining the blood pressure value non-invasively. The most commonly used methods are the auscultatory method and the oscillometric method.

2.2.1 Auscultatory Method

The principle of auscultatory method in determining the blood pressure is based on the auscultation of the sounds generated by the pulse wave propagating through the brachial artery from the heart to the body surface when blood flows through the arteries: the detection of Korotkoff sounds [9]. It is generally accepted that there are five distinct phases of Korotkoff sounds and each phase is characterized by the volume and quality of sound heard as the pressure cuff deflates[10], as illustrated in Figure 2.

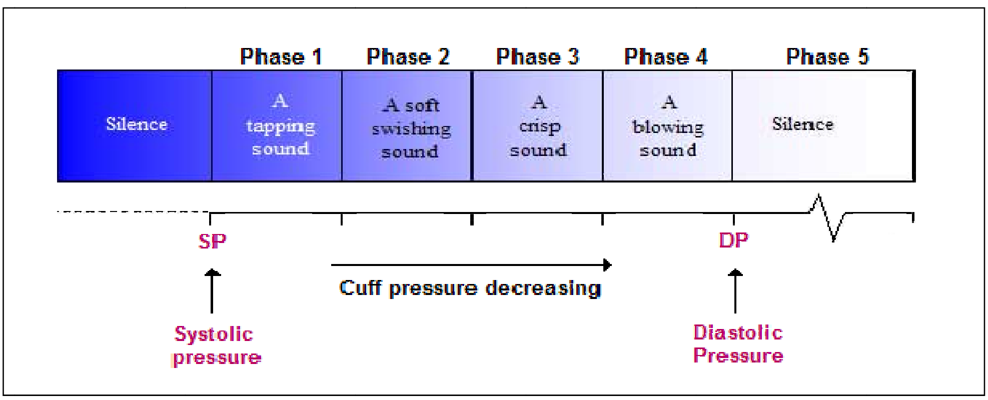

Figure 2 Distinct phases of Korotkoff sounds [10]

When the pressure cuff is inflated beyond the systolic pressure, the artery is completely occluded and no blood can flow through it. Consequently, no sounds are heard above the systolic pressure. As the cuff pressure is gradually lowered, it eventually falls below that of the systolic pressure and some blood does force its way through the artery. During the brief period where the cuff pressure equals the systolic pressure, a sharp tapping sound is heard: Phase 1. At this point, the systolic pressure is obtained [11].

When the measurement process goes through the Phase 1, Phase 2, Phase 3 and Phase 4 of Korotfoff sounds, the blood flow in the artery is actually not normal, and the resulting turbulence produces those Korotkoff sounds. At the point where the cuff pressure falls below that of the diastolic pressure, Korotkoff sounds cease to be heard all together and the blood flow has returned to normal: Phase 5. The diastolic pressure is defined at this point [10].

The detection and interpretation of Korotkoff sounds can be accomplished by human or machine. A conventional application of auscultatory method in measuring the blood pressure is widely used by doctors using mercury sphygmomanometer and stethoscope. In addition, aneroid gauges constitute a good alternative to the mercury sphygmomanometer in determining blood pressure value due to the toxicity of mercury[12]. Figure 3 shows the conventional sphygmomanometers that are used by doctors in performing routine clinical blood pressure measurements.

(a) Mercury Column (b) Aneroid Gauge

Figure 3 Sphygmomanometers

For machine reading, electronic blood pressure monitors replace the conventional mercury sphygmomanometer with a pressure transducer and the stethoscope with a piezoelectric microphone positioned against the compressed artery for detecting the Korotkoff sounds to make the blood pressure measurement possible [4]. However, the auscultatory method of determining the blood pressure is not widely implemented in most of the electronic blood pressure monitors [13].

2.2.2 Oscillometric Method

The oscillometric method does not use Korotkoff sounds to determine blood pressure but it monitors the amplitude of pressure change in the cuff as the cuff is deflated from above the systolic pressure. The principle of oscillometric method is dependent on the transmission of intra-arterial pulsation to the occluding cuff through body surface: the oscillation signal [14]

An approach using this technique could start with inflating the pressure cuff to above the systolic pressure and the pressure is then gradually decreased at a controlled rate. At pressures exceeding the systolic pressure, the artery is occluded. Only blood pulsations that are closely proximal to the occluded segment will be transmitted to the edge of the cuff, causing small oscillations in the cuff pressure [5].

When the cuff is slowly deflated, the cuff pressure, and hence the external pressure on the artery will be lowered to that of the systolic blood pressure. As the cuff pressure goes down, small amounts of blood pass through the compressed artery segment. The increasing blood flow causes the amplitude of the pressure pulses in the cuff to increase. These pressure pulses continue to increase in amplitude with decreasing cuff pressure until they reach a maximum amplitude at which point they begin to decrease with decreasing cuff pressure. The cuff pressure at which the pulse amplitude is the greatest is known as Mean Arterial Pressure (MAP) [9]. Figure 4 shows the detected oscillation signal as the cuff is deflated from above the systolic pressure.

The systolic and diastolic pressures are characterized and measured by the detected MAP and the cuff pressure at different oscillation amplitudes. This is usually done by means of a pressure transducer to measure the cuff pressure and the control unit with an algorithm to calculate blood pressure from the recorded oscillations. There are several methods of calculating the blood pressure value from the measured oscillations. All these need to determine the so-called oscillation envelope from the measured oscillation amplitudes. The envelope is an imaginary line that connects the peak of each pressure pulse and forms an outline. On the basis of this curve, the blood pressure is calculated with an algorithm and experimentally obtained coefficients [15].

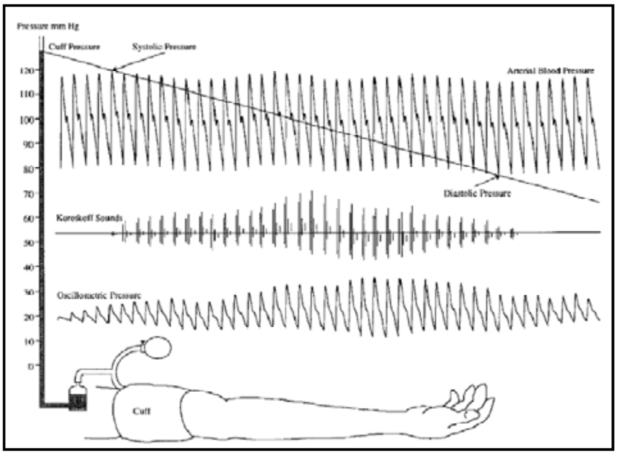

Figure 4 Non-invasive blood pressure measurements [3]

2.3 Comparison Between Auscultatory and Oscillometric Method

In comparing the differences in the applications of the auscultatory and the oscillometric method, the important thing to realize is that in the auscultatory method, the systolic and diastolic points are fairly well-defined by the sudden appearance and disappearance of Korotkoff sounds, while in the oscillometric method, they are somewhat ill-defined points on a continuously varying amplitude profile that never goes fully to zero [11].

The major problem in the conventional auscultatory method that widely used by doctors is not on the instrument itself, but the interface of the instrument with the ear of the observer which is the doctor. Sensing of systolic and diastolic pressures, by means of stethoscope, varies from person to person because of the sensitivity of the observer. In addition, the condition of the observer can affect readings such as slight deafness after cold [16].

Watson*, et. al.* [17] in their research of comparing the accuracy between the oscillometric blood pressure monitor, mercury sphygmomanometer and the invasive intra-arterial measurement, found that the blood pressure values assessed with the mercury sphygmomanometer were higher when compared with the invasive intra-arterial measurement due to the different sensitivity of the observers.

Moreover, the detection of Korotkoff sounds accomplished by machine, i.e. auscultatory blood pressure monitors are unreliable in noisy environment, as the piezoelectric microphone may cause misinterpretation in detecting Korotkoff sounds. In order to reduce any undesired error, complex detection circuits have to be developed. In fact, this is one of the reasons why most of the electronic non-invasive blood pressure monitors are not using auscultatory method [8].

On the other hand, the oscillometric blood pressure monitors have neither a stethoscope nor a microphone in measuring the blood pressure because they do not use Korotkoff sounds to determine blood pressure. Therefore, quite environment are not necessary in giving reliable measurements. In addition, the circuitry is simpler and easy to use because it is not necessary to position anything accurately over the artery like those devices that use auscultatory method [5].

However, the implementation of the oscillometric method has been problematic in measuring the blood pressure of patients with irregular heartbeat. The determination of the systolic and diastolic pressures becomes inaccurate when the recorded oscillation envelope is not in the normal shape. In this case, the auscultatory method presents the only satisfactory way in providing an accurate measurement of blood pressure [18].

5.0 HARDWARE IMPLEMENTATION

The hardware of the online micro-controller based non-invasive blood pressure monitoring system (e-BPM) consists of the medical hardware, analog circuit, micro-controller and serial communication interface. Figure 5 shows the block diagram of the e-BPM.

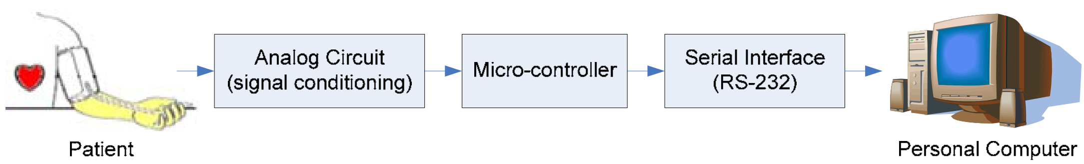

Figure 5 The e-BPM system block diagram

In performing a blood pressure measurement, the medical hardware delivers the pressure inside arm cuff to the pressure sensor port. The analog circuit converts the measured cuff pressure into usable analog waveform, extracts the oscillation pressure from the cuff pressure and compensates undesirable signal noise. The micro-controller samples the signal waveforms and performs analog-to-digital conversion followed by sending the data to PC via serial communication interface for analysis to determine the values of blood pressure and pulse rate. In addition, the micro-controller controls the whole operation of the hardware.

3.1 Circuit Design

In designing active filters, unity-gain Sallen-Key topology is applied to ensure high gain accuracy because its gain is not dependent on component values. Besides that, the amplifications that can be used when designing the Sallen-Key provide for easier selection of circuit components. In addition, all the filters are designed to provide the Butterworth response where they provide maximum flatness in the pass-band with moderate roll-off past cutoff [19].

In general, cutoff frequency of Sallen-Key active filters can be represented by the equations below:

$$f_c = \frac{1}{2\pi R_1 C_1}\text{, for first-order filter} \tag{3.4}$$

$$f_c = \frac{1}{2\pi\sqrt{R_2 R_3 C_2 C_3}}\text{, for second-order filter} \tag{3.5}$$

3.2 Low-Pass Filter

For mitigating the effects of the sensor noise, a first-order active low-pass filter with 650 Hz of cutoff frequency is recommended [20]. A 750 Ω resistor and a 330 nF capacitor are selected for this purpose since the 750 Ω series impedance is low enough for most ADCs. In practical, the high cutoff frequency, f_c can be calculated from the Equation 3.4:

$$\begin{aligned} f_c &= \frac{1}{2\pi R_1 C_1} \\ &= \frac{1}{2\pi(750)(330\text{n})} \\ f_c &= 643\text{Hz} \end{aligned}$$

The connection of the PIC16F84A to control the source and detection mode of the sensors is shown in Figure 9. This concepts is extend to the other measurement channels. The sampling at every positive edge of the burst clock which corresponds to every 2 ms after the each electrode selected to be the detecting electrode. The sampling occur during the positive edge to ensure the signal captured at the steady state.

3.3 High-Pass Filter

The output of the low-pass filter consists of two signals; the oscillation signal (≈ 1 Hz) riding on the cuff pressure signal (≤ 0.04 Hz). Hence, a second-order active high-pass filter is designed to extract the oscillation signal from the cuff pressure signal. For this purpose, cutoff frequency is chosen to be approximately 0.75 Hz to ensure the cuff pressure signal is filtered effectively. Figure 6 shows the frequency response of the designed filter. In practical, the designed filter has low cutoff frequency which can be calculated from the Equation (3.5):

$$f_c = \frac{1}{2\pi\sqrt{R_2 R_3 C_2 C_3}},$$

whereas $R_2 = 39$ kΩ, $R_3 = 11$ kΩ, $C_2 = 22$ µF, $C_3 = 4.7$ µF

$$f_c = \frac{1}{2\pi\sqrt{(39k)(11k)(22\mu)(4.7\mu)}}$$

$$f_c = 0.756\text{Hz}$$

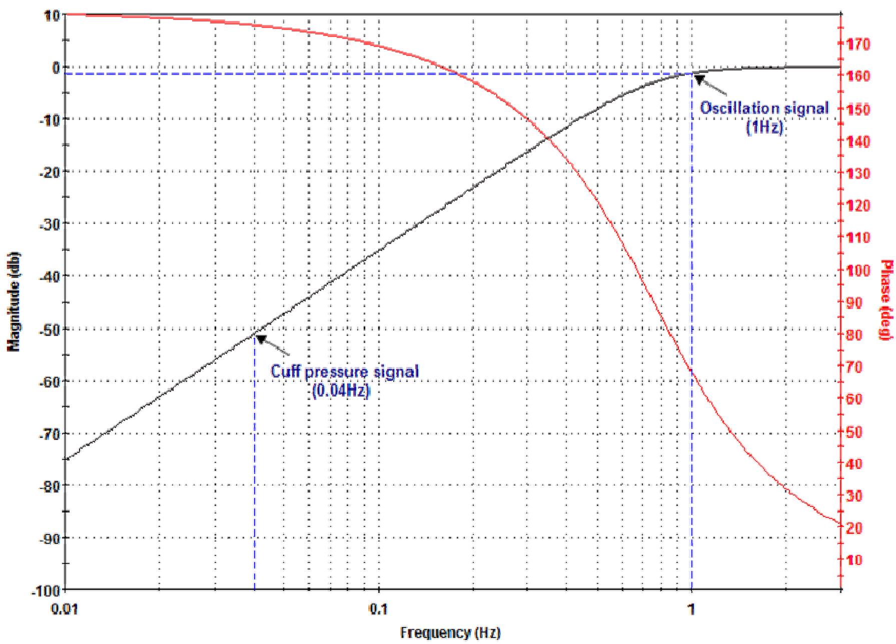

Figure 6 High-pass filter frequency response

3.4 Signal Amplifier

Signal amplifier provides amplification to the oscillation signal before the signal is sent to the ADC input of micro-controller. In general, the oscillation signal varies from person to person. It varies from less than 1 mm Hg to 3 mm Hg [14]. From the transfer function of the MPX5050 pressure sensor as in Equation (3.3), this will translate to a voltage output of 12 mV to 36 mV signal.

Referring to the frequency response of the high-pass filter which is illustrated in Figure 6, the high-pass filter gives an attenuation of 2 dB to the oscillation signal (1 Hz). The value of gain, *G* can be calculated below:

$$-2 \text{ dB} = 20 \log G$$
$$G = 0.7943$$

Therefore, the oscillation signal becomes 9.5 mV to 28.6 mV respectively. To ensure the amplified oscillation signal is within the output limit of the amplifier, the amplification factor of the amplifier is chosen to be approximately 150. The exact gain value of the designed signal amplifier can be calculated from the equation below:

$$G = 1 + \frac{R_4}{R_5}, \text{ whereas } R_4 = 22 \text{ k}\Omega \text{ and } R_5 = 150\ \Omega$$
$$= 1 + \frac{22\text{k}}{150}$$
$$G = 148$$

Thus, the amplified oscillation signal becomes 1.41 V to 4.23 V in representing the oscillation signal from 1 mm Hg to 3 mm Hg respectively. Figure 7 shows the schematic of the designed analog circuit. The cuff pressure signal (V_{01}) and the oscillation signal (V_{02}) are sent to the ADC input of micro-controller for digitization.

3.5 Operation Flow Chart

The micro-controller does not perform the measuring algorithm to determine blood pressure value and pulse rate in the e-BPM. It sends the measured pressure values to PC for analyzing. The operation flow chart of the micro-controller is summarized in Figure 8.

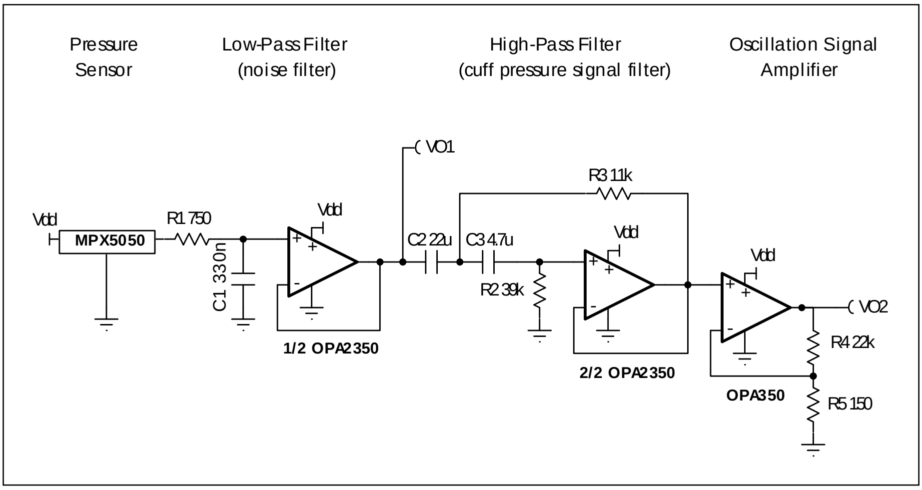

Figure 7 Analog circuit

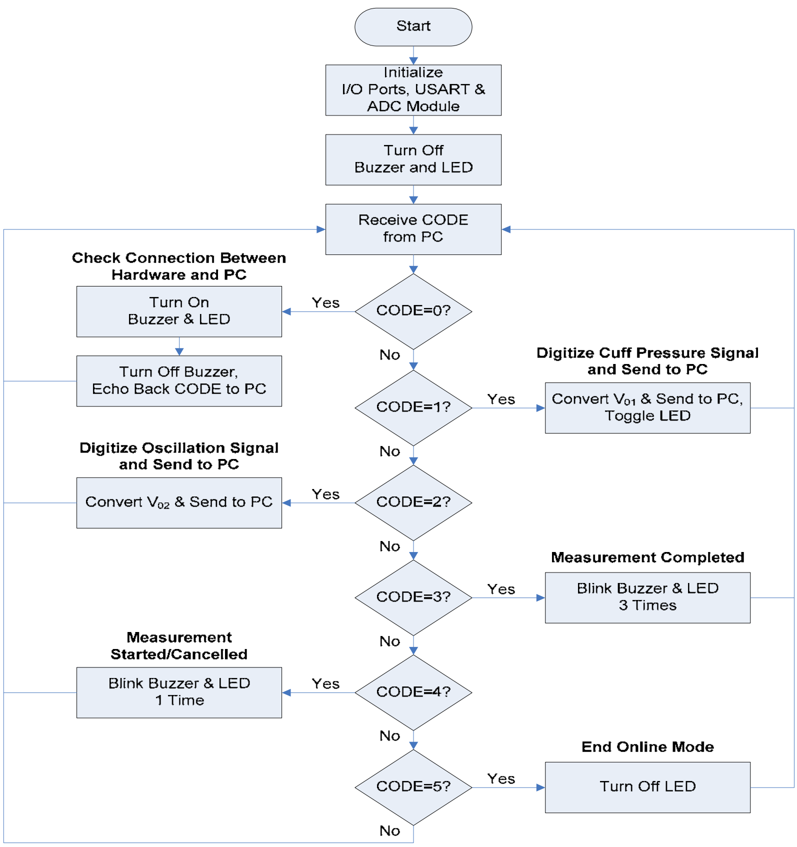

Figure 8 Micro-controller operation flow chart

Combining all the designed circuits, the e-BPM hardware is developed. Figure 9 shows the developed e-BPM circuit on a strip board with pressure cuff and inflation bulb while Figure 3.13 illustrates the complete e-BPM hardware.

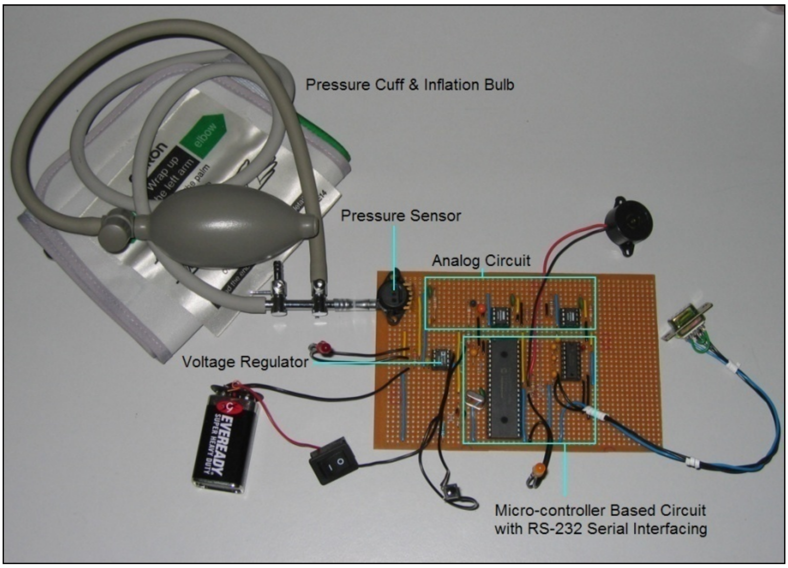

Figure 9 The e-BPM strip board circuit

4.0 RESULTS

Figure 10 illustrates the displayed measurement results on GUI after a measurement is performed. Systolic pressure, diastolic pressure and pulse rate are shown in the seven-segment displays. Mean pressure and maximum oscillation amplitude are displayed in the Oscillation Signal display panel with the captured oscillation signal. From the measured systolic and diastolic pressures, blood pressure level is determined and displayed in the Blood Pressure Classification frame.

In addition, when the 'Print Result' label is clicked, the system prints the measurement results on a paper when a printer is connected to the PC. The printed paper shows the measured blood pressure value, pulse rate, maximum oscillation amplitude and level of blood pressure as illustrated in Figure 11. The Patient's Name and the Remarks fields are printed for doctors to make any comments for future reference.

On the other hand, when either the systolic point or the diastolic point is not found from the oscillation signal envelope due to the deflation point is either set to more or less than the appropriate rate, an error message is displayed and the user is advised to select an appropriate deflation point. Figure 12 shows the error message displayed when the systolic pressure is not found while Figure 13 shows the error message displayed when the diastolic pressure is not found.

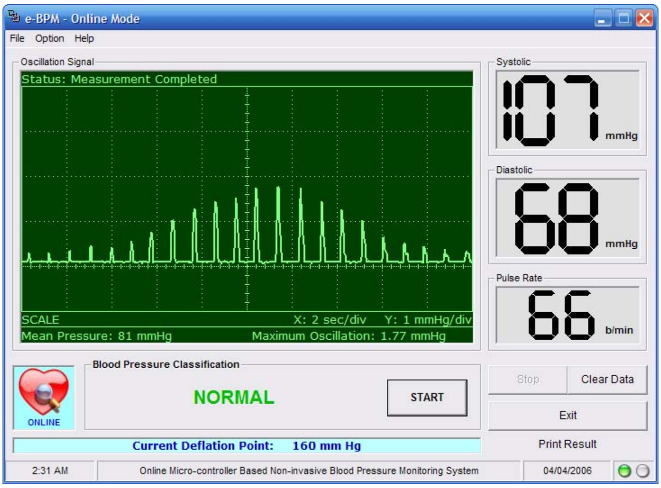

Figure 10 Displayed measurement results

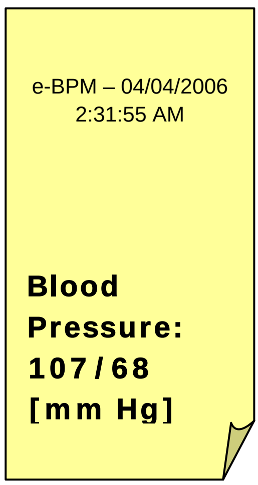

Figure 11 Printed measurement results

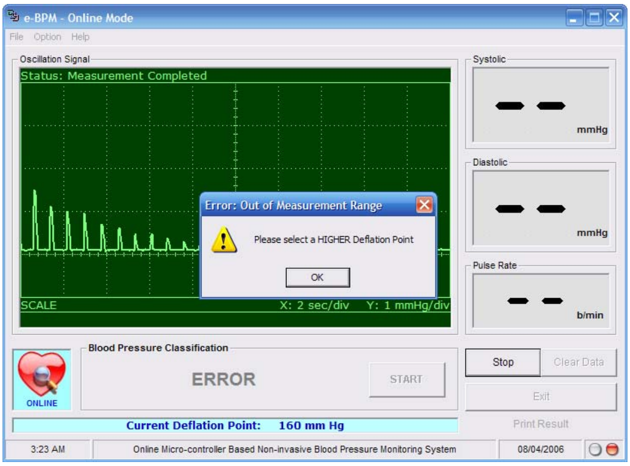

Figure 12 Error message when systolic pressure is not found

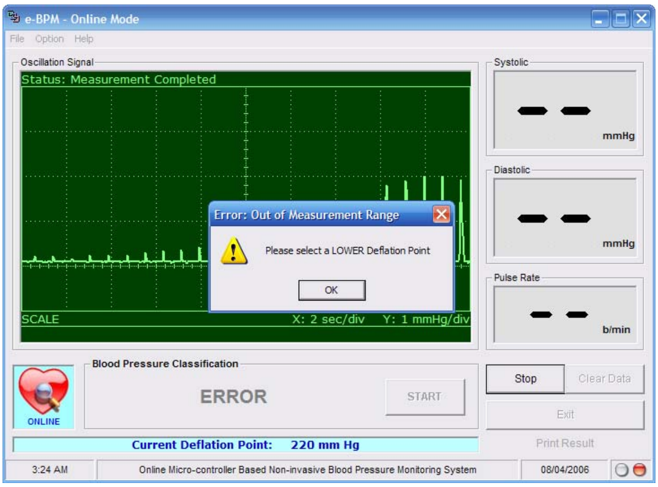

Figure 13 Error message when diastolic pressure is not found

Simulations are performed in the offline mode according to the desired blood pressure level, heartbeat condition and pulse rate which are entered by the user. When the user input is not complete, the offline simulation cannot be performed and the 'Input Incomplete' label is displayed in the Oscillation Signal display panel. Otherwise, the simulation is started and the oscillation signal is plotted in the Oscillation Signal display panel.

Each simulation takes 20 seconds to complete the oscillation signal plotting. Once the simulation is completed, the result is displayed. Figure 14 illustrates the simulated measurement results on GUI after a simulation is performed. Systolic pressure, diastolic pressure and pulse rate are shown in the seven-segment displays. However, mean pressure and maximum oscillation amplitude are not shown in the offline mode.

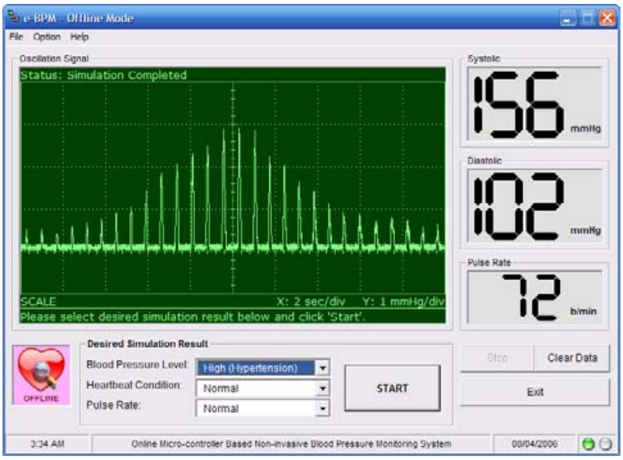

Figure 14 Displayed simulation results

System validation is carried out after the e-BPM is developed in order to examine the accuracy of the system. For this purpose, its measurement results are compared with the A&D TM2655P arm-type electronic blood pressure monitor. Table 1 shows the results gained during the validation process. From the results, mean values are obtained for discussions and these values are shown in Table 2.

In the results validation process, the e-BPM is tested in six consecutive samples: three males and three females. For each sample, a measurement is performed by the TM2655P blood pressure monitor and followed by the e-BPM in two minutes later. The measurement of blood pressure and pulse rate by each device is carried out three times for each sample within 30 minutes.

From the recorded results shown in Table 1, the maximum difference (error) occurred in the measurement of blood pressure between the TM2655P blood pressure monitor and the e-BPM is 16 mm Hg for systolic pressure and 8 mm Hg for diastolic pressure. For pulse rate, the maximum error recorded during the validation process is 1 beat per minute.

Table 1 Validation results

Patient	Sex	TM2655P			e-BPM		
		SP	DP	PR	SP	DP	PR
		109	63	68	110	64	68
A	Male	106	60	66	113	63	67
		115	62	68	113	58	67
		112	67	95	124	75	96
B	Male	115	67	96	119	70	96
		113	68	97	118	65	95
		119	79	70	123	82	69
C	Male	124	83	67	127	83	69
		115	80	70	131	83	70
		97	62	74	95	59	73
D	Female	92	64	71	97	59	70
		92	59	71	94	58	71
		104	66	69	103	66	70
E	Female	106	59	70	104	61	70
		100	65	69	100	62	69
		110	71	82	115	70	82
F	Female	116	68	79	113	73	79
		109	65	82	101	65	81

Referring to the obtained mean values in Table 2, the maximum difference (error) occurred in the measurements of blood pressure between the TM2655P blood pressure monitor and the e-BPM is 8 mm Hg for systolic pressure and 3 mm Hg for diastolic pressure while the maximum error of the measured pulse rate is 1 beat per minute.

Table 2 Mean results

Patient	TM2655P			e-BPM		
	SP	DP	PR	SP	DP	PR
A	110	62	67	112	62	67
B	113	67	96	120	70	96
C	119	81	69	127	83	69
D	94	62	72	95	59	71
E	103	63	69	102	63	70
F	115	68	81	110	69	81

As a conclusion, the developed e-BPM is accurate in giving the measurement of pulse rate. For blood pressure measurements, the accuracy of the system is still acceptable by referring to the obtained mean values. However, the applied coefficients i.e. systolic and diastolic ratio means should be reviewed in order to improve the accuracy in performing the blood pressure measurement.

5.0 DISCUSSION

In order to validate effectively the measurement results of a new developed blood pressure measurement device, the validation process must be carried out with an accurate device. This is usually done by using the invasive method i.e. the intra-arterial measurement because this method gives punctual values in every heartbeat and blood pressure continuous waveform. Blood pressure is simultaneously measured intra-arterially and with the developed measurement device. Then, the invasive measurement is compared with the measurement taken with the developed device [17].

However, the validation process in this study can only be performed by comparing the measurement results between two non-invasive blood pressure measuring device, i.e. the TM2655P and the e-BPM. Since the simultaneous measurement with both of the measurement devices is not possible, it is hard to prove that whether the difference (error) in the measured values of blood pressure are caused by the device error or the changing in the samples' blood pressure.

6.0 CONCLUSION

In this study, a prototype of the online micro-controller based non-invasive blood pressure monitoring system (e-BPM) is successfully designed and developed while at the same time, achieving all the objectives of this thesis.

Generally, the e-BPM is a blood pressure measurement device that uses the principles of the oscillometric method to determine patients' blood pressure and pulse rate for routine clinical use solely for blood pressure measurement. The system is designed to give doctors a safer and more convenient way to record their patients' blood pressure.

Specifically, a significant contribution of this study is towards the non-invasive blood pressure measurement technique which a blood pressure measurement device that shows the measurement results with oscillation signal waveform is developed. The captured oscillation signal waveform is important in giving doctors information on the patient's heartbeat conditions. Moreover, the developed system can also be used for educational purposes in colleges and universities, especially in the fields of medicine and bioinstrumentation. The system shows the simulated measurement results with oscillation signal waveform, indeed giving the students a comprehensive exposure in the application of non-invasive blood pressure measurement.

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