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Automatic Blood Pressure and Heart Rate Measurement using Oscillometric Method

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ABSTRACT

High blood pressure's strong correlation with cardiovascular diseases and high morbidity has made measuring blood pressure a necessity in identifying those at risk. This paper presents the design and construction of an automatic blood pressure and heart rate monitoring device that can measure a user's blood pressure and heart rate through an inflatable hand cuff wrapped around the upper arm using oscillometric method. The device consists of integrated pressure sensor, analog signal-conditioning circuitry, analog switch, analog to digital converter, microcontroller hardware and software, cuff, mini air pump, valve, and liquid crystal display. The system was realized with about 80% success rate in blood pressure measurement and very high accuracy.

Key words: Blood Pressure, Heart rate, Oscillometric, Analog-to-digital converter, Microcontroller

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INTRODUCTION

Blood pressure is possibly one of the most important pressures that are commonly measured. Perfusion of oxygen and nutrients depends on pressure gradients, and blood pressure is an important indicator of the condition of the cardiovascular system. There is need to measure and track the blood pressure of patients who suffer from hypertension and other related diseases. Blood pressure is the pressure exerted by the blood at right angles to the walls of the blood vessels, while blood flows through the arteries. Up to 25 percent of patients who are diagnosed with hypertension do not suffer from hypertension, but instead from white-coat hypertension. This is the elevation of arterial pressure due to anxiety or stress produced by a health professional while taking a blood pressure test. Office blood pressure measurement has important limitations. In particular, a single office blood pressure reading often does not represent a patient's true blood pressure status. This is because a random error characterizes a single measurement of a variable such as blood pressure, which changes continuously over time. This is why personal blood pressure monitors can help in detecting true hypertension [1]. There may also be a systematic error related to the patient's alerting reaction to the measurement procedure and setting (i.e. white coat effect) and the inability of office blood pressure to collect information on blood pressure during usual daytime activities and during sleep. Following the pioneering work in the 1960s, several techniques have been developed to perform blood pressure measurements outside of the physician's office in order to overcome the limitations of the office blood pressure [2]. Two of them have become widely used in clinical practice: 24-h ambulatory blood pressure monitoring and home blood pressure monitoring.

Blood pressure monitoring systems use techniques such as tonometry, ultrasonic, oscillometric methods and Korotkoff measurements. The pressure measured when the heart contracts and sends blood out of the heart is called systolic; it is the peak pressure in the arteries during the cardiac cycle. The pressure measured when the heart dilates with blood flowing back into the heart is called diastolic; it is the lowest pressure at the resting phase of the cardiac cycle.

Blood pressure measurement can be achieved by invasive and non-invasive methods. Invasive technique involves measuring blood pressure directly, and which is most accurately achieved by inserting a needle attached to a tube (cannula) into an artery. The tube contains sterile fluid and is connected to an electronic pressure sensor. Pressure is constantly monitored, beat by beat, and shown on a visual display. This technique is normally only used in hospital as there is a risk of severe bleeding if the needle is displaced. Constant supervision is necessary. Non-invasive techniques measure changes from outside the body. The non-invasive auscultatory and oscillometric measurements are simpler and quicker than invasive measurements, require less expertise, have virtually no complications, and are less unpleasant and less painful for the patient [1]. However, noninvasive methods may yield somewhat lower accuracy and small systematic differences in numerical results. Non-invasive measurement methods are more commonly used for routine examinations and monitoring.

An automatic blood pressure and heart rate monitor is a device used to measure an individual's blood pressure and heart rate. In 2004, a semiautomatic blood pressure monitor which utilizes the principle of oscillometry in its operation was designed [3]. The inflation of its occlusive cuff is carried out in a manual way. In the Freescale semiconductor application note AN1571 [4], the oscillometric method of blood pressure measurement was utilized. Most commercial non-invasive automatic blood pressure monitors use either oscillometric method or/and automatic detection of Korotkoff sounds [5].The major challenge with automatic blood pressure measurement is ambient noise and motion artifacts which are created by body movements. The work in [6] is on the measurement of heart rate using facial image gotten from a webcam. The automatic blood pressure and heart rate monitoring device proposed in this work made use of efficient oscillometric amplifier design, microcontroller and liquid crystal display.

SYSTEM DESIGN

The design proposed in this work is based on the oscillometric method of blood pressure measurement. This method is employed by the majority of automated non-invasive devices. A limb and its vasculature are compressed by an encircling, inflatable compression cuff. The blood pressure reading for systolic and diastolic blood pressure values are read at the parameter identification point. The simplified measurement principle of the oscillometric method is a measurement of the amplitude of pressure change in the cuff as the cuff is inflated from above the systolic pressure. The amplitude suddenly grows larger as the pulse breaks through the occlusion. This is very close to systolic pressure. As the cuff pressure is further reduced, the pulsation increase in amplitude reaches a maximum and then diminishes rapidly. The index of diastolic pressure is taken where this rapid transition begins. Therefore, the systolic blood pressure (SBP) and diastolic blood pressure (DBP) are obtained by identifying the region where there is a rapid increase then decrease in the amplitude of the pulses respectively. Mean arterial pressure (MAP) is located at the point of maximum oscillation. The block diagram of the blood pressure and heart rate monitor is shown in figure 1 while the descriptions of the main blocks are shown in the next sub-sections.

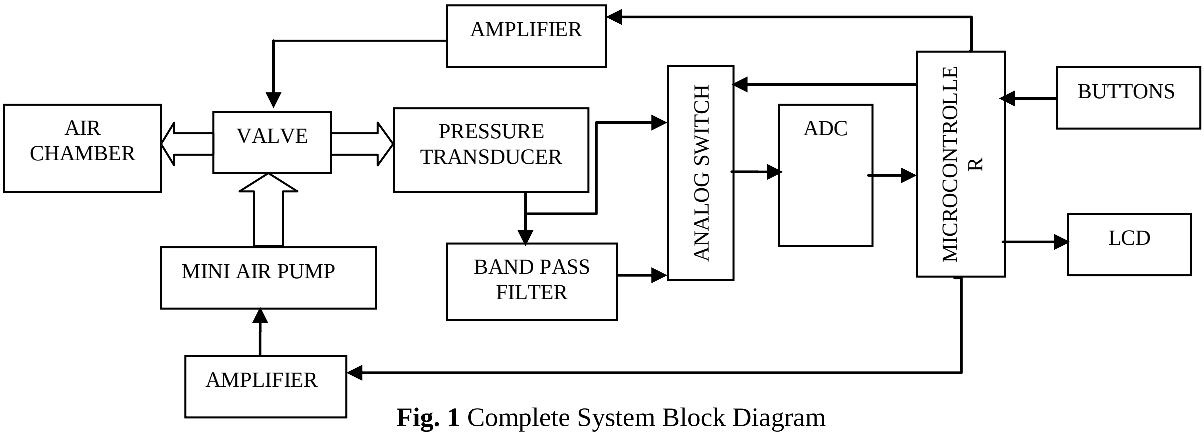


Fig. 1 Complete System Block Diagram

Analog-to-Digital Converter: The ADC0804 is a CMOS 8-bit successive approximation analog-to-digital converter that uses a differential potentiometric ladder similar to the 256R products. This converter is designed to allow operation with the NSC800 and INS8080A derivative control bus with tri-state output latches directly driving the data bus. This analog-to-digital converter appear like memory locations or I/O ports to the microprocessor and no interfacing logic is needed. Differential analog voltage inputs allow increasing of the common-mode rejection and offsetting the analog zero input voltage value. In addition, the voltage reference input can be adjusted to allow the encoding of any smaller analog voltage span to the full 8 bits of resolution.

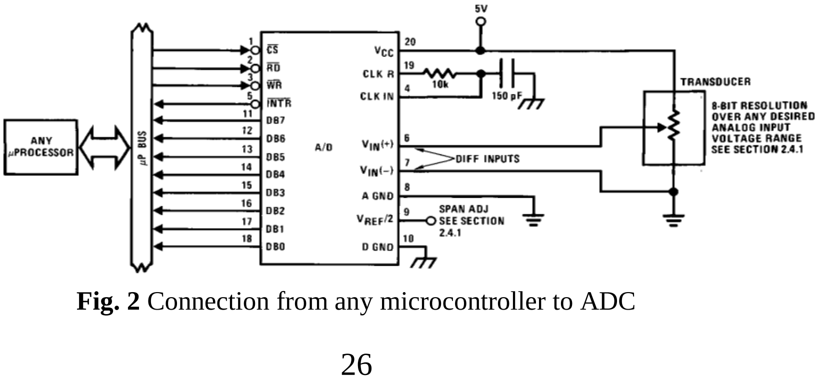


Fig. 2 Connection from any microcontroller to ADC

74VHC4066 Quad Analog Switch: These devices are digitally controlled analog switches utilizing advanced silicon-gate CMOS technology. These switches have low “on” resistance and low “off” leakages. They are bidirectional switches, thus any analog input may be used as an output and vice-versa. Also the 4066 switches contain linearization circuitry which lowers the “on” resistance and increases switch linearity. The 4066 devices allow control of up to 12V (peak) analog signals with digital control signals of the same range. Each switch has its own control input which disables each switch when low. All analog inputs and outputs and digital inputs are protected from electrostatic damage by diodes connected to the V_{cc} and ground.

Pressure Transducer: The MPX5050/MPXV5050G series piezo-resistive transducer is a state–of–the–art monolithic silicon pressure sensor designed for a wide range of applications, but particularly those employing a microcontroller or microprocessor with A/D inputs. This single element transducer combines advanced micromachining techniques, thin–film metallization, and bipolar processing to provide an accurate, high level analog output signal that is proportional to the applied pressure. The MPXV5050GP pressure transducer from Motorola is used to sense the pressure from the arm cuff. The pressure transducer produces the output voltage proportional to the applied differential input pressure. The tube from the cuff is connected to the input. The transfer characteristic is shown in figure 3.

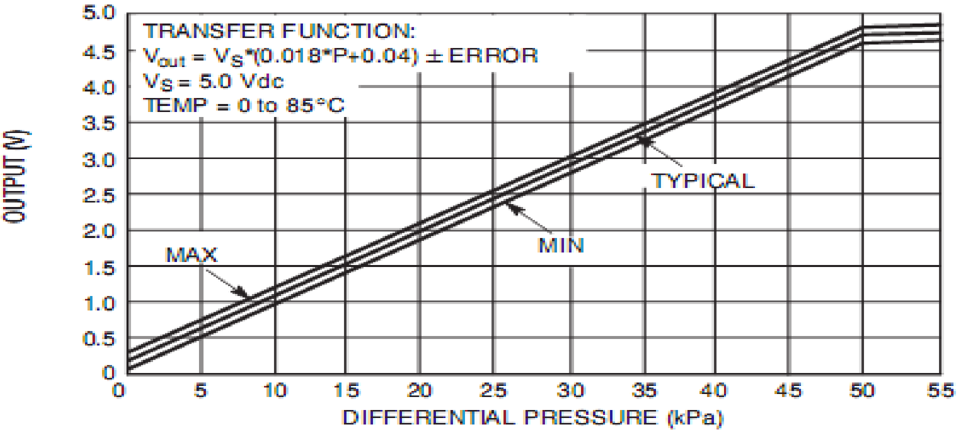


Fig. 3 Output voltage vs. Differential input pressure

Band Pass Filter Design: The band-pass filter stage is designed as a cascade of the two active band-pass filters. The reason for using two stages is that the overall band-pass stage would provide a large gain and the frequency response of the filter will have sharper cut off than using only single stage. This method will improve the signal to noise ratio of the output.

First Band-pass filter: The band pass filter is designed in an inverting amplifier configuration, with the first stage having less gain than the second stage. Using the desired values for the lower cut-off frequencyf_{c_1}, Gain A, and capacitorC_1, the values of resistors R_1 and R_2 can be determined as follows:

The gain factor A = - $\frac{R_2}{R_1}$ ……………………. (1)

$R_1 = \frac{1}{2\pi f_{c_1} C_1}$ ……………………. (2)

R_2 = - R_1A ……………………. (3)

The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output. Using a desired value for the higher cut-off frequencyf_{c_2}, the value of capacitor C_2 can be determined as follows:

$C_2 = \frac{1}{2\pi f_{c_2} R_2}$ ……………………. (4)

Taking the lower cut-off frequency f_{c_1} = 0.338Hz, Gain A = 12, and capacitor value C_1 = 47µF, the values of resistors R_1 and R_2 can be determined from equation (2)

$R_1 = \frac{1}{2\pi\ X\ 0.338\ X\ 47\ X\ 10^{-6}}$ = 10018.65Ω (approximately 10k Ω)

From equation (3)

R_2 = - 10X 12 = - 120k Ω

The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output. Taking the higher cut-off frequency f_{c_2} = 6.631Hz, R_2 = 120K Ω the value of capacitor C_2 can be calculated from equation (4)

$C_2 = \frac{1}{2\pi\ X\ 6.631\ X\ 120}$ = 0.2 µF (approximately 200nF)

Second Band-pass filter: The second band pass filter also has an inverting amplifier configuration, and a higher gain. Using the desired values for the lower cut-off frequencyf_{c_1}, Gain A, and capacitorC_1, the values of resistors R_1 and R_2 can be determined as follows:

The gain factor A = - $\frac{R_2}{R_1}$ ……………………. (5)

$R_1 = \frac{1}{2\pi f_{c_1} C_1}$ …………………….. (6)

$R_2 = - R_1 A$ …………………….. (7)

The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output. Using a desired value for the higher cut-off frequency f_{c_2}, the value of capacitor C_2 can be determined as follows:

$C_2 = \frac{1}{2\pi f_{c_2} R_2}$ ………………………. (8)

Taking the lower cut-off frequency f_{c_1} = 0.338Hz, Gain A = 33.3, and capacitor value C_1 = 47µF, the values of resistors R_1 and R_2 can be determined from equation (6)

$R_1 = \frac{1}{2\pi X 0.338 X 47 X 10^{-6}}$ = 10023.65Ω (approximately 10k Ω)

From equation (7)

R_2 = - 10X 33.3 = - 333k Ω

The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output. Taking the higher cut-off frequency f_{c_2} = 19.91Hz, R_2 = 333k Ω the value of capacitor C_2 can be calculated from equation (8)

$C_2 = \frac{1}{2\pi X 19.91 X 333}$ = 2.402 X10^{-2} µF (approximately 24nF)

The schematics for both filters (cascaded band pass filters) are shown in figure 4.

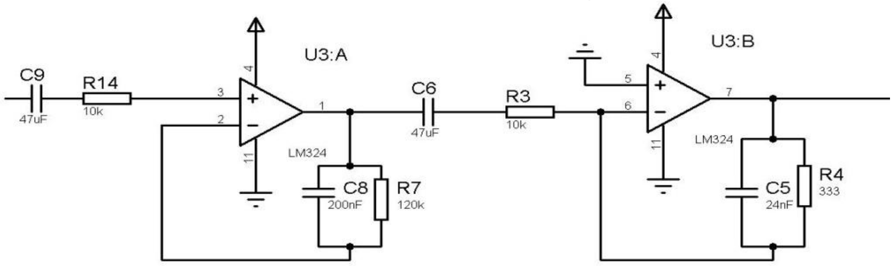


Fig. 4 Cascaded band pass filters

AC Coupling Stage: The ac Stage 1 is used to provide the DC Stage 2 DC level of the waveform is to be located at approximately half 2.5 V. Therefore, $R_3 = R_4 =$ [illegible]

5v

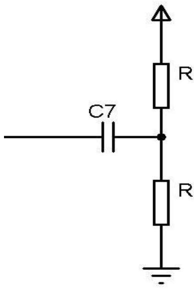


Fig. 5 AC coupling stage for DC bias level

Valve Connection

P = IV

0.5W = IV

I = $\frac{0.5}{6}$ = 0.083A

I = 83mA

$\frac{Load}{h_{fe}}$ X 10 = I_b

$\frac{0.083}{30,000}$ x 10 = I_b = 2.76 x 10^{-5}A

$I_b = \frac{V_{cc} - V_{BE}}{R}$

R = $\frac{5-(0.6X\ 2)}{27.6\mu A} = \frac{3.8}{27.6\mu A}$ = 137681Ω

R = 138k Ω

SOFTWARE DESIGN

The flowchart in figure 6 is a pictorial representation of the sequence of tasks executed by the microcontroller.

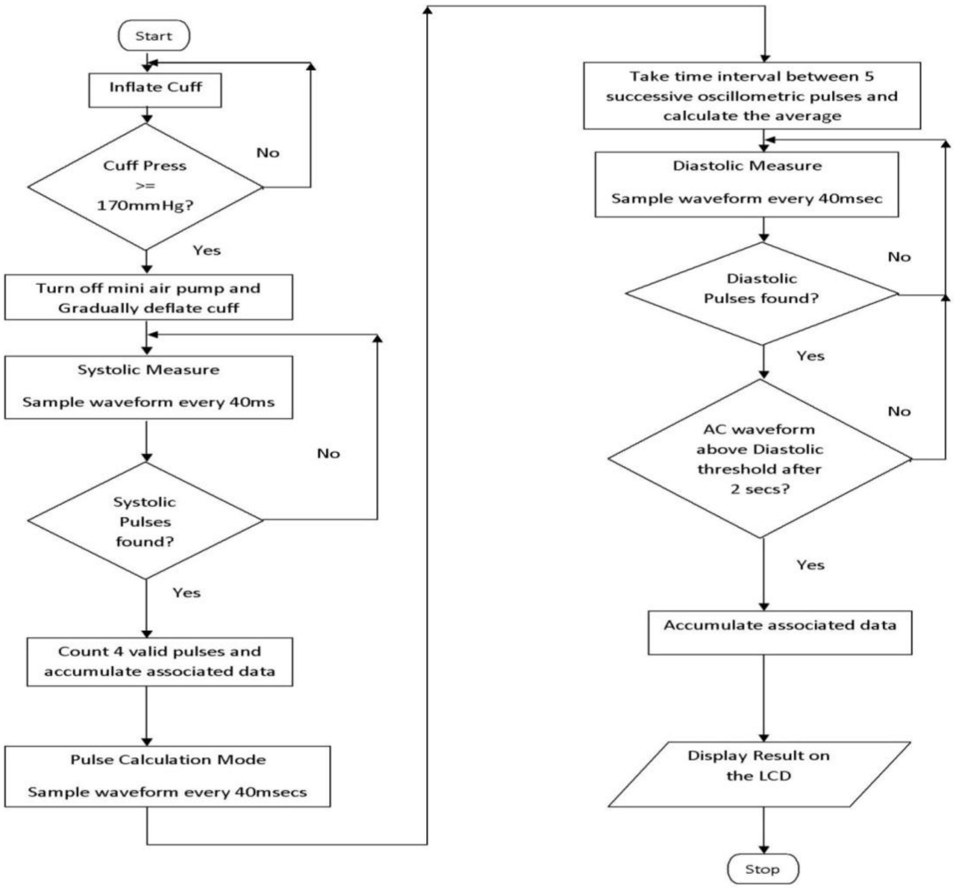


Fig. 6 Program Flow Chart

The system starts when the user pushes the start button of the device. Once the start button has been pushed, the measurement process begins by inflating the hand cuff. While the cuff is being inflated, if the user feels very uncomfortable or painful, he/she can push the reset button (emergency button) to stop the motor, quickly deflate the cuff and stop the measurement. This will ensure that the safety of the user is well maintained while using the device. If the cuff-inflating procedure goes smoothly, the air will be pumped into the cuff until the pressure inside the cuff reaches 170 mmHg. After that, the motor will be stopped and the air will be slowly released from the cuff. Once the microcontroller has obtained the values of systolic and diastolic blood pressure and heart rate, it will report the result of the measurement by displaying the obtained data on the LCD screen. After that if the reset button is pushed the program will return to the START state again waiting for the next measurement.

SYSTOLIC PRESSURE MEASUREMENT

After the motor pumps the pressure up to 170 mmHg which is approximately more than the systolic pressure of normal healthy people, the cuff starts deflating and the program enters Systolic Measurement state. In this state, the microcontroller enables control1 pin of the analog switch and the program will observe the AC waveform from the Analog-to-Digital Converter pin. When the pressure in the cuff decreases to a certain value, the blood begins to flow through the arm. The systolic pressure is obtained at this point. At the start, there is no pulse and when the pressure in the cuff decreases until it reaches the systolic pressure value, the oscillation starts and grows. The number of pulses that has maximum values above the threshold voltage (4.0v) is counted. If the program counts up to 4, the program enters the Systolic calculation state. At this state, the program enables control2 pin of the analog switch and records the DC voltage from the Analog-to-Digital Converter pin. Then it converts this DC voltage value to the pressure in the cuff to determine the systolic pressure of the patient. From the transfer characteristic of the pressure transducer, the systolic pressure can be determined by looking at the DC voltage of the Analog-to-Digital Converter pin. Let the DC voltage that is read off of the ADC pin be ‘DC_voltage'. From the pressure transducer's transfer characteristic given in figure3, pressure can be calculated based on the transducer voltage.

Slope = $\frac{4.7V}{50KPa}$ = 0.094.

Thus, the pressure in the cuff in the unit of kPa can be calculated as $pressure\_kPa = \frac{transducer\_voltage}{slope}$.

Then converting the pressure back to mmHg unit is achieved by multiplying the pressure in KPa by $\frac{760mmHg}{101.325kPa}$.

Thus the pressure in the mmHg unit is expressed as $pressure\_mmHg = pressure\_kPa \times \frac{760mmHg}{101.325kPa}$.

After the program finishes this calculation, it enters the Rate measure state to determine the pulse rate of the patient.

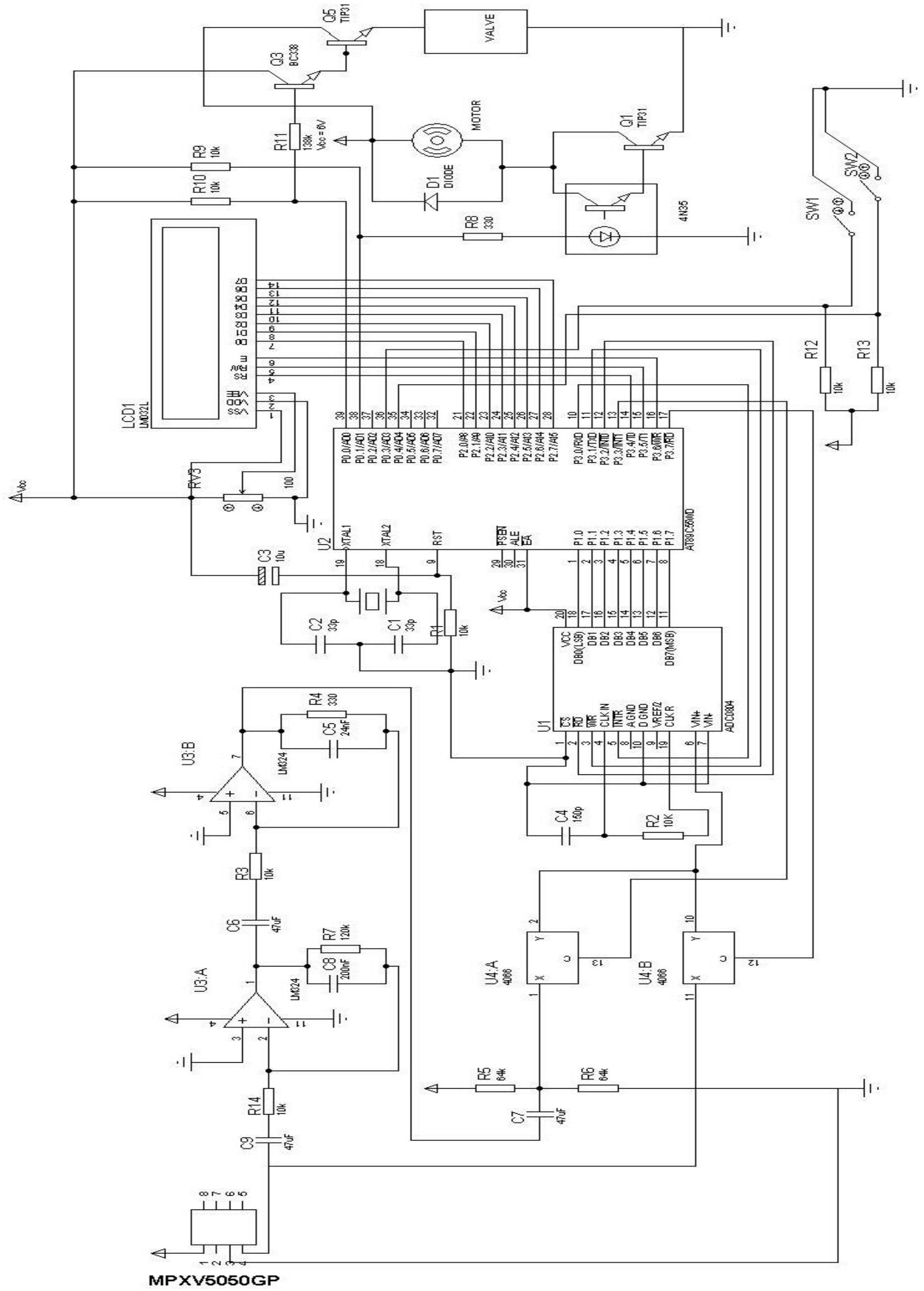


Fig. 7 Complete Schematic for Automatic Blood Pressure and Heart Rate Monitor

PULSE RATE MEASUREMENT

After the program finished calculating the systolic pressure, then it starts monitoring the pulse rate of the patient. The pulse rate is chosen to be determined right after determining the systolic pressure because at this point the oscillation of the waveform is strongest. The program samples the AC waveform every 40 millisecond. It then records the time interval when the values of the AC waveform cross the voltage value of 2.5 volts. The program then takes the average of five time intervals so that the heart rate will be as accurate as possible. After the heart rate is determined, the program then enters the Diastolic measure state, in which it tries to measure the diastolic pressure of the patient.

DIASTOLIC PRESSURE MEASUREMENT

In this state, the program is still sampling the signal at every 40 millisecond. While the cuff is deflating, at some point before the pressure reaches diastolic pressure, the amplitude of the oscillation will decrease. To determine the diastolic pressure, the DC value at the point when the amplitude of the oscillation decreases to below the threshold voltage is recorded. This is done by looking at the time interval of 2 seconds. If the AC waveform does not go above the threshold in 2 seconds, it means the amplitude of the oscillation is actually below the threshold. The DC value can then be converted back to the pressure in the arm cuff using the same procedure as described in the Systolic Pressure Measurement section.

After the program finishes calculating the diastolic pressure, it will display the information acquired from the measurement on the LCD.

RESULTS AND DISCUSSION

A prototype Automatic Blood Pressure and Heart Rate Monitor was built as shown in the schematics in figure 7. The microcontroller unit is the main component that controls the operations (such as motor and valve control) and calculations until the measurement is completed. When the start button is pushed, the microcontroller sends control signal which energizes the mini-air pump and valve to pump air into the cuff. The microcontroller also monitors the signal from the pressure transducer, when it reaches 170mmHg (approximately 2.21 volts) it cuts-off supply to the mini-air pump and gradually deflate the arm cuff through the valve. The output of the pressure transducer (sensor) is split into two paths for two different purposes. One is used as the cuff pressure while the other is further processed by the analog signal-conditioning circuitry. Since the pressure transducer (MPXV5050GP) is signal-conditioned by its internal operational amplifier, the cuff pressure can be directly interfaced with an analog-to-digital (A/D) converter for digitization. The other path will filter and amplify the raw cuff pressure signal to extract an amplified version of the cuff pressure oscillations each time pressure in the arm increases during cardiac systole. While the arm-cuff is being deflated, the microcontroller enters the calculation state. In this state, as blood begins flowing through the brachial artery again, it will cause small pulsations that will be picked up by the pressure sensor. The corresponding waveform signal as shown in figure 8 is generated by the analog signal-conditioning circuitry and passed on to the microcontroller via the analog switch and the analog-to-digital converter for further processing. Based on specified threshold voltages, the systolic, diastolic and heart rate measurements are determined.

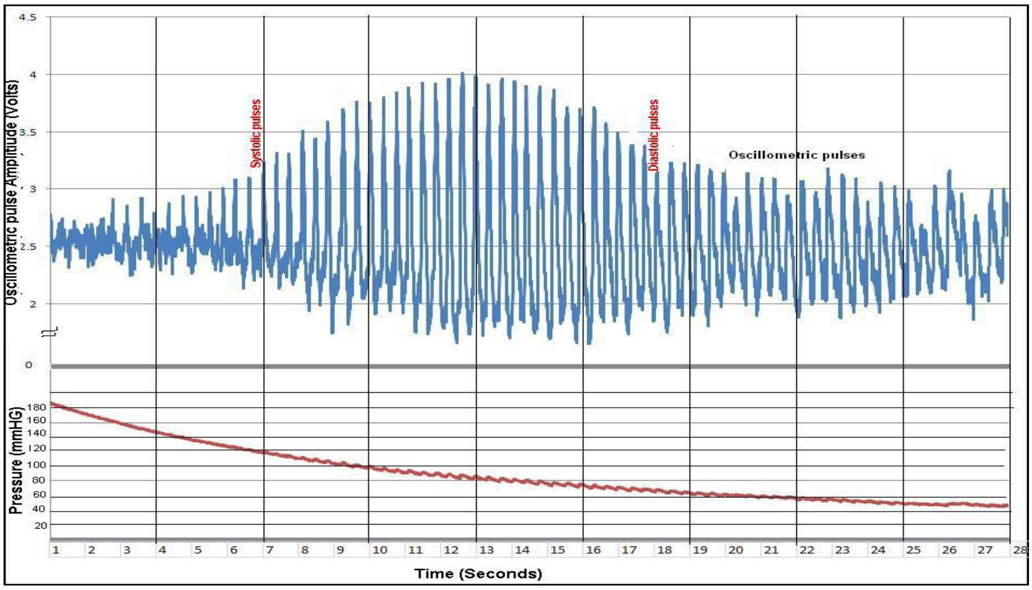
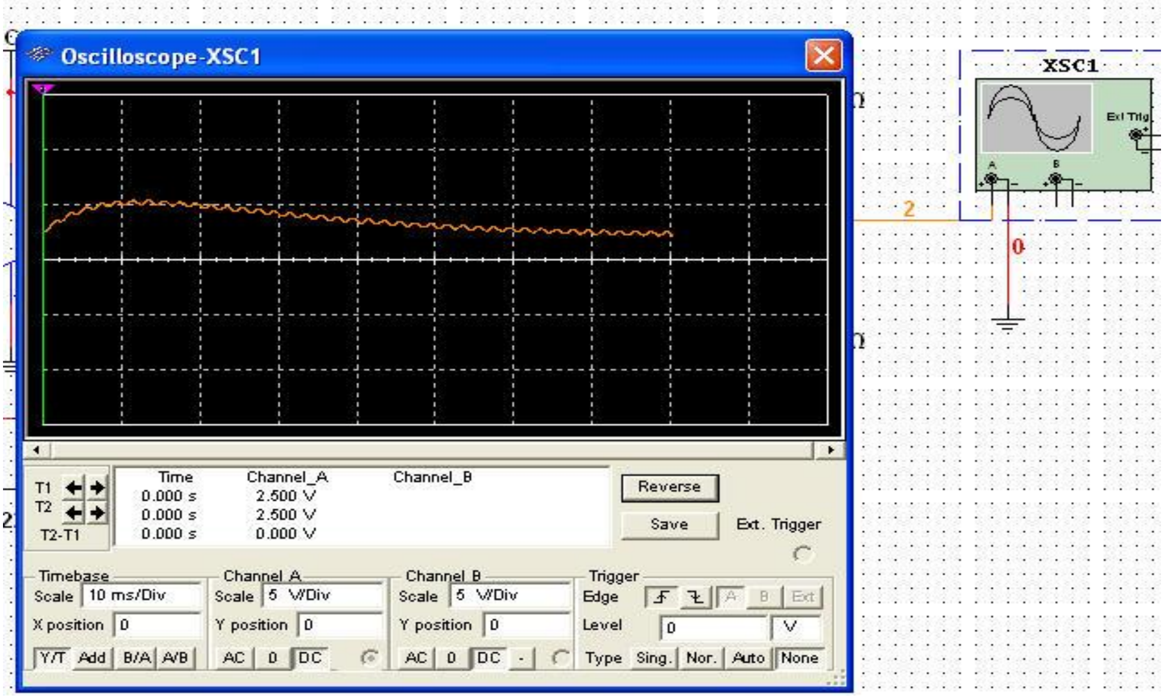


Fig. 8 Oscillometric Pulse

The analog part of the system was simulated using Multisim application to see the response of the filter and below is a sample screen shot of the simulations. The entire circuit was then simulated using Proteus to test the software's effect on the system components. They all performed well.



	Time	Channel_A	Channel_B
T1	0.000 s	2.500 V	
T2	0.000 s	2.500 V	
T2-T1	0.000 s	0.000 V	

Timebase: Scale 10 ms/Div, X position 0
Channel A: Scale 5 V/Div, Y position 0
Channel B: Scale 5 V/Div, Y position 0
Trigger: Level 0 V

Fig. 9 Multisim simulation of output from the band-pass filter stage

The hardware design was also tested and all the components were found to be working optimally.

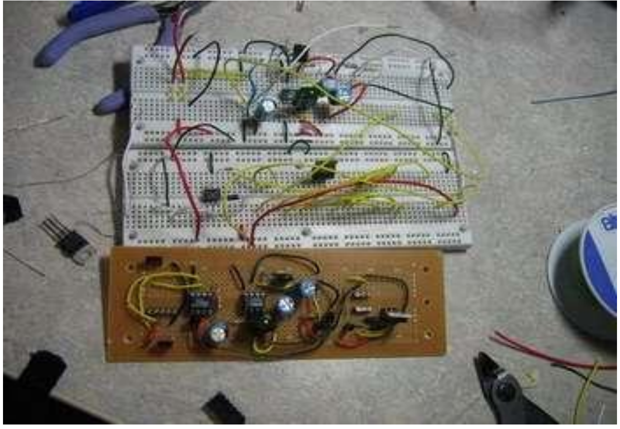


Fig. 10 Hardware implementation

Fig. 11 Testing with Oscilloscope

As mentioned earlier, all the measurements are mainly dependent on the waveforms from the circuit and the pressure sensor is very sensitive to even a slight movement of the user. As a result, it is possible that sometimes the device fails to obtain the desired data, especially if the user does not stay still or wears the cuff improperly. The three measurements- systolic blood pressure, diastolic blood pressure and heart rate have different success rates. The success rate for the heart rate measurement is very high for getting an accurate value. Finding the pressure values, is more challenging because they depend on the amplitude of the waveform, and the amplitude varies a lot during the measurement. However, if the user stays still and wears the cuff right, the measurement has 80% success rate.

Safety Measures

Since this is a medical instrumentation device, the safety of the user is paramount. The cuff while being driven by 6 volts motor can squeeze the arm really hard and cause injury if being used improperly. In the device some levels of security has been incorporated making sure that the operation can be aborted by the user at anytime. The microcontroller is programmed in the way such that if the pressure in the cuff is greater than 170 mmHg, the motor will stop. For most people, the pressure at 170 mmHg will only cause a little discomfort to the arm. This design makes sure that the pressure inside the cuff will never exceed the maximum limit of 170 mmHg. The second safety measure is the provision of an emergency button for the user. While the motor is pumping and the cuff is being inflated, if the user encounters too much discomfort or pain, he/she can press this button to stop the operation immediately. The motor will be stopped and the valve will be opened to release the air out of the cuff.

CONCLUSION

In this work, the oscillometric method was employed to determine a patients' blood pressure and heart rate parameters. In measuring systolic pressure, after the motor pumps the pressure up to 170 mmHg which is approximately more than the systolic pressure of normal healthy people, the cuff starts deflating and the program enters Systolic Measure state. In this state, the program will looks at the AC waveform from the filter. When the pressure in the cuff decreases to a certain value, the blood begins to flow through the arm. At this time a look at the oscilloscope, confirms the onset of the oscillation. The systolic pressure can be obtained at this point. After the program finished calculating the systolic pressure, then it starts monitoring the pulse rate of the patient. The program then takes the average of five time intervals so that the heart rate will be as accurate as possible. After the pulse rate is determined, the program enters the Diastolic Measure state. In this state, the program is still sampling the signal at every 40 millisecond. While the cuff is deflating, at some point before the pressure reaches diastolic pressure, the amplitude of the oscillation will decrease. To determine the diastolic pressure, the DC value at the point when the amplitude of the oscillation decreases to below the threshold voltage is recorded. The measurements taken by the system are acceptably accurate (please see 'Accuracy' section above). The operations of the device are reliable and have not produced any major problems. The power consumption of the device is minimal.

In the design of the device accomplished in this project, there is no provision for storage of blood pressure readings. Therefore, we recommend that future improvements on this work should include a storage medium in the design that can store the result and make it available at any desired time.

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