ARM SIMULATOR
FOR BLOOD PRESSURE MEASUREMENT

A dissertation submitted in
partial fulfillment of the requirements for the degree of

Master of Technology

by

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M.Tech. Dissertation Approval

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ABSTRACT

Arm simulator is a device for simulating behavior of the arm for testing and calibration of a noninvasive blood pressure (BP) meter. The project objective is to develop an arm simulator for auscultatory as well as oscillometric methods of BP measurement over full clinical range of pressure, heart rate, and arrhythmia. It is designed using a 16-bit microcontroller with on-chip ADC and DAC. It has four keys and graphical LCD for setting the simulation parameters including the heart rate, systolic pressure, diastolic pressure, arrhythmia, and pulse volume. The Korotkoff sounds and oscillations in the cuff are generated based on the set parameters and in response to time-varying pressure in the cuff as dynamically sensed by a pressure sensor. In addition to its use for testing and calibration of a non-invasive blood pressure meter, it can be used as a teaching aid for correctly using a blood pressure meter, particularly in the cases of unusually low BP or arrhythmia.

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List of Symbols and Abbreviations

Abbreviation	**Term**
A	arrhythmia
ADC	analog-to-digital converter
B	beat per minute
BP	blood pressure
DAC	digital-to-analog converter
DP	diastolic pressure
HR	heart rate
LCD	liquid crystal display
MAP	mean arterial pressure
P	pulse volume
SP	systolic pressure
SMD	surface mounted device

Chapter 1
INTRODUCTION

1.1 Overview

Measurement of blood pressure (BP) is one of the common steps for assessing a patient's cardiovascular system. Finding the condition of abnormal blood pressure, such as hypertension (high blood pressure) and hypotension (low blood pressure) is important as it may not have any symptoms. For accurate BP reading, the measuring instrument should be tested and calibrated and the measurement should be carefully carried out. Testing of the instrument cannot be carried out using human subjects because their pressure levels depend on physiological factors such as sleep, body position, smoking, emotional state, etc. Taking multiple readings of the same subject to test the precision of the instrument or for comparing readings from two instruments may lead to change in the BP value. Further, with normal subject we cannot get the full range of BP values. Abnormal cardiac condition poses problem in BP measurement and a healthcare worker does not get exposure to these conditions by taking measurements on normal subjects. Therefore, different types of arm simulators have been developed, which simulate the behavior of the arm and are used for testing and calibrating the noninvasive BP monitors.

Several simulators for BP measurement using oscillometric method have been reported [6][7] and many instruments have now become available commercially. Most of these have the facility for testing the BP monitor based on oscillometric method but some also provide simulation of Korotkoff sound for auscultatory method. A brief description of some of these instruments is given in Appendix D. These simulators often lack flexibility in settings and are generally expensive. Hence for the measurement of BP under different cardiovascular conditions, a compact portable BP simulator is needed.

1.2 Project Objective

The objective of the project is to design and build an arm simulator for BP measurement using auscultatory as well as oscillometric method. For generating Korotkoff sound and pressure pulses, a 16-bit microcontroller with on-chip ADC and DAC is used. The instrument has four keys and a graphic LCD for conveniently setting the parameters. The sounds or are generated based on the set parameters and in response to time-varying pressure in the cuff as dynamically sensed by a pressure sensor.

1.3 Report Outline

The second chapter provides an overview of the basics of BP and various BP measurement techniques. Chapter 3 describes the design approach. Work done on hardware is presented in Chapter 4. Software and test results are presented in next chapter. The last chapter summarizes the work done and some suggestions for future work.

Chapter 2
BLOOD PRESSURE MEASUREMENT

2.1 Physiology of the Heart

Cardiovascular system consists of the heart and the blood vessels which circulate blood throughout the body. The blood transports nutrients and oxygen to the cells. Heart is a muscular organ which pumps the blood throughout the body. It consists of four chambers, the left atrium, the left ventricle, the right atrium and the right ventricle as shown in Figure 2.1 [1]. Blood enters into the right atrium through the two venacava, superior venacava (from the body's upper extremities such as head and neck) and inferior venacava (from the body's lower extremities). The incoming blood fills the right atrium and the coronary vein also gets emptied into the right atrium. When the right atrium is full, it contracts and forces blood through the tricuspid valve into the right ventricle. When the ventricular pressure exceeds the atrial pressure, the tricuspid valve closes and pressure in the ventricle forces the semilunar pulmonary valve to open and the pulmonary artery circulates the deoxygenated blood into the lungs. In the lungs, the red blood cells give up carbon dioxide and are recharged with oxygen. The oxygenated blood enters into the left atrium through pulmonary vein and then it is pumped via mitral valve into the left ventricle by the contraction of the atrial muscle. As the left ventricular muscles contract, the mitral valve gets closed. Pressure build-up in the ventricle forces the aortic valve to open and the blood flows into the aorta and circulates inside the whole body. This cycle of blood circulation is repeated with each beats of the heart [1].

The sequence of events during a heart beat is known as the cardiac cycle as shown in Figure 2.2. It consists of two major periods, systolic and diastolic. The systolic period is defined as the period of contraction, specifically of the ventricle muscle. The diastolic period is the period of dilation of the heart chambers as they fill with blood. Each beat of the heart involves five major stages. The first two stages include the "ventricular filling" stage. The next three stages involve the movement of blood from the ventricles to the pulmonary artery (in the case of the right ventricle) and the aorta (in the case of the left ventricle). Throughout the cardiac cycle, the blood pressure increases and decreases.

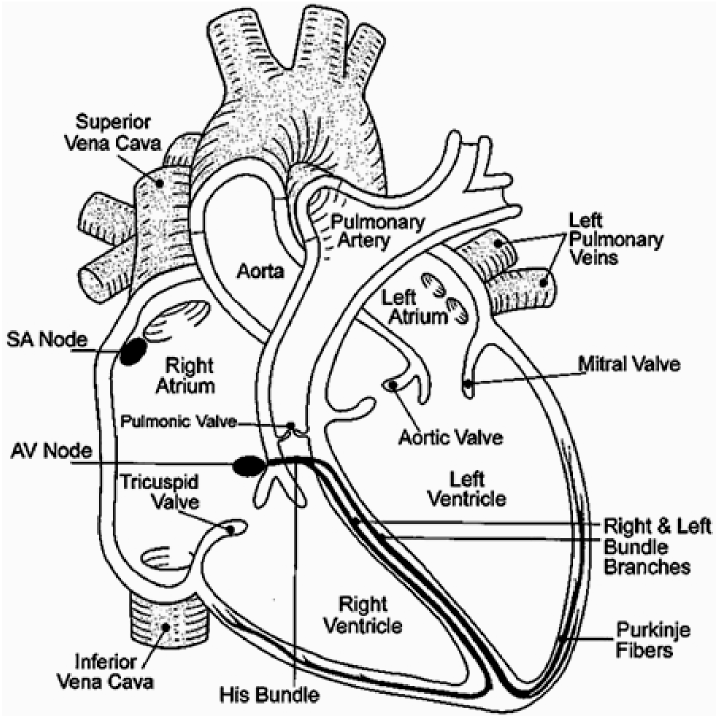


Figure 2.1 The heart [1]

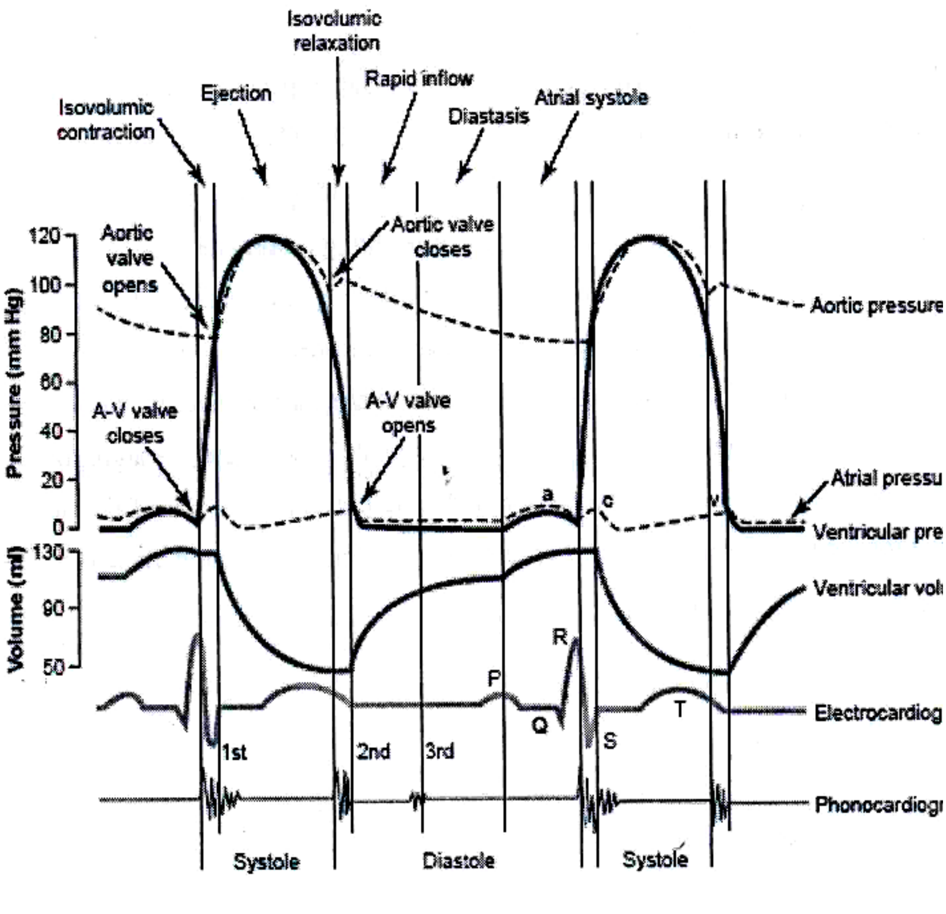


Figure 2.2 Various events during the cardiac cycle [2]

2.2 BP Measurement Techniques

The blood pressure is measured either using invasive (direct) or non-invasive (indirect) methods. Direct method gives accurate blood pressure measurement but it requires catheterization. This method is used for continuous monitoring of blood pressure in intensive care unit (ICU) and coronary care unit (CCU). For routine clinical measurement, indirect method is preferred. It is less accurate and it also depends on the patient position. It is generally measured with the patient sitting quietly and comfortably with the back support for at least five minutes and the arm supported at the level of the heart. Noninvasive methods include (i) auscultatory method, (ii) oscillometric method, (iii) ultrasonic method, and (iv) tonometry method.

2.3 Invasive Method

For taking direct measurement, a catheter or a needle type probe is inserted directly into the area of interest through arteries or vein [3]. Two types of probes are available, catheter tip probe and fluid filled probe. In the catheter tip probe, the sensor is mounted on the tip of the probe and the pressure exerted on the sensor is converted into a proportional electrical signal. In the fluid-filled catheter probe, the pressure is exerted by a fluid-filled column to the external transducer, which converts the pressure into the electrical signal, which is amplified and processed to give systolic, diastolic, and mean pressure values and may also be used for recording or display of the pulse waveform.

2.4 Auscultatory Method

This method is also known as the sphygmomanometer method for indirect BP measurement [3]. The blood pressure is measured using a cuff inflated by a squeeze bulb or an electrically operated pump, a mercury manometer, and a stethoscope as shown in Figure 2.3 [3]. The cuff is wrapped around the arm (which should be at about the heart level) and a stethoscope is placed on the brachial artery. The cuff is inflated to a pressure above the systolic pressure so that the flow of blood is occluded. The cuff is deflated slowly, and the stethoscope is used to hear the sound from the artery. The point at which the first sound is heard is the systolic pressure. This sound occurs because the blood flow under the cuff gets converted from laminar to turbulent form. As the pressure is slowly decreased further, the flow in each cardiac beat increases and the sound gets more intense. As the pressure is decreased further, the flow increases but it becomes less turbulent and sound gets weaker. The pressure below which the sound disappears is the diastolic pressure, because below this pressure the flow under the cuff is not turbulent.

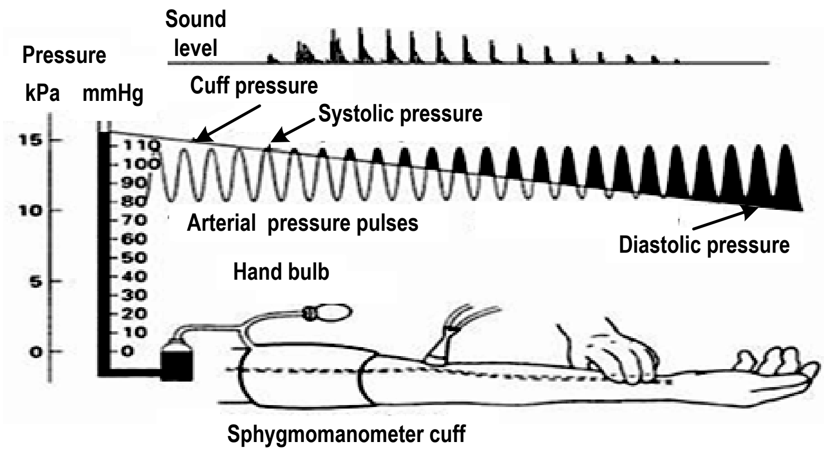
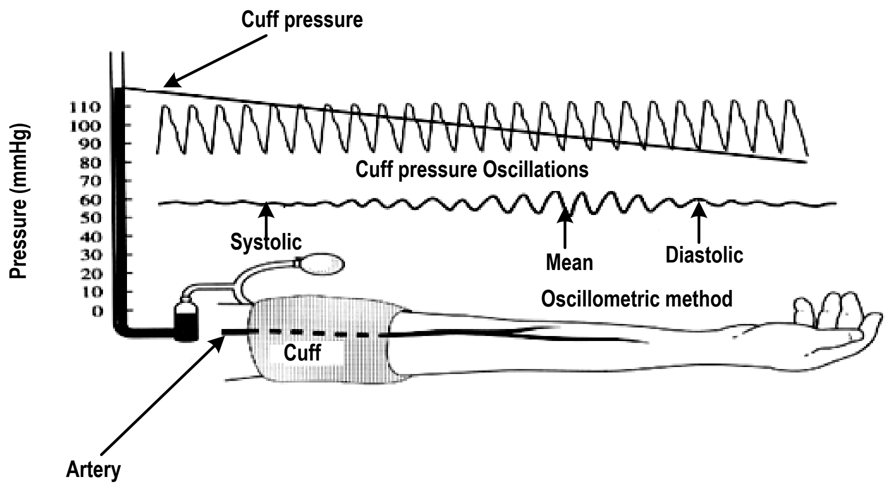


Figure 2.3 Auscultatory method for indirect blood pressure measurement [3]

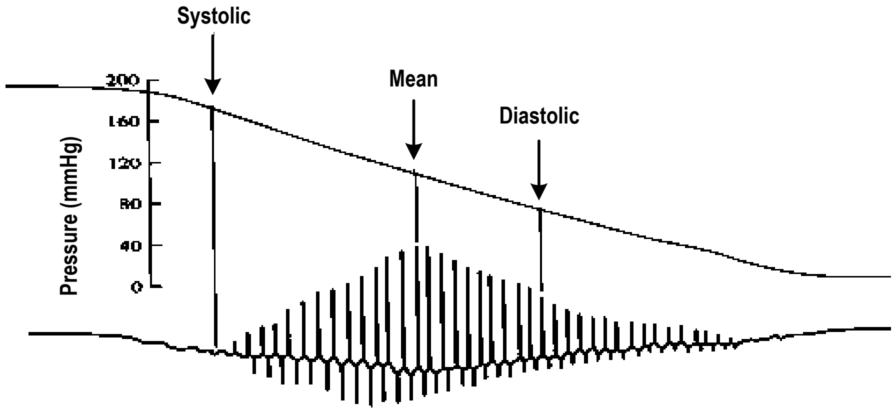
A tapping like sound is heard with each heart beat when the pressure is below the systolic pressure but above the diastolic pressure, and it is known as the Korotkoff sound [3]. These sounds are heard in five phases: (i) initial 'tapping' sound (cuff pressure = systolic pressure), (ii) sounds with increasing intensity, (iii) sounds with maximum intensity, (iv) sounds getting muffled, and (v) sounds disappear. The cuff need to be inflated to a pressure slightly above the systolic pressure and it should be deflated at an appropriate rate to clearly hear the sounds in successive beats, without unduly extending the measurement time. Use of this technique requires experience in recognizing the sound and it cannot be used in noisy environment. It is prone to mechanical errors e.g. mercury leakage, air leakage, obstruction in the cuff etc. It may not give accurate results for infants and hypertensive patients.

2.5 Oscillometric Method

The oscillometric method [3], as shown in Figure 2.4 works on the same principle as the auscultatory method, but it does not use a stethoscope. When the cuff pressure is in between the systolic and diastolic pressures, each cardiac cycle causes a small change in the cuff pressure, which has the appearance of oscillations. These oscillations, caused by the blood flow in artery below the cuff, are sensed using a pressure transducer, ac coupled, and amplified. The appearance and end of the oscillation indicate the time at which the cuff pressure equals the systolic and diastolic pressures respectively. Figure 2.4 (b) shows the oscillation in the cuff pressure. The point at which the oscillation begins to increase rapidly is the systolic pressure. The point of maximum oscillation corresponds to the mean arterial pressure. The pressure at which oscillation decreases rapidly is the diastolic pressure. The readings are not affected by environmental noise, such as those present in, emergency and clinical rooms. Most of the automated electronic BP instruments use this technique. This



(a)



(b)

Figure 2.4 Oscillometric method of blood pressure measurement (a) Cuff placement (b) Oscillation in cuff pressure [3]

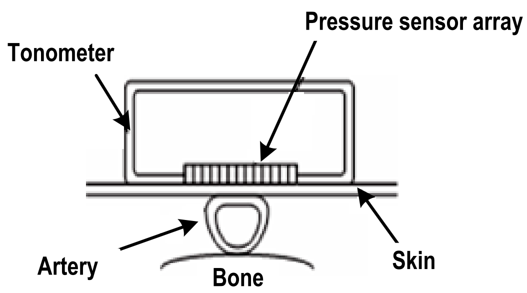


Figure 2.5 Tonometry method for blood pressure measurement [4]

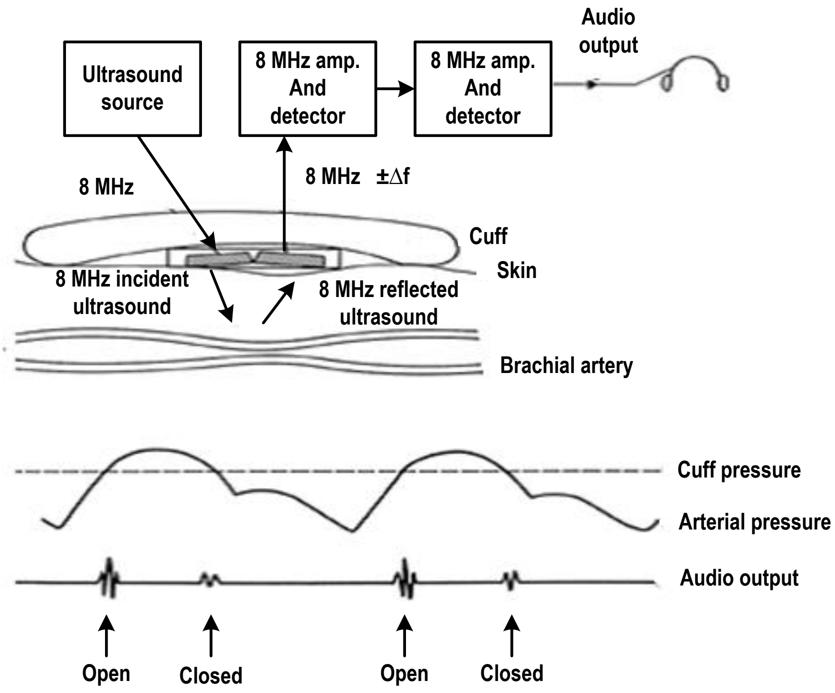


Figure 2.6 Ultrasonic method for indirect blood pressure measurement [4]

method is well suited for measuring the mean arterial pressure. In this method, an excessive movement of patient or vibration during measurement may result in inaccurate readings.

2.6 Tonometry Method

In this method [4], shown in Figure 2.5, superficial artery is compressed with the use of flat plates by placing it over the surface of the skin. These plates are supported from below by a bone. An array of sensors cylindrical in shape is used to sense the radial stress of the artery known as the arterial rider. Strain gauge sensor of arterial rider detects the arterial pulsation. The pressure is estimated by division of force by contact area of the arterial rider. A side plate is used to set the effect of skin tension to zero in vertical direction. This method is noninvasive and can be used to monitor blood pressure continuously. But this method has relatively higher cost, also wrist movement of patient may give inaccurate reading.

2.7 Ultrasonic Method (Doppler Method)

Doppler sensor, as shown in Figure 2.6, is used to measure blood pressure by means of detecting motion of the blood vessel. For transmission and reception of the signal, 8 MHz crystals are placed over the arm with the help of a compression cuff [4]. An ultrasound source transmits signal to the blood vessel. The reflected signal is transduced by the receiving crystal and amplified. Artery movement (closing and opening) is indicated by reception of reflected signal. Difference in frequency between transmitted and reflected signal is proportional to the velocity of wall motion and blood cells. When cuff pressure is set between diastolic pressure and systolic pressure, the blood vessel opens and closes with each heart beat. As the cuff pressure is increased, the time between opening and closing of the artery decreases till both pressure values become equal. At this point the reading of pressure is the systolic pressure. As the cuff pressure is decreased, the time between opening and closing of the artery increases until the artery does not close at all. The reading at this point is the diastolic pressure. This method can be used in noisy environment and it can be used with infant and hypotensive subject. Movement by the patient may change the alignment between the sensor and vessel thus the reflected signal may not give a correct reading.

2.8 BP Simulators

An arm simulator for BP measurement by oscillometric method was reported by Glover [6]. It has a monitor (valve, pump and transducer) for deflating and inflating the cuff as shown in Figure 2.8. The pressure pulses are generated using a microprocessor, pressure transducer and pulse generator, with the facility for selecting the beat rate, systolic pressure, diastolic pressure, and mean arterial pressure. The transducer converted the cuff pressure into electrical signal, which was acquired by the microprocessor through the ADC. The pulse amplitude was varied with the pressure with the maximum amplitude at the mean arterial pressure, as shown in Figure 2.7. The pulses were applied to the pressure chamber, with the help of a transducer with an electrical coil and diaphragm. During the generation of these pulses, a valve decoupled the pressure chamber from the cuff. This feature helps in power saving as the pressure pulses do not get coupled to the large volume of air in the cuff.

Another simulator for BP measurement using oscillometric method was reported by Kerl [7]. It simulates pressure pulses using an elastomeric bladder, a microprocessor, a pressure sensor, and a stepper motor. Elastomeric bladder consists of elastomeric tube that is compressed by a piston and bearing driven by a stepper motor. The simulator is connected to the cuff using a T connecter as shown in Figure 2.9. The pressure sensor senses the pressure from the cuff and it is given to the processer. The microprocessor induces one or more pulses by compressing and expanding the elastomeric bladder using a stepper motor. The pulses are generated as shown in Figure 2.10 and 2.11.

Several BP simulators are now commercially available. Some of these are briefly described in Appendix D.

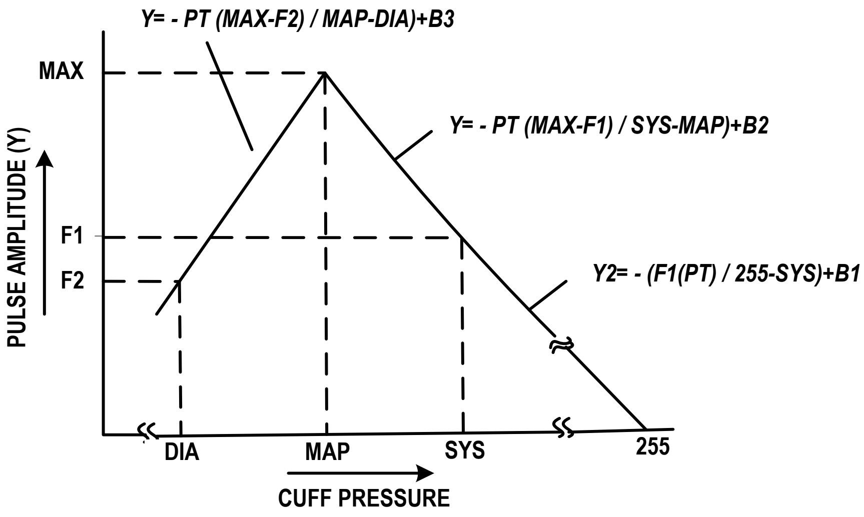


Figure 2.7 Pulse amplitude as a function of cuff pressure in the arm simulator described in [6]

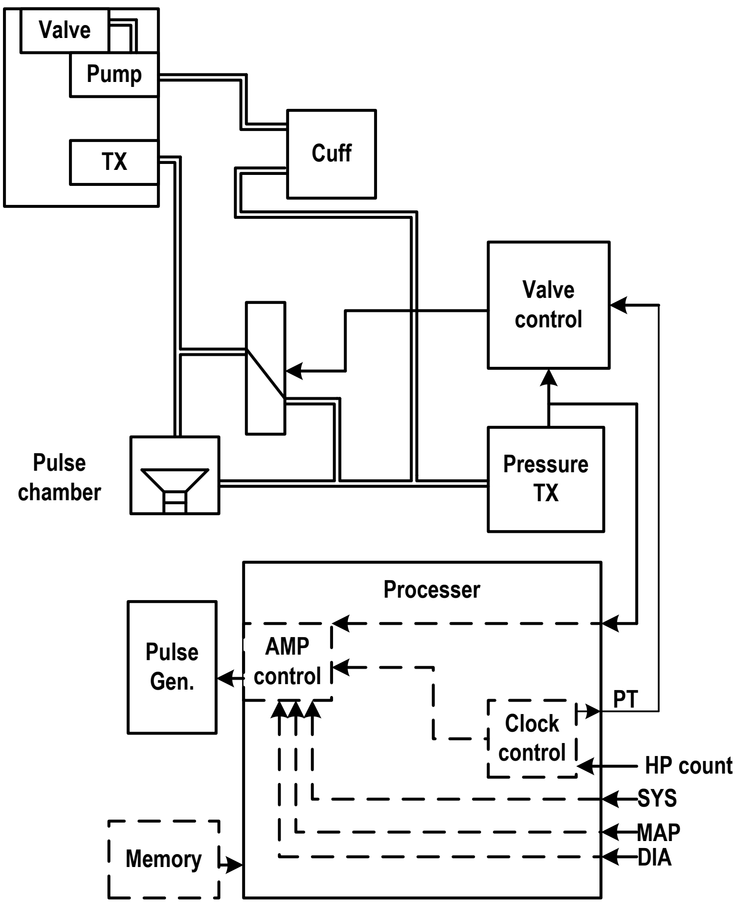


Figure 2.8 Block diagram of blood pressure simulator arm described in [6]

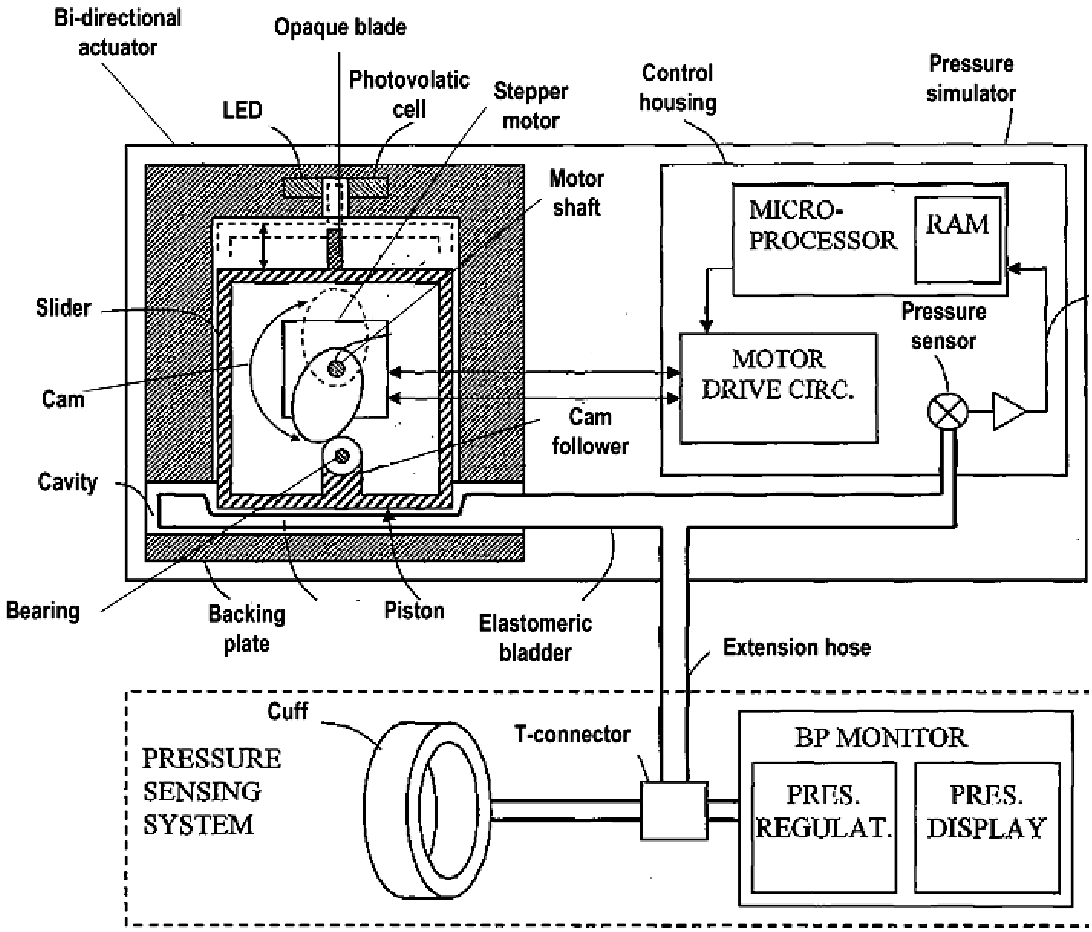


Figure 2.9 Compact blood pressure simulator described in [7]

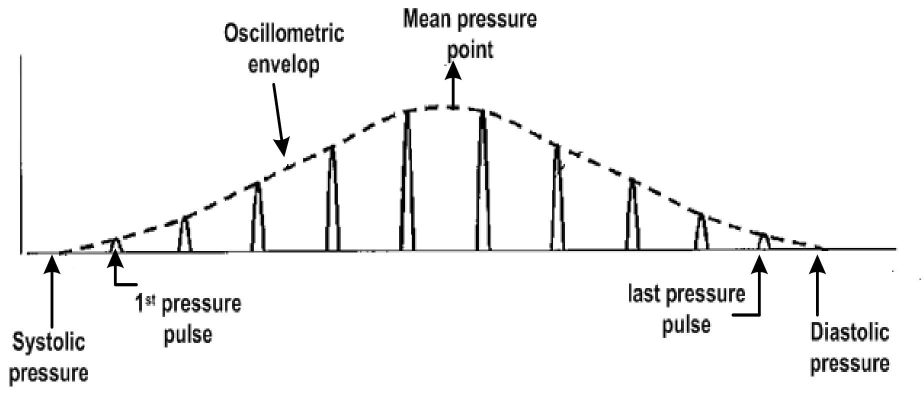


Figure 2.10 Simulated pressure pulse waveform cuff pressure verses time [7]

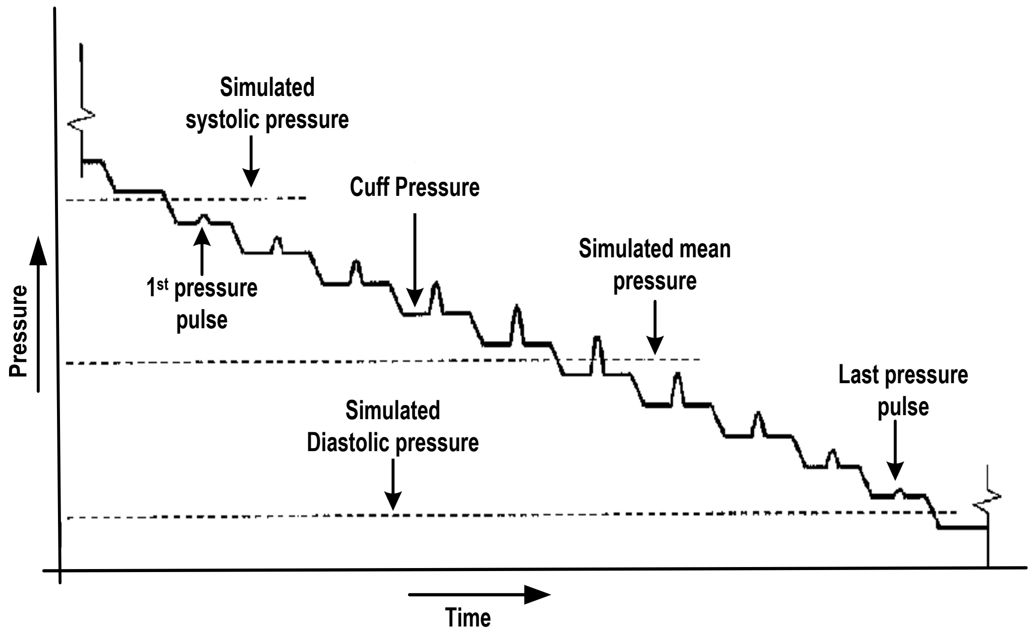


Figure 2.11 Cuff pressure verses time in the simulator described in [7]

Chapter 3
DESIGN APPROACH

3.1 The Instrument Setup

The project objective is to develop an arm simulator for simulating BP reading over full clinical range of pressure, heart rate, and different types of arrhythmia. It can be used for testing and calibration of a noninvasive blood pressure meter and as a teaching aid for correctly using a blood pressure meter, particularly on patients with unusually low BP or arrhythmia. The simulation involves generation of Korotkoff sounds for measurement by auscultatory method and generation of pressure pulses in the cuff for measurement by oscillometric method.

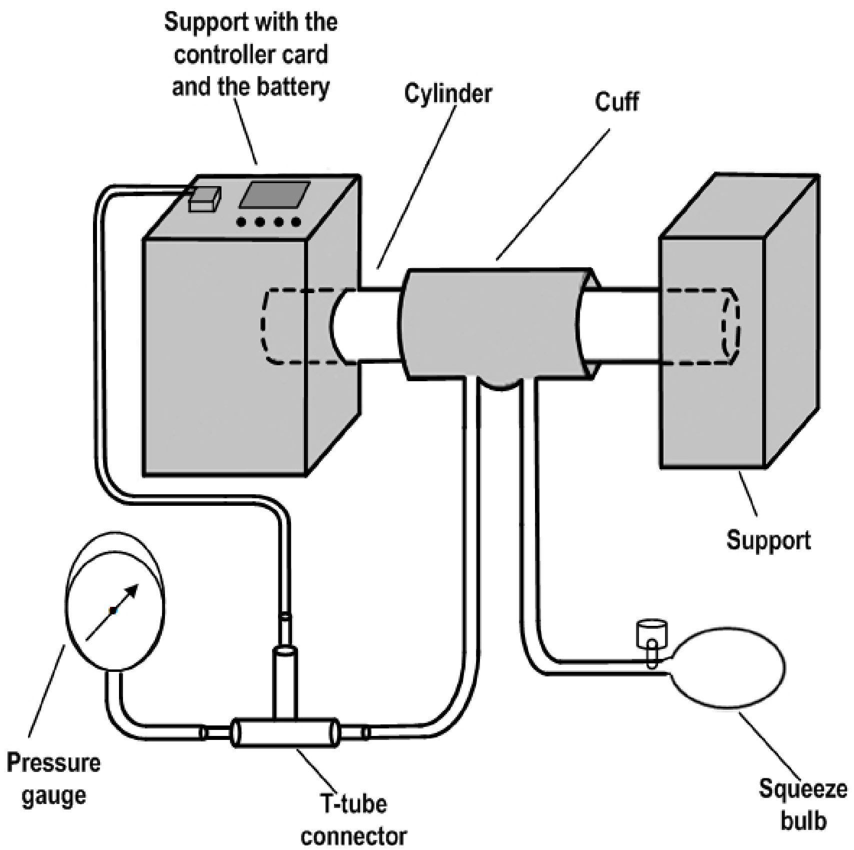


Figure 3.1 Arm BP simulator setup

The instrument setup, as shown in Figure 3.1, consists of a hollow rigid cylinder placed horizontally and supported at the two ends. The left support has the battery and the controller card consisting of the pressure sensor and the electronic circuit board (along with the keys and the display). The cuff for measuring the BP is wrapped on the cylinder. The simulation is carried out by generating the sounds and pressure pulses in accordance with the parameters set through the control panel and the time-varying pressure in the cuff as dynamically sensed by the pressure sensor.

3.2 Block Diagram of the Arm Simulator

A schematic representation of the arm simulator is shown in Figure 3.2. It consists of the heart beat generator, Korotkoff sound (K-sound) generation, oscillation generation, cuff pressure sensor, and amplitude calculator. For designing it as a low-cost and portable instrument, the blocks in the figure are realized using a single 16-bit microcontroller with on-chip ADC and DAC. The instrument has facility for setting the simulation parameters including the heart rate, level of arrhythmia, pulse volume, systolic pressure, and diastolic pressure. The Korotkoff sounds and oscillations in the cuff are generated based on the set parameters and in response to time-varying pressure in the cuff as dynamically sensed by the pressure sensor.

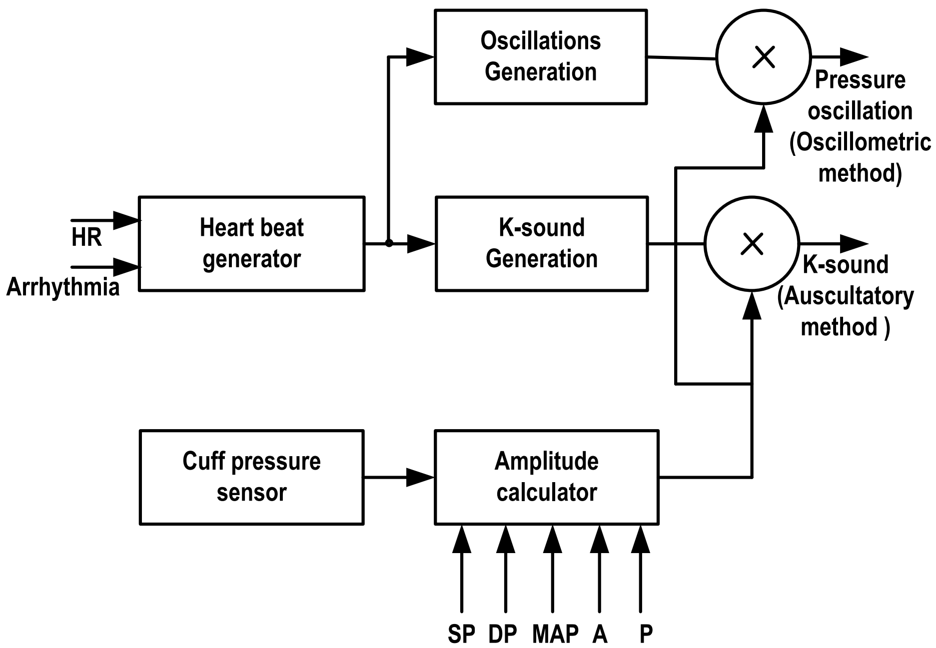


Figure 3.2 A schematic representation of the arm simulator

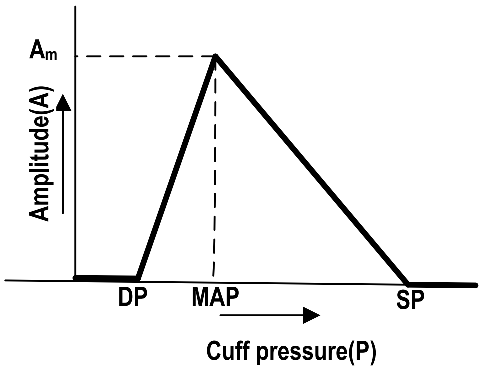


Figure 3.3 K-sound amplitude as a function of cuff pressure

The design simulates heart beat with a settable heart rate and level of arrhythmia. The heart rate is the number of heart beats per minute (bpm). It is simulated by generating a square wave, with a fixed on-time. The off-time is varied according to the selected heart rate. In arrhythmia, the heart has an irregular rhythm. It is simulated by varying the off period in accordance with a random number. Arrhythmia A0 corresponds to a perfectly regular beat, whereas A4 corresponds to a very irregular heart beat.

An integrated pressure sensor is used for sensing the air pressure in the cuff and it is used for determining the amplitude of the Korotkoff sound and the pressure oscillation generated at the onset of each heart beat.

The Korotkoff sound is the arterial sound heard through a stethoscope placed on to the brachial artery, distal to the cuff of the sphygmomanometer. In this design, Korotkoff sound is generated using pre-stored samples in the processor memory and by outputting these samples through its on-chip DAC.

The mean arterial pressure P_{MA} is calculated from the set values of the systolic pressure P_S and the diastolic pressure P_D as

$$P_{MA} = P_D + (P_S - P_D) / 3 \qquad (3.1)$$

Amplitude of the sound is scaled according to the cuff pressure using the relation shown in the Figure 3.3. The amplitude is zero for pressure P below the diastolic pressure P_D. As P increases from P_D to the mean arterial pressure P_{MA}, the amplitude increases linearly to the peak amplitude A_m. As P further increases from P_{MA} to the systolic pressure P_S, the amplitude linearly decreases to zero and remains zero for values higher than P_S .The relationship between P and A can be written as,

$$A = \begin{cases} 0, & P \le P_D \\ A_m (P - P_D) / (P_{MA} - P_D), & P_D < P \le P_{MA} \\ A_m (P_S - P) / (P_S - P_{MA}), & P_{MA} < P \le P_S \\ 0, & P_S < P \end{cases} \qquad (3.2)$$

The DAC output is amplified by an audio amplifier and it drives a speaker to generate the sounds. A linear actuator with its forward and reverse motions controlled by the processor output pins can be used for generating oscillations in the cuff.

Chapter 4
INSTRUMENT HARDWARE

4.1 Introduction

A block diagram of the hardware of the arm simulator is shown in Figure 4.1. It has a microcontroller at its core for realizing the functions of (i) heart beat generation in accordance with the set heart rate and arrhythmia, (ii) amplitude calculation in accordance with the sensed value of the cuff pressure and the set values of systolic and diastolic pressures, (iii) outputting of the Korotkoff sounds and actuator controls for coupling oscillations in the cuff, (iv) receiving the inputs for setting the parameters. For this purpose, DSPIC33FJ128GP802, a 16-bit microcontroller from Microchip, is selected. It is a 28-pin processor with on-chip ADC, DAC, and timers, and some port pins with internal pull-ups. For inputting the simulation parameters, a keypad and LCD have been used. For keeping the instrument compact, it was decided to use 4 keys and monochrome LCD of Nokia 3310, directly interfaced to the microcontroller. Timer 1 of the microcontroller is used to scan the keypad every 50 ms. Timer 2 and Timer 4 are used to generate cardiac pulses, in accordance with the set beat rate and arrhythmia.

The arm of the arm simulator is in the form of a hollow rigid cylinder, and the cuff is wrapped around it. A MEMS-based integrated pressure sensor is used to sense the cuff pressure. It is connected to the cuff and the gauge using a T-connector as shown earlier in Figure 3.1. The sensor converts pressure variations to voltage and the output is given as input to the on-chip ADC of the microcontroller. The amplitude is calculated as per the relationship shown earlier in Figure 3.3, using the value of the cuff pressure and the set values of systolic pressure (SP), diastolic pressure (DP), and pulse volume (P). One burst of Korotkoff sound is stored as samples in the processor memory as part of the program. These samples are scaled by the calculated amplitude and output through the on-chip DAC at the onset of each cardiac beat. These sound pulses are amplified using an audio power amplifier IC and output is heard from the speaker. Pressure pulses in the cuff are generated by the forward/reverse movement of the shaft of a linear actuator, which is placed in the cylinder with its shaft protruding through a small hole and pressing against the cuff. Two port pins of the microcontroller are used for controlling the linear actuator: on/off, forward/reverse.

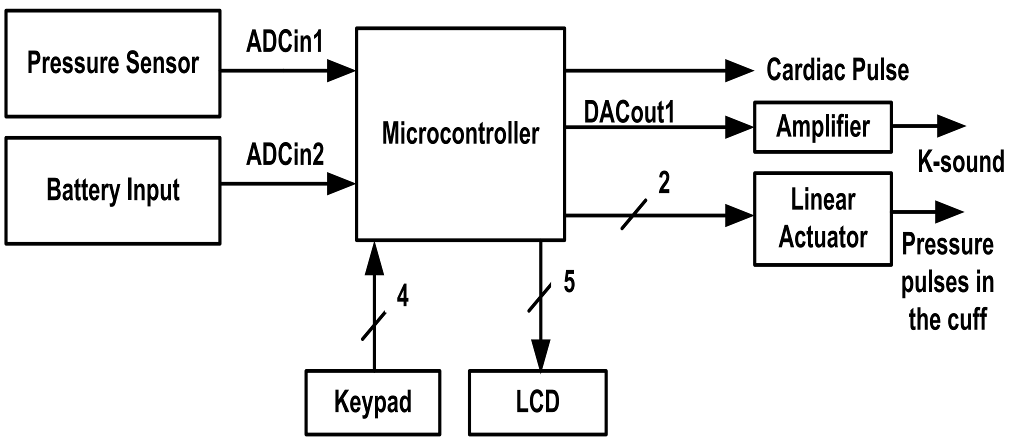


Figure 4.1 Block diagram of arm simulator

Table 4.1 Assignment of the port pins of the 28 pin microcontroller DSPIC33FJ128GP802 for various functions

Port pin	Function
RA.0	ADC_{in} for pressure
RA.1	ADC_{in} for battery sense voltage
RA.4	Cardiac pulse out (for monitoring)
RB.0	PGC (for debugger)
RB.1	PGD (for debugger)
RB.2	Up key
RB.3	Down key
RB.4	Left key
RB.5	Right key
MCLR	For debugger

Port pin	Function
RB.6	Cardiac pulses
RB.7	SCK of LCD
RB.8	RES of LCD
RB.9	SCE of LCD
RB.10	SD_{in} of LCD
RB.11	D/C of LCD
RB.13	DAC_{out} for K-sound
RB.14	Linear actuator on/off
RB.15	Linear actuator forward/reverse

4.2 Microcontroller

At the core of the controller circuit is the 28-pin microcontroller IC Microchip DSPIC33FJ128GP802. The entire circuit has been designed to reduce the number of components and interconnections. The user interface for setting the simulation parameters consists of four keys and Nokia 3310 type monochrome LCD. The LCD is interfaced serially. The keys are directly connected to the port pins. The microcontroller is operated using its internal R-C oscillator.

The microcontroller can be powered by 3 to 3.6 V supply. In our application, it is powered by 3.3 V. The pin assignment of the port pins of the microcontroller is given in Table 4.1.

4.3 Pressure Sensor

A MEMS-based integrated pressure sensor (Freescale MPX5050GP) has been used for sensing the pressure in the cuff. It senses the gas pressure, i.e. pressure above the atmospheric pressure, as coupled to its pressure port on its side as shown in Figure 4.2. It has a range of 0 – 50 kPa (or 0 – 375 mmHg), with a sensitivity of 90 mV/ kPa (or 12 mV/mmHg). It has an accuracy of 2.5% V_{FSS} and can be used with a supply voltage of 4.75 to 5.25V. In our application, it is powered by 5 V.

Attempts were made to sense the cuff pressure without using any direct coupling to it. An air-filled rubber chamber with a tube connecting it to the pressure port of the sensor was placed between the cuff and the arm. It was found that the sensed pressure reflected the variation in the cuff pressure. However offset and calibration factor varied with the material and the location of the chamber with respect to the cuff. Hence this method was considered not to be suitable for an accurate sensing of the cuff pressure. It was decided to couple the cuff pressure directly to the sensing port of the sensor by a T-connector placed between the cuff and the pressure gauge of the monitor, as shown earlier in Figure 3.1. The coupling is made using a 2 mm internal diameter rubber tube (a piece of cycle valve tubing).

4.4 Keypad and Display

A set of 4 keys along with a graphic LCD are used for setting the parameters for simulation and for changing the mode between setting and operation.

The keypad consists of four keys directly connected to the port pins (RB.2, RB.3, RB.4, RB.5) of the microcontroller. These pins do not need external pull-ups. The keys are labeled as up, down, left and right keys.

For displaying the parameters, a Nokia 3310 type graphical LCD with 84x48 pixels has been used. It has an on-board low power CMOS controller PCD8544, which provides all the necessary display functions, including generation of LCD supply and bias voltages. Its display RAM stores the display data received from the microcontroller. It can be operated with a supply voltage of 2.7 – 3.3 V. In our application, it is powered by 3.3 V. It has 5 signal pins: serial clock SCK (Pin 2), serial data SD_{in} (Pin 3), data/command D/C (Pin 4), chip enable SCE (Pin 5) and reset RST (Pin 8). These pins are connected to the pins RB.7 – 11 of the microcontroller as shown in Table 4.1.

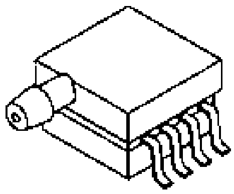


Figure 4.2 Cuff pressure sensor (Freescale MPX5050GP)

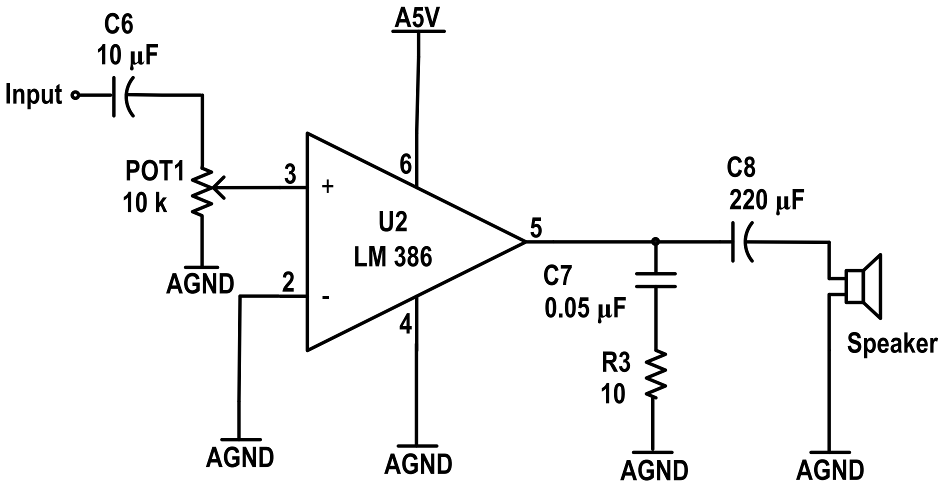


Figure 4.3 Circuit diagram of the power amplifier

4.5 Power Amplifier

As the DAC output cannot directly drive a speaker for generating audible Korotkoff sounds, an LM386 IC (U2) is used as a power amplifier for driving the speaker. It can deliver 125 mW continuously into an 8 Ω load and can be used with 4 -12 V supply. In our application, it is powered by 5 V. The circuit with the amplifier IC connected in the R-C coupled non-inverting amplifier mode with gain of 20 is shown in Figure 4.3. A 10 k preset pot is used for volume control.

4.6 Circuit Diagram of the Controller Board

The complete circuit diagram of the controller board of the arm simulator is shown in Figure 4.5, with the microcontroller "Microchip DSPIC33FJ128GP802" U1 as its core component. The microcontroller has internal power-up reset and boots with its internal R-C clock. It has internal program memory and is programmed to run using its internal clock generator. Connector CON1 is used for loading the program and for debugging the program operation using the development kit "Microchip PICkit™3".

LED1, connected to RA.4 of U1, is used to indicate the cardiac beats. The same output is also available at RB.6 for monitoring. The pressure sensor "Freescale

MPX05050GP” is labeled as PS1. Its analog output is connected to pin RA.0 of U1. This port pin is configured as ADC input. An attenuated value of the battery voltage is connected to RA.1 which is configured as another ADC input of U1 for monitoring the battery voltage.

The four keys (SW1, SW2, SW3, SW4) are connected to pins RB.2 – RB.5 of U1. The signal pins of the graphic LCD, LCD1, are connected with RB7 – RB11 of U1. The sound output is given as the DAC output from U1 at its pin marked as DAC1RN. The output is amplified using LM386, U2 for driving the speaker. The pins RB.14 and RB.15 of U1 give the control outputs for the linear actuator for generating pressure pulses.

4.7 Power supply

The instrument is designed to operate by an external battery voltage of 7 – 9 V. The power amplifier is powered by 5 V, while the microcontroller is powered by 3.3 V analog and digital supplies. The LCD is also powered by 3.3 V. All these voltages are obtained by using linear regulators as shown in Figure 4.4. The two voltage regulators U5 (LM7805) and U6 (LM1117) are used to supply the analog sections of the hardware with regulated +5 V and 3.3 V. The digital section is powered by regulated +5 V and 3.3 V from another set of regulators U3 (LM7805) and U4 (LM1117). An attenuator formed by R5 and R6 produces a voltage, $V_{Bsense} = V_{Bin}\, R_6/(R_5+R_6)$, for sensing the battery voltage and is connected to RA.1 as an ADC input.

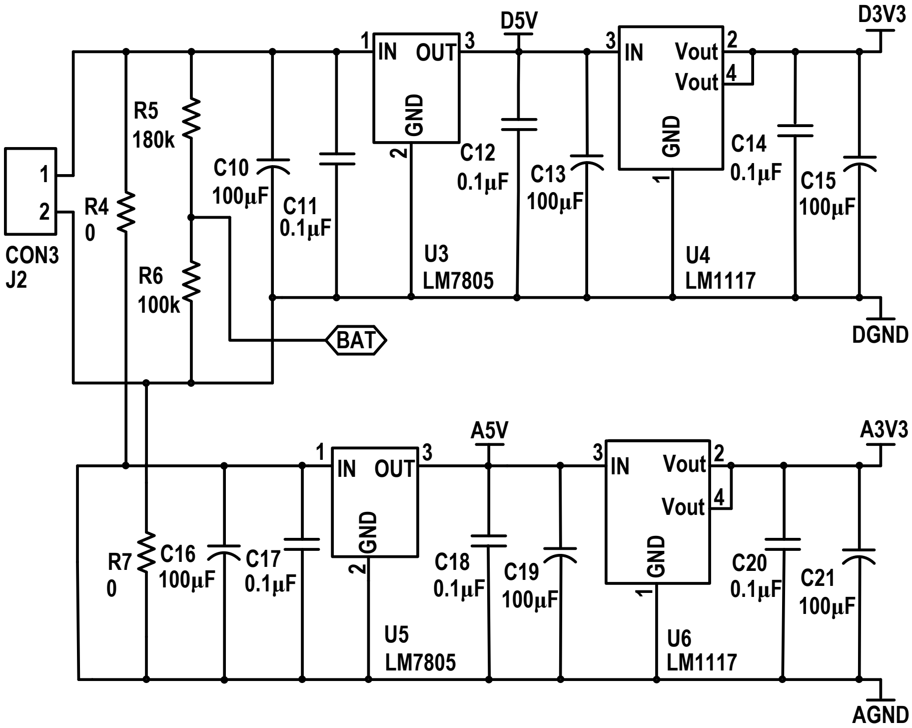


Figure 4.4 Power supply

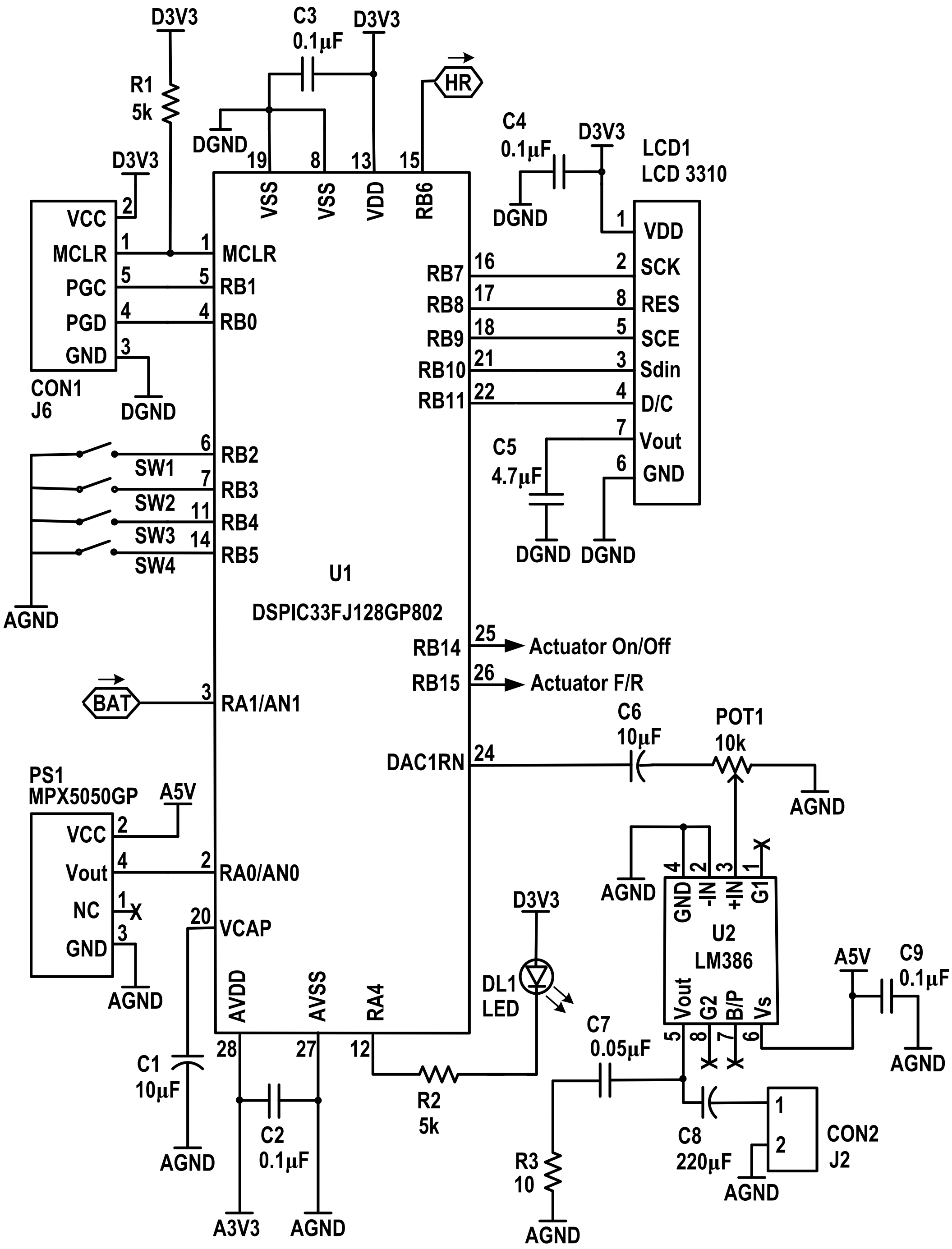


Figure 4.5 Circuit diagram of the arm simulator

Chapter 5
SOFTWARE AND TEST RESULTS

5.1 Introduction

The microcontroller program was written to scan the keys, update the display with the user specified parameters, and carry out the simulation. The program has two modes: setting mode and the operation mode. In the setting mode, the keys and display are used for setting the simulation parameters and sensing the battery voltage. In the operation mode, the BP arm simulation is carried out in accordance with the set parameters and sensed value of the cuff pressure. The program was written in C. After compiling, it was loaded in the microcontroller program memory by connecting the development kit "Microchip PICkit^{TM}3" to the debug connector CON1. The initialization part of the main program involves setting the system clock, initializing the I/O port pins, ADC, DAC, timers and, displaying default parameters and their values on the graphical display. Subsequently the program enters the setting mode, where an interrupt service routine is used to scan the four input keys every 50 ms and the setting of the parameters is updated in the internal memory and on the display. The sensed battery voltage is read through the ADC and displayed. Through a combination of two key presses, the mode can be changed to operation mode for carrying out the simulation. Another key combination is used for shifting back from the operation mode to the setting mode.

5.2 Display

The alphanumeric characters and graphic symbols are displayed by setting the pixel values on the display, by sequentially writing the appropriate set of command and data bytes. The Nokia 3310 type display has on-board LCD controller PCD 8544, and it has serial interface for writing command and data with pins as described earlier in Section 4.4. Level on D/C input of the LCD should be properly set before sending command and or data bytes to the display. The received byte is taken as a command byte if D/C = 0, and a data byte otherwise. A flowchart of these write operations is shown in Figure 5.1. It involves initialization, addressing the location, and writing the set of data bytes.

The LCD controller chip is reset by applying a low on RST pin (active low) for 2.5 μs. The reset pulse initializes all the internal settings: power-down mode bit PD = 1, horizontal addressing bit V = 0, normal instruction set bit H = 0, display blank, address counter X6 to X0 = 0, Y2 to Y0 = 0, temperature control mode (TC1, TC0 = 0), bias BS2 to BS0 = 0, V_{LCD} = 0.

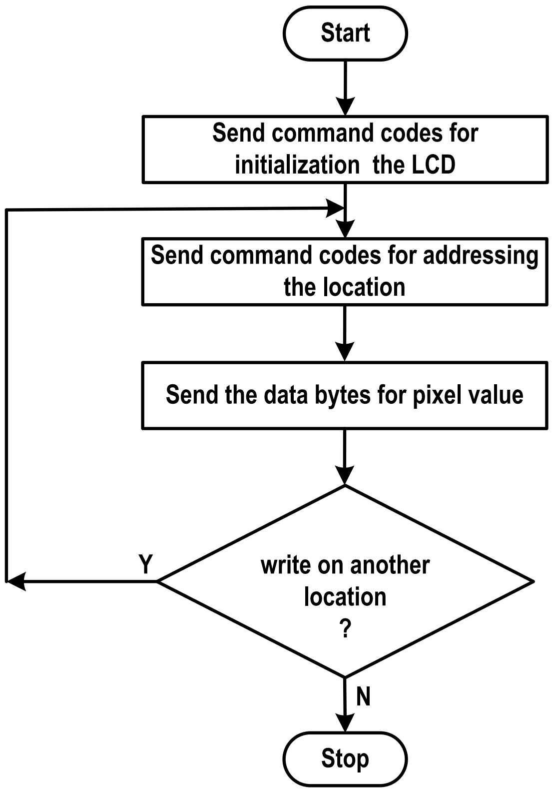


Figure 5.1 Flowchart for writing data to the LCD controller

After power-on, the RAM contents are undefined. We can initialize the LCD by sending the commands according to our application, with a delay of 1.25 μs after each command. A high level pulse on the enable pin (SCE) initializes the serial interface. In each byte, the MSB is transmitted first. The set of initialization commands are LCD extended command (0x21), LCD contrast (0xC8), temperature coefficient (0x06), LCD bias mode (0x13), horizontal addressing mode (0x20), and LCD mode (normal). These can be sent in any sequence.

The LCD pixels are arranged as 84 columns and 48 rows. The 48 rows are logically grouped into 6 pages, with each column in a page having 8 pixels. As there are 84 columns, each page can have 14 characters, each of 6x8 pixels. We actually use 5x7 matrixes for each character leaving one pixel separation. A byte controls the pixels of one column (8 pixels) in a page. Addressing of each column in a page is by 2 registers: X register addresses the page number and Y addresses the column number. For example, writing '0' into both X and Y registers, will select the group of first 8 pixels of the first column. After each data byte, the Y register gets automatically incremented. Hence writing a character involves, sending command for its X and Y position followed by sending the five data bytes for the character. The bytes for all the ASCII characters are stored sequentially in the program itself. The sequence of operations for writing a data byte to the LCD controller, represented as a flow chart, is shown in Figure 5.2.

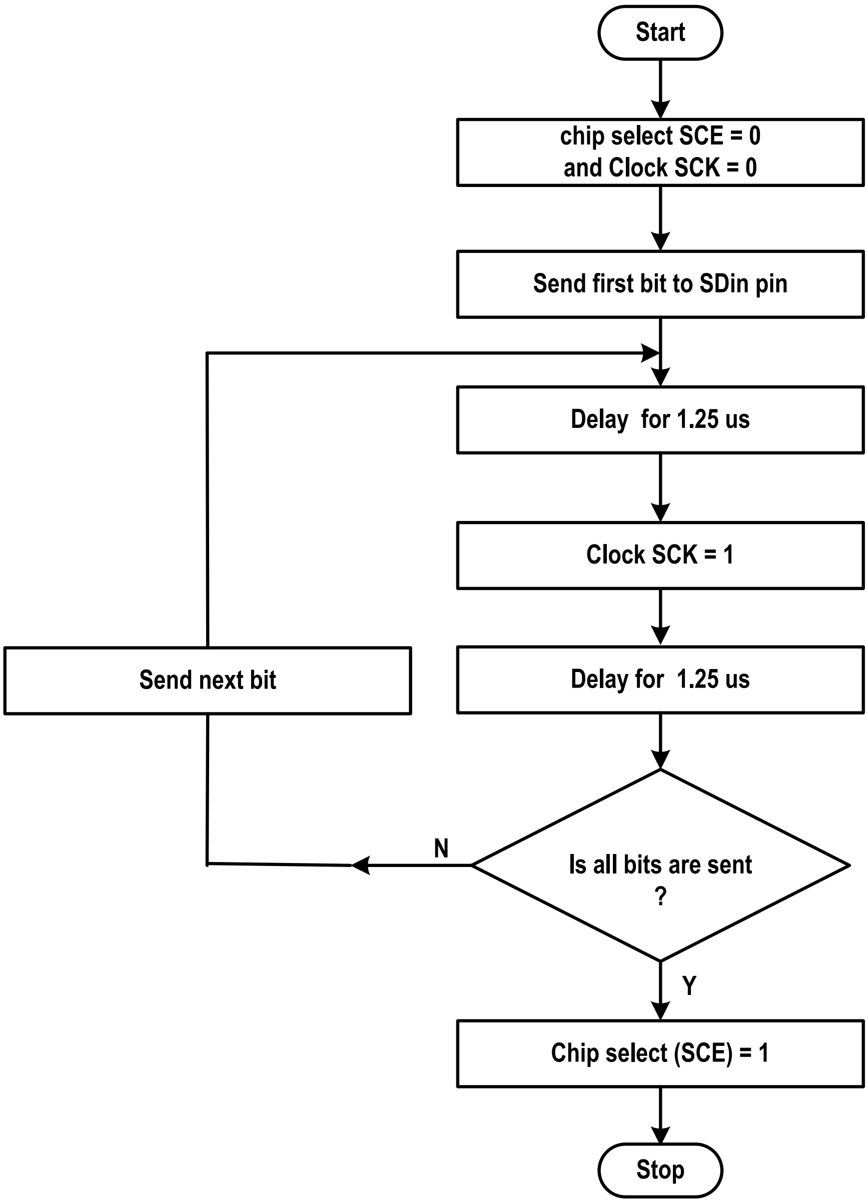


Figure 5.2 Flowchart for sequence writing of the data byte

5.3 Parameter Setting

As shown in Figure 5.3, the keys are marked as left, right, up, and down. The keys can be used for changing the mode between setting and operation. The program starts in the setting mode. In this mode, the parameter selected for setting its value is indicated by '*' after the parameter, as shown in Figure 5.4. It can be changed by using left or right keys. Its value can be changed by pressing up or down keys. After setting the parameter values, operation mode can be selected by simultaneously pressing the left and right keys. Transition back from the operation to the setting mode can be made by simultaneously pressing up and down keys. The choices available for different parameter selections are as listed below:

SP: 20 – 230 mmHg, increase or decrease in 5 mmHg step (default = 120).

DP: 0 – 140 mmHg, increase or decrease in 5 mmHg step (default = 80).

Beat rate: 20 – 150 bpm, increase or decrease in 5 bpm step (default = 70).

Arrhythmia: 0 – 4 levels (default = 0).

Pulse volume: 0 – 4 levels (default = 4).

In the setting mode, the keys are scanned every 50 ms, using timer 1, as shown in the flowchart in Figure 5.6. The selected parameter can be changed by pressing the left and the right keys, the value of the selected parameter can be changed by pressing the up and down keys, and the mode can be changed to the operation mode by simultaneous pressing of the left and the right keys.

5.4 BP Simulation

In operation mode, a square wave with on time T_{on} and off time T_{off} is generated for outputting the cardiac pulses on the RB.6 pin (and also for LED indication on RA.4), in accordance with the set heart rate and the level of arrhythmia. The cardiac cycle time T_c is the inverse of the set heart rate. The on time is fixed as 200 ms (slightly longer than the Korotkoff sound duration). The off time for regular heart beat is calculated as $T_{offo} = T_c - T_{on}$. A signed random number r (range: $\pm$ 1) is generated and this number and the level of arrhythmia a (range: 0-4) are used to calculate the off time as $T_{off} = T_{offo}(1 + r\,a/4)$

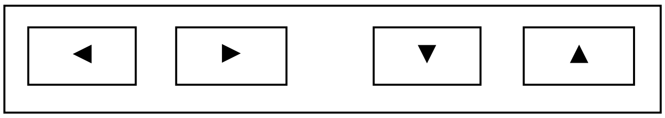


Figure 5.3 Keypad layout

```
B=070* A1  V4
S=120  D=080
```

Figure 5.4 Setting mode display

```
B=070  A1  V4 **
S=120  D=080 100
```

Figure 5.5 Operation mode display

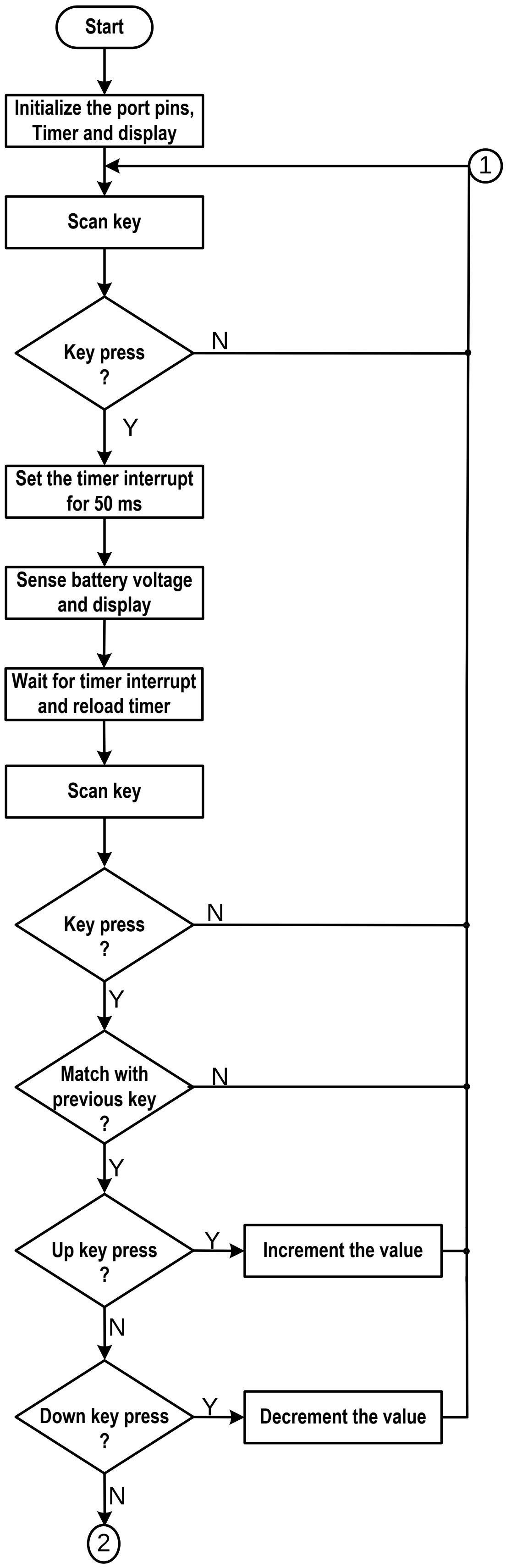


Figure 5.6 Flowchart for operation and setting mode (Cont…)

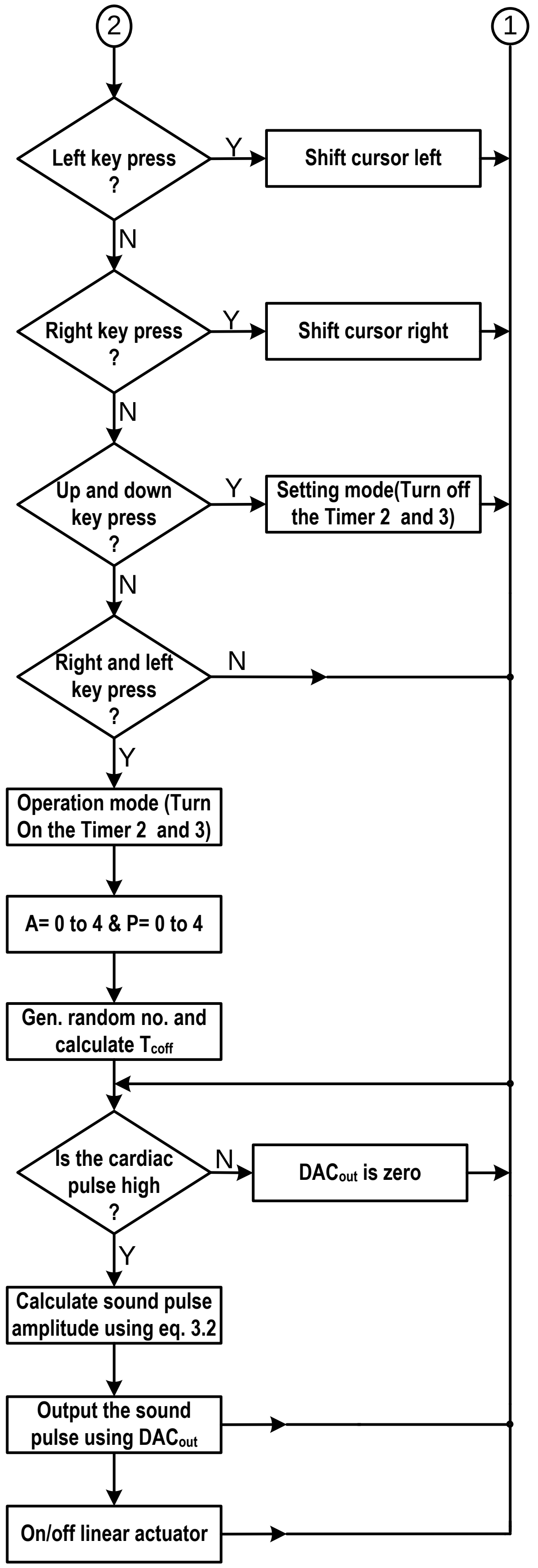


Figure 5.6 Flowchart for operation and setting mode

At the start of each cardiac cycle, pulse out is given by outputting a low to high transition. The value of the pressure in the cuff is read. A scaling factor for the amplitude of the Korotkoff sound is calculated in accordance with the settings of SP, DP and the sensed value of the cuff pressure as given earlier in Equation 3.2 and Figure 3.4 in the third chapter. It is then scaled by the pulse volume and the resulting factor is used to scale the stored samples of the Korotkoff sound. The sound is output as DAC out on pin DAC1RN. Simultaneously the controls for the dc motor of the linear actuator (on/off, forward/reverse) are generated on pins RB.14 and RB.15. Now pin RB.6 (and also pin RA.4) are made low. A new random number is generated and used to calculate T_{off} and after the lapse of this time, a new cardiac cycle begins. If the keypad receives a simultaneous pressing of up and down keys during this period, then the program returns from the operation mode to the setting mode.

5.5 Assembly and Testing

The circuit was assembled and tested on a bread board. Subsequently, a PCB layout was designed in two iterations. In the first design, 2 line x 16 character LCD was used. To make the circuit compact, the design was revised by using Nokia 3310 type monochrome graphic LCD. The hardware and software descriptions refer to the revised design. As this LCD uses serial interface, the number of microcontroller pins required for interfacing reduced and it helped in implementing a few extra features.

A complete circuit of the arm simulator of the first design is given in Appendix C. The circuit was assembled on the PCB of size 102 mm x 98 mm. In this board, the ground plane has been provided on the component side to reduce environmental pick up. Supply and signal lines are on the solder side. Care is taken to minimize the length of the supply track for ICs. Positive supply for each IC is decoupled by 0.1μF ceramic capacitors placed as close as possible to the ICs. The component placement and track layout of the PCB are also given in Appendix C.

The circuit schematic and the PCB layout of the revised circuit using the graphic LCD are also given in Appendix C. The test results included here are from a bread-boarded version of the revised design.

5.6 Results

Waveforms from the instrument were recorded for different settings of simulation parameters and different patterns of cuff inflation and deflation. These results, given in Figure 5.7 to Figure 5.14, show a satisfactory operation of the instrument.

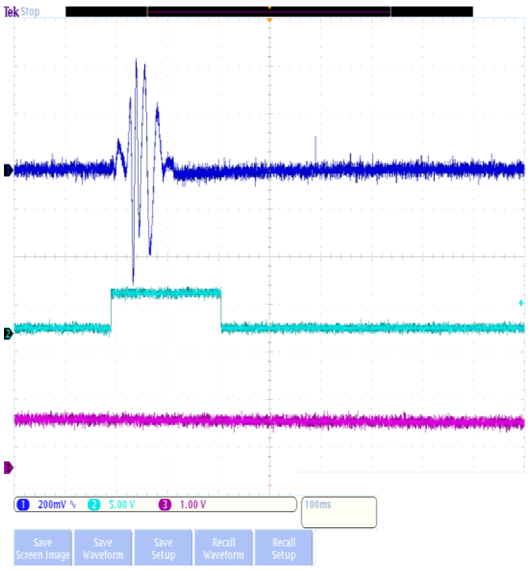


Figure 5.7 CRO recording of one cycle of simulator waveforms with a small and slow variation in the cuff pressure, with HR=70, A=0, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure

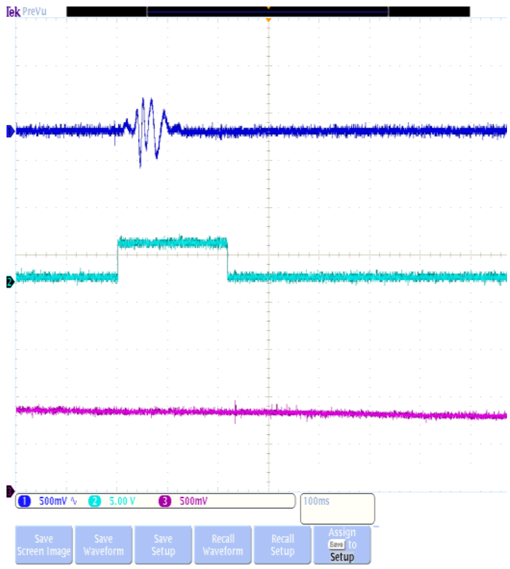


Figure 5.8 CRO recording of one cycle of simulator waveforms with a slow and large variation in the cuff pressure, with HR=70, A=0, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure.

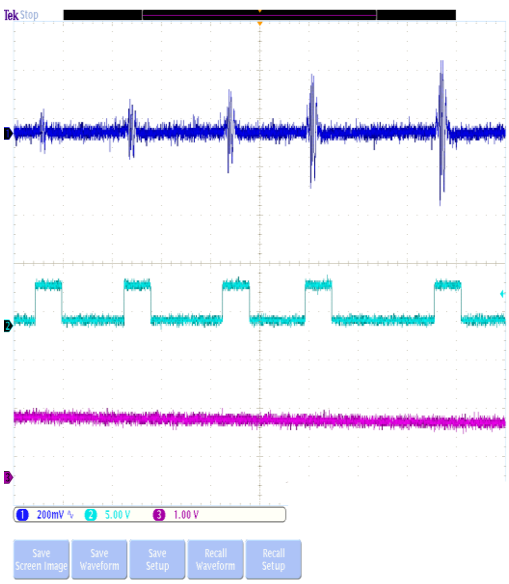


Figure 5.9 CRO recording of multiple cycles of simulator waveforms with a slow and very small variation in the cuff pressure, with HR=70, A=1, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses,Ch.3: cuff pressure.

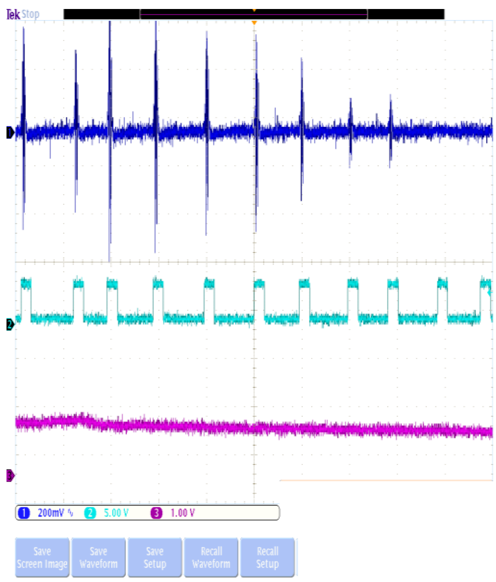


Figure 5.10 CRO recording of multiple cycles of simulator waveforms with a slow decrease in the cuff pressure, with HR=70, A =2, P=4, SP=120, DP=30: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure.

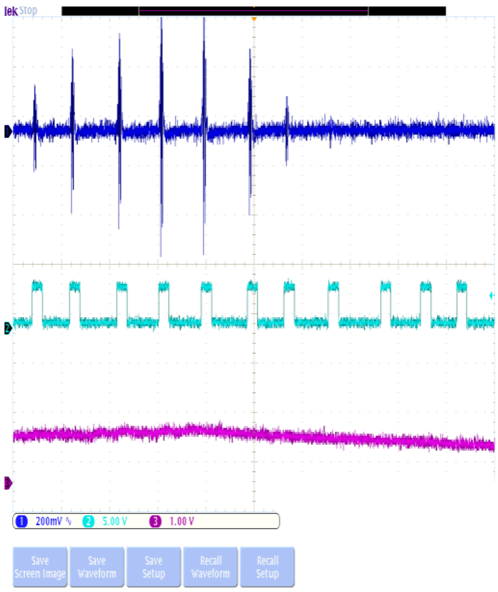


Figure 5.11 CRO recording of multiple cycles of simulator waveforms with slowly decreasing cuff pressure, with HR=70, A=5, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure.

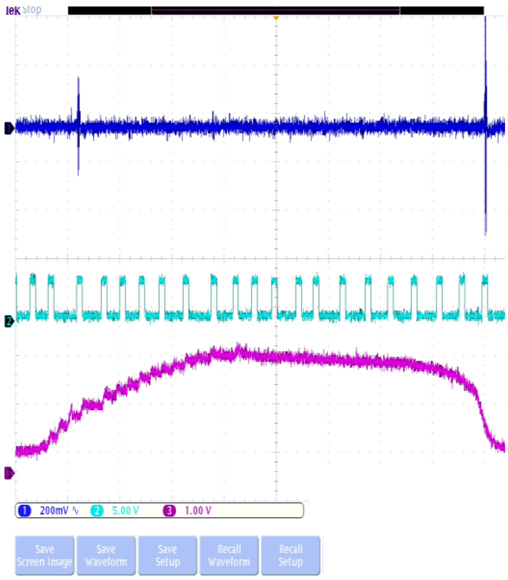


Figure 5.12 CRO recording of multiple cycles of simulator waveforms with fast increase and decrease in the cuff pressure, with HR=70, A=5, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure.

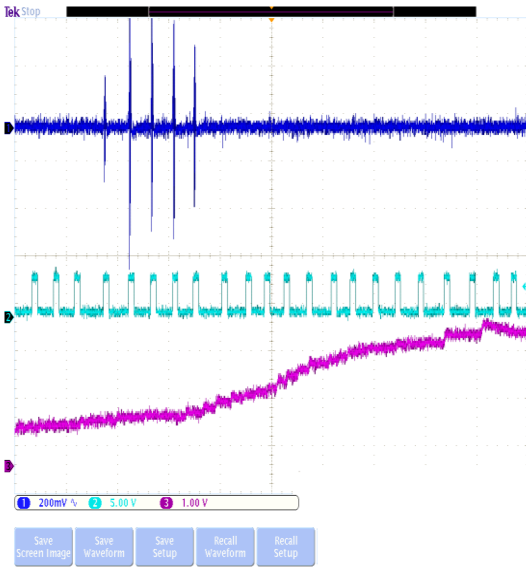


Figure 5.13 CRO recording of multiple cycles of simulator waveforms with slowly increasing cuff pressure, with HR=70, A=5, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure.

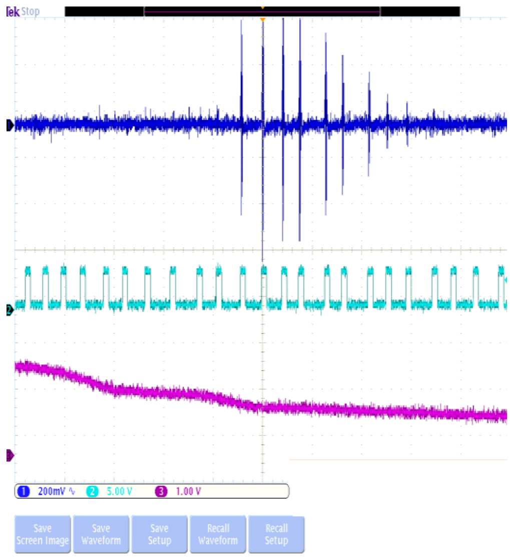


Figure 5.14 CRO recording of multiple cycles of simulator waveforms with slowly decreasing cuff pressure, with HR=70, A=5, P=4, SP=120, DP=80: Ch.1: Korotkoff sounds, Ch.2: Cardiac pulses, Ch.3: cuff pressure.

Chapter 6
SUMMARY AND CONCLUSION

6.1 Summary

The objective of this project was to develop a portable arm simulator for noninvasive BP measurement, with clinical range of systolic and diastolic pressure, heart rate, arrhythmia, and pulse volume. It should facilitate testing and calibration of BP monitors and should be usable as a teaching aid for correctly using a blood pressure meter under a wide range of cardiovascular conditions. After studying the literature on designing such instruments and information on available instrument, a microcontroller based arm simulator for BP measurement was designed. In the first stage of the project, a microcontroller based circuit was bread-boarded and tested. It used a 2 line x 16 character display and 28-pin 8-bit microcontroller PIC16F1939 as the controller for user interface as well as for sensing and waveform generation. The design was subsequently modified to use Nokia 3310 type monochrome of graphical (48x84) LCD and 28-pin 16-bit microcontroller DSPIC33FJ128GP802. This processor is particularly suited for realizing the circuit with a low component count as it has on-chip ADC, DAC, and internal pull ups on I/O pins. An integrated MEMS based pressure sensor has been used to continuously monitor the cuff pressure, for displaying the pressure as well as for generating the Korotkoff sounds for the auscultatory method and oscillations in the cuff for the oscillometric method. The instrument has all the features needed for simulating the arm during pressure measurement.

Circuit design and software development have been carried out for reducing the component count without a compromise on features of the instrument. It has four keys and graphical LCD for setting the simulation parameters including the heart rate, level of arrhythmia, pulse volume, systolic pressure, and diastolic pressure. The Korotkoff sounds and oscillations in the cuff are generated based on the set parameters and in response to time-varying pressure in the cuff as dynamically sensed by a pressure sensor.

6.2 Suggestions for Future Work

1) The circuit board has control outputs for the linear actuator. A suitable linear actuator needs to be connected and tested. The required peak duty cycle corresponding to the maximum pulse volume for generating the requisite torque needs to be worked out.

2) The instrument has separate setting and operation modes. This was primarily used because of 2 line x 16 character display. As the revised design uses a graphic display permitting 6 line x 14 character displays, the setting and operation mode may be merged. This will facilitate changing the settings during the simulation.

3) The circuit currently uses components needing 3.3 V and 5 V supplies. It can be redesigned so that all the components can be powered by 3.3 V, and the entire circuit can be powered by a cell phone battery, and a dc/dc converter.

4) The instrument needs to be mechanically assembled as a portable unit.

Appendix A
USER MANUAL

A.1 Overview

Arm BP simulator is an instrument for simulating the behavior of the arm for testing and calibration of noninvasive BP meters. It can also be used as an aid for training the healthcare staff in correctly using a blood pressure meter, under a wide range of cardiovascular conditions, particularly those involving unusually low BP or arrhythmia. The simulation involves generation of Korotkoff sounds for measurement by auscultatory method and generation of pressure pulses for measurement by oscillometric method. The instrument setup is shown in Figure A.1, consists of a hollow rigid cylinder placed horizontally and supported at the two ends. The left support has the battery, pressure sensor, and the electronic circuit board along with its control panel (keys and display). The sounds and pressure pulses are generated in accordance with the parameters set through the control panel and the time varying pressure in the cuff as dynamically sensed by the pressure sensor.

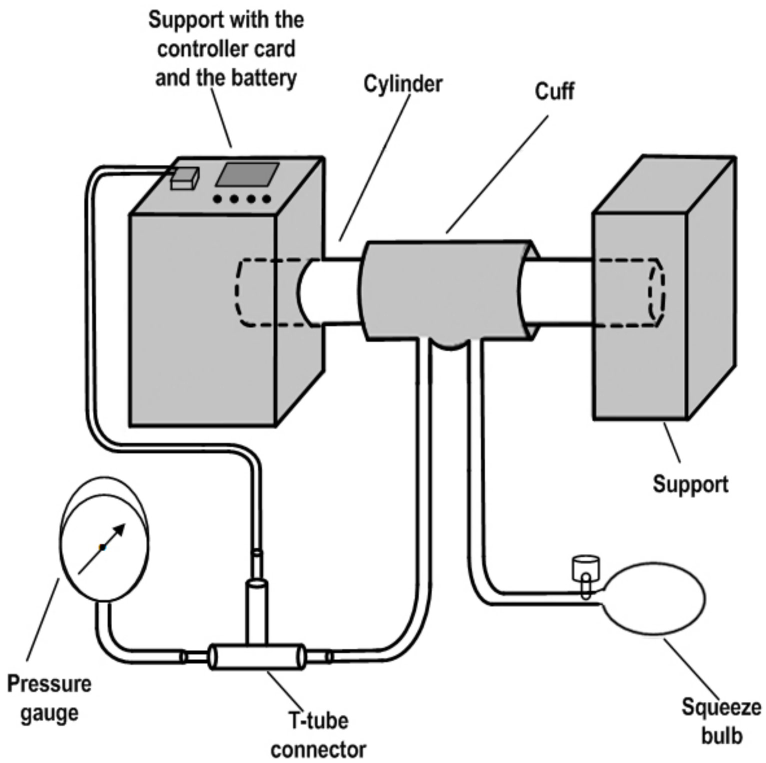


Figure A.1 Arm BP simulator setup

A.2 Control Panel

The control panel has four keys, as shown in Figure A.2. These keys along with the LCD are used for setting the modes and the parameters. There are two modes: (i) setting mode and, (ii) operation mode. At power on, the instrument is in "setting" mode. The display shows the default set of parameter values as shown in Figure A.3.

In setting mode, the parameter selected for setting its value is indicated by '*' after the parameter, as shown in Figure A.3. It can be changed by using left or right keys. Its value can be changed by pressing up or down keys. After setting the parameter values, operation mode can be selected by simultaneously pressing the left and right keys. Transition back from operation to setting mode can be made by simultaneously pressing up and down keys.

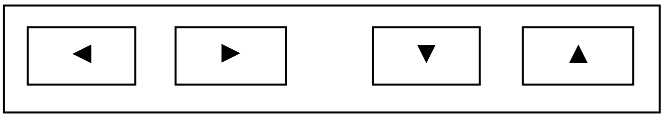


Figure A.2 Keypad

```
B=070* A1  V4
S=120  D=080
```

Figure A.3 Setting mode display

```
B=070  A1  V4 **
S=120  D=080 100
```

Figure A.4 Operation mode display

Presence of blinking '**' in the top right corner of the display, as shown in Figure A.4, indicates that the instrument is in operation mode. In this mode, the instrument displays the values set earlier and the cuff pressure as sensed by the pressure sensor. It generates Korotkoff sound and pressure pulses in accordance with the parameter values of the heart beat, systolic pressure, and diastolic pressure, and sensed pressure.

A.3 Operation

1. Wrap the cuff on the artificial arm (cylinder).

2. Place the T-connector between the pressure gauge and its connecting tube and connect the pressure sensor tube to the T-connector.

3. Switch on the instrument. The instrument will be in "setting" mode at power on. Select the parameter to be selected by using left/right keys and the parameter value by up/down keys.

4. After the selection of parameter, select "operation" mode by pressing left and right keys simultaneously. The mode is indicated by the presence of blinking "**" in the right top corner of the display.

5. The instrument internally generates pulses at rate of the set heart rate and randomly modulated as per arrhythmia level. The contraction phase of the heart in each beat is indicated by turning on of '**' in the top right corner. The cuff pressure is continuously sensed. If it is greater than the set diastolic pressure and less than the set systolic pressure, the Korotkoff sounds and pressure pulses are generated. The sound and pulse amplitude are selected depending on the value of the sensed pressure.

A.4 Specifications

- Beat rate: 20 to 150 beats/minute
- Systolic pressure: 20 to 230 mmHg (> diast. pressure)
- Diastolic pressure: 0 to 140 mmHg (< syst. pressure)
- Pulse volume: 5 levels (0–4)
- Arrhythmia level: 5 levels (0–4)
- Pressure sensor: 0 to 300 mmHg
- Control panel: monochrome graphic LCD and 4 keys
- Power: 7–9 V dc, Current consumption: 200 mA
- Accessories: T-connector

Appendix B
COMPONENT LIST

B.1 Component list of PCB-1 (16-bit microcontroller, display, keypad and power amplifier)

Component designator	Part Number/value	Component description	Quantity
C1	50 pF	Capacitor ,ceramic, chip	1
C2, C6	10 μF	Capacitor, electrolytic, chip	2
C7	0.05 μF	Capacitor, ceramic, chip	1
C8	220 μF	Capacitor, electrolytic, chip	1
C3, C4, C5, C9, C11, C12, C14, C17, C18, C20	0.1 μF	Capacitor, ceramic, chip	10
C10, C13, C15, C16, C19, C21	100 μF	Capacitor, electrolytic, chip	6
DL1	LED	Red colour	1
J2, J4	CON2	2-pin connector	2
J6	CON1	6-pin connector	1
LCD 16x2	LCD1	16x2 LCD	1
MPX5050GP	PS1	Pressure sensor, 8-pin, SMD	1
POT1, POT2	10 kΩ	Potentiometer	2
R1, R4	5 kΩ	Resistor, chip	2
R3	51 kΩ	Resistor, chip	1
R5	10Ω	Resistor, chip	1
R6	100 kΩ	Resistor, chip	1
R7	10 kΩ	Resistor, chip	1
R9, R8	0 Ω	Resistor, chip	2
SW1, SW2, SW3, SW4	SW SPST	Switch	4
U1	DSPIC33FJ128GP802	IC, microcontroller, 28-pin, DIP	1
U2	LM386	IC, audio amplifier , 6-pin, DIP	1
U3, U5	LM 7805	IC, regulator , 3-pin, SMD	2
U4, U6	LM1117	IC, regulator , 3-pin, SMD	2

B.2 Component list of PCB-2 (16-bit microcontroller, display, keypad and power amplifier)

Component designator	Part Number/value	Component description	Quantity
C1	50 pF	Capacitor ,ceramic, SMD	1
C2, C6	10 µF	Capacitor ,ceramic, SMD	2
C7	0.05 µF	Capacitor ,ceramic, SMD	1
C8	220 µF	Capacitor, electrolytic, SMD	1
C3, C4, C5, C9, C11, C12, C14, C17, C18,C20	0.1 µF	Capacitor ,ceramic, SMD	10
C10, C13, C15, C16, C19,C21	100 µF	Capacitor, electrolytic, SMD	6
DL1	LED	Red colour	1
J4, J2	CON2	2-pin connector	2
J6	CON1	6-pin connector	1
R3	51 kΩ	Resistor, SMD	1
R6	100 kΩ	Resistor, SMD	1
R9, R8	0 Ω	Resistor	2
R4, R1	5 kΩ	Resistor, SMD	2
R5	10 Ω	Resistor, SMD	1
R7	10 kΩ	Resistor, SMD	1
MPX5050GP	PS1	Pressure sensor, 8-pin, SMD	1
Nokia 3310	LCD1	Display	1
POT1	10 kΩ	Potentiometer	1
SW1, SW2, SW3, SW4	SW SPST	Switch	4
U1	DSPIC33FJ128GP802	IC, microcontroller, 28-pin, SOIC	1
U2	LM386	IC, audio amplifier , 6-pin, DIP	1
U3, U5	LM7805	IC, regulator , 3-pin, SMD	2
U4, U6	LM1117	IC, regulator , 3-pin, SMD	2

Appendix C

SCHEMATIC DIAGRAM AND PCB LAYOUT

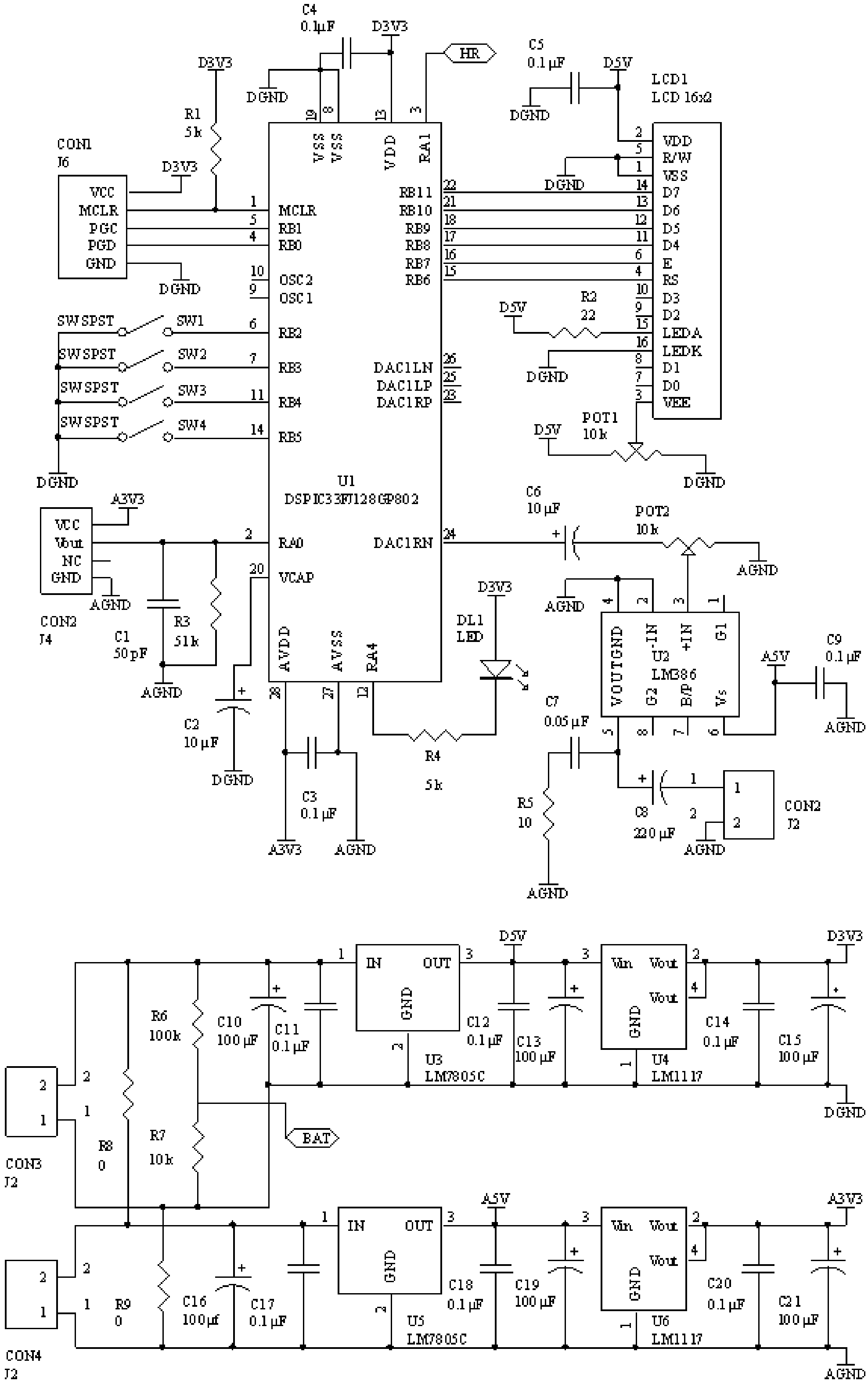


Figure C.1 Circuit of arm simulator using LCD 16X2 with power supply

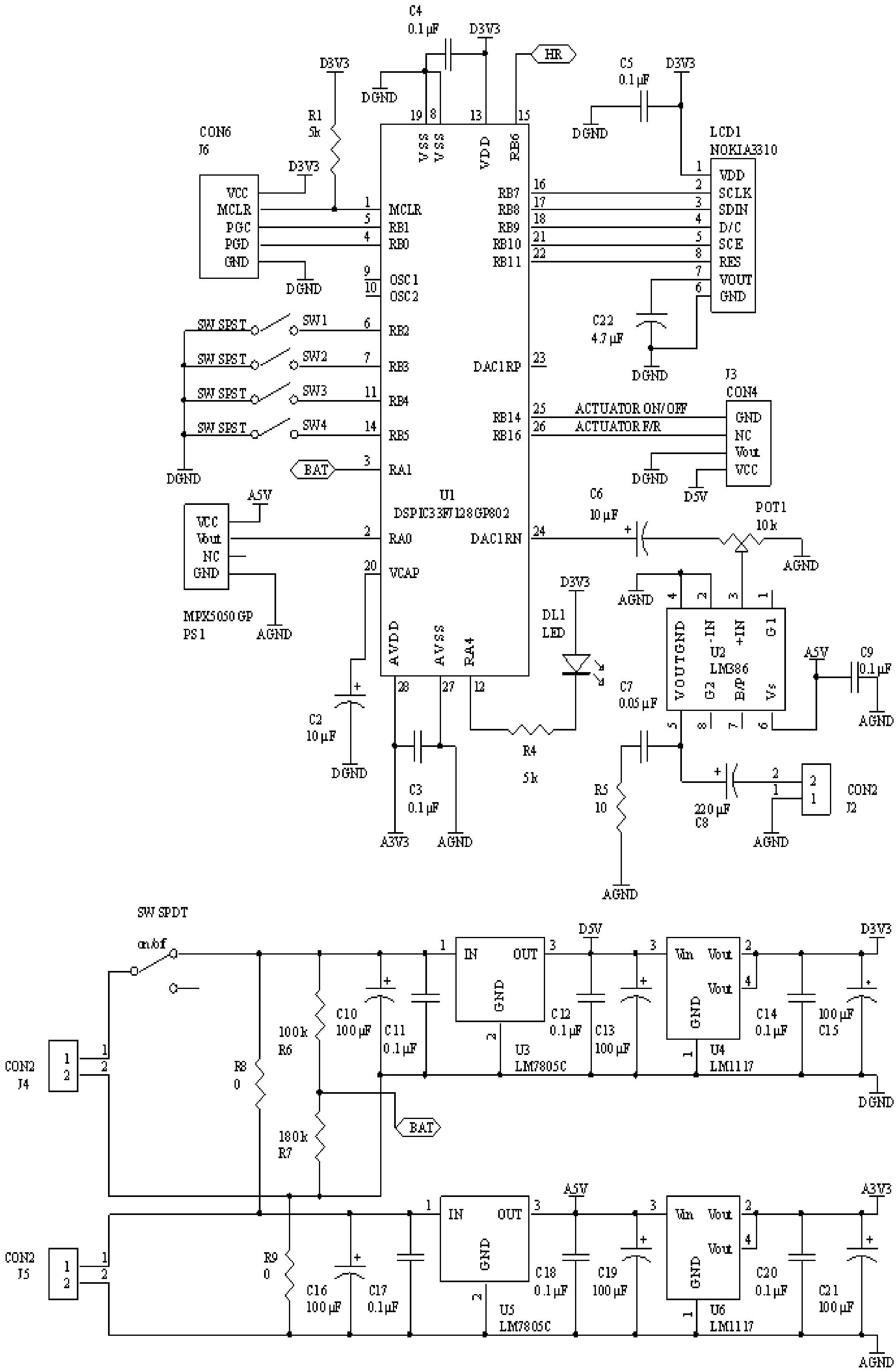


Figure C.2 Circuit of arm simulator using Nokia 3310 LCD with power supply

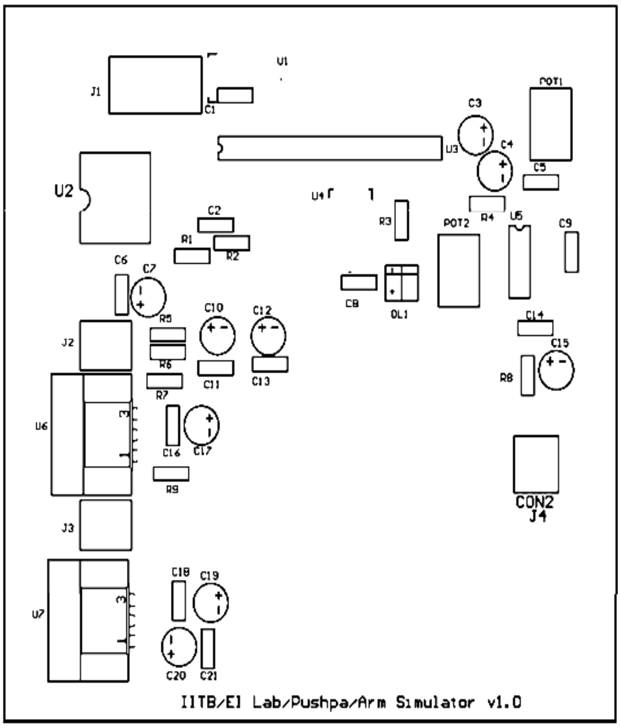


Figure C.3 Top overlay of the arm simulator PCB (102 mm X 98 mm) circuit schematic as given in Figure C.1

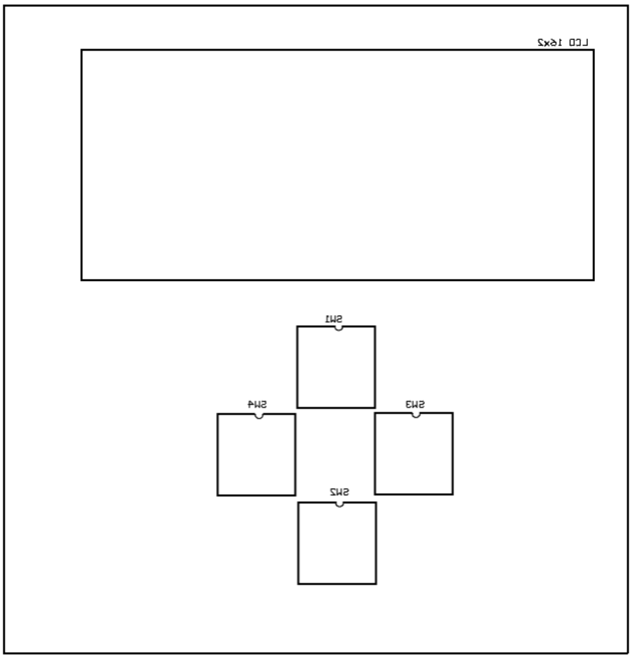


Figure C.4 Bottom overlay of the arm simulator PCB (102 mm X 98 mm) circuit schematic as given in Figure C.1

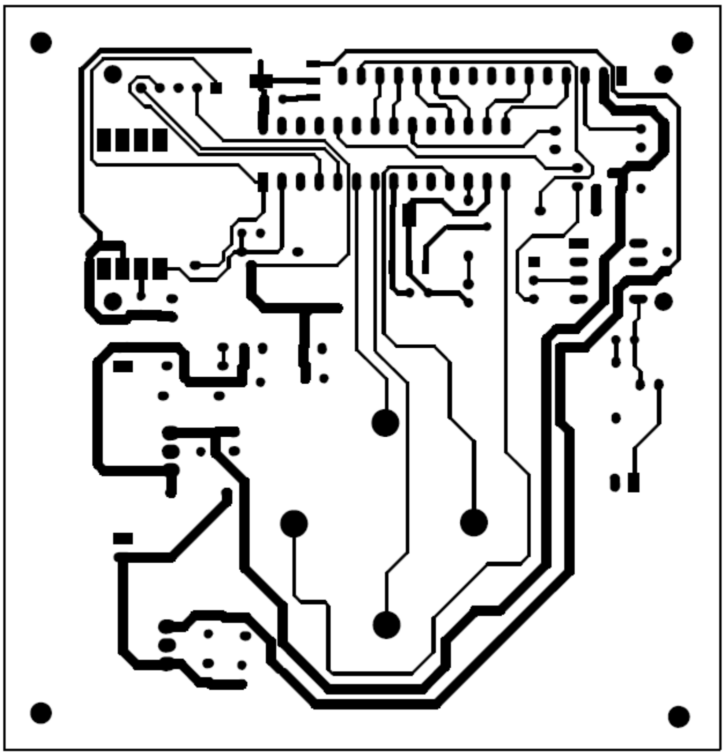


Figure C.5 Top side of the arm simulator PCB (102 mm X 98 mm) circuit schematic as given in Figure C.1

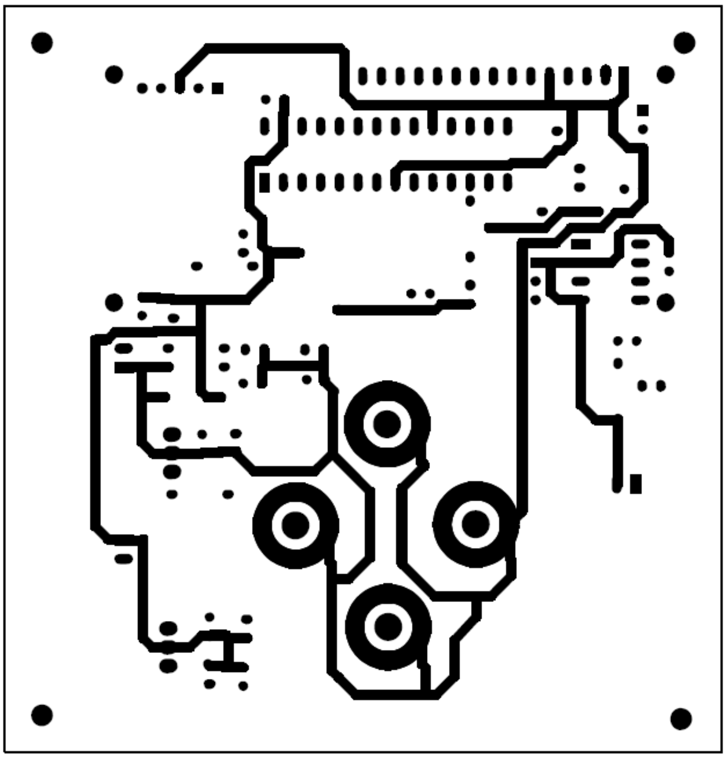


Figure C.6 Bottom side of the arm simulator PCB (102 mm X 98 mm) circuit schematic as given in Figure C.1

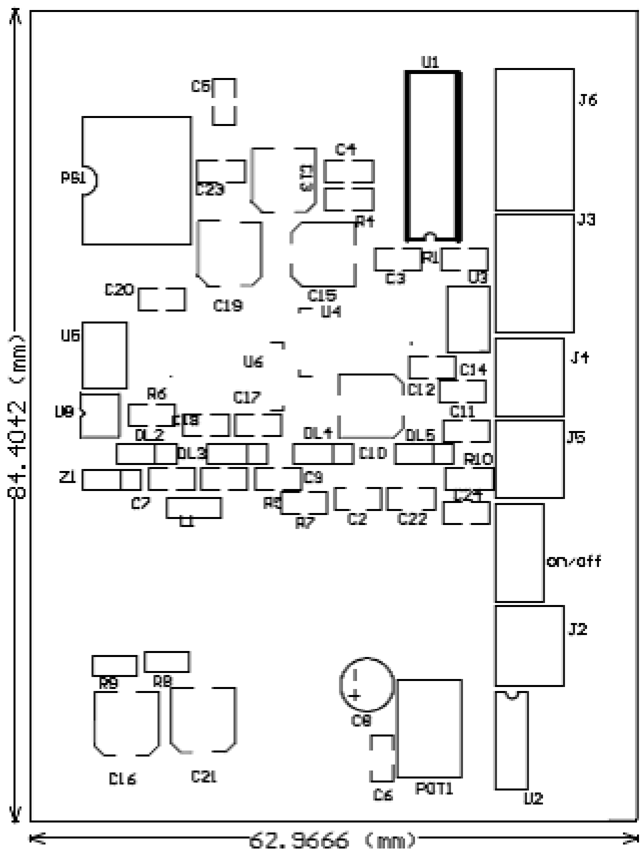


Figure C.7 Top overlay of the arm simulator PCB (62.966 mm X 84.402 mm) circuit schematic as given in Figure C.2

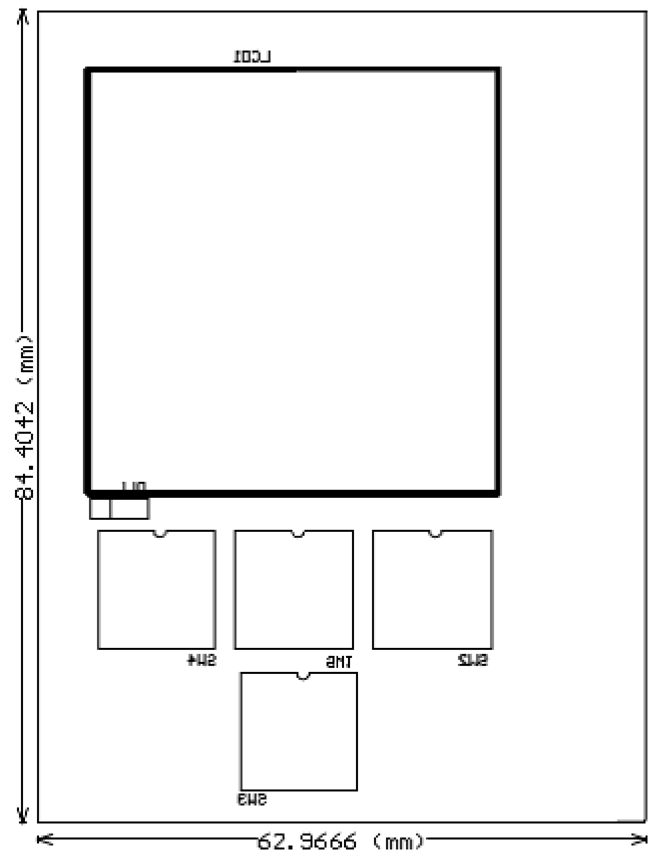


Figure C.8 Bottom overlay of the arm simulator PCB (62.966 mm X 84.402 mm) circuit schematic as given in Figure C.2

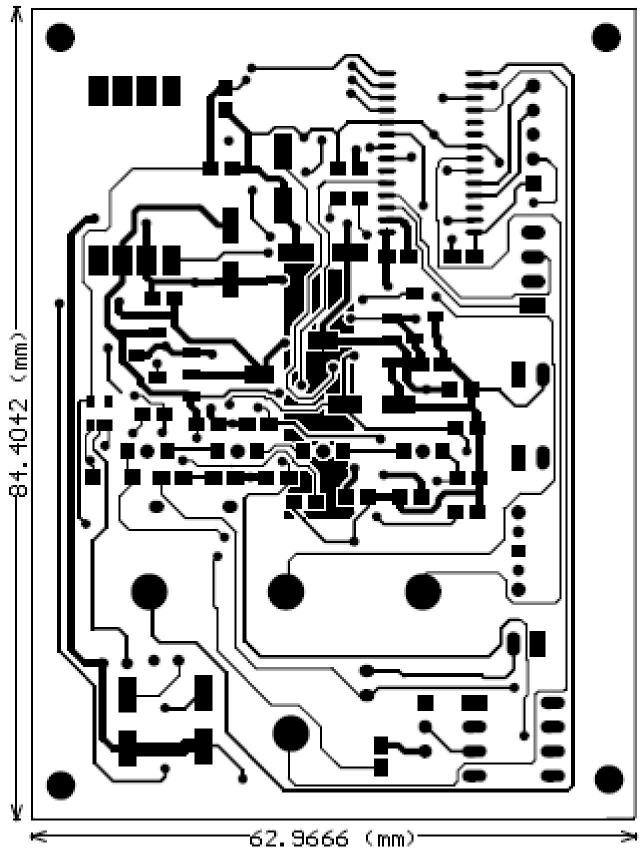


Figure C.9 Top side of the arm simulator PCB (62.966 mm X 84.402 mm) circuit schematic as given in Figure C.2

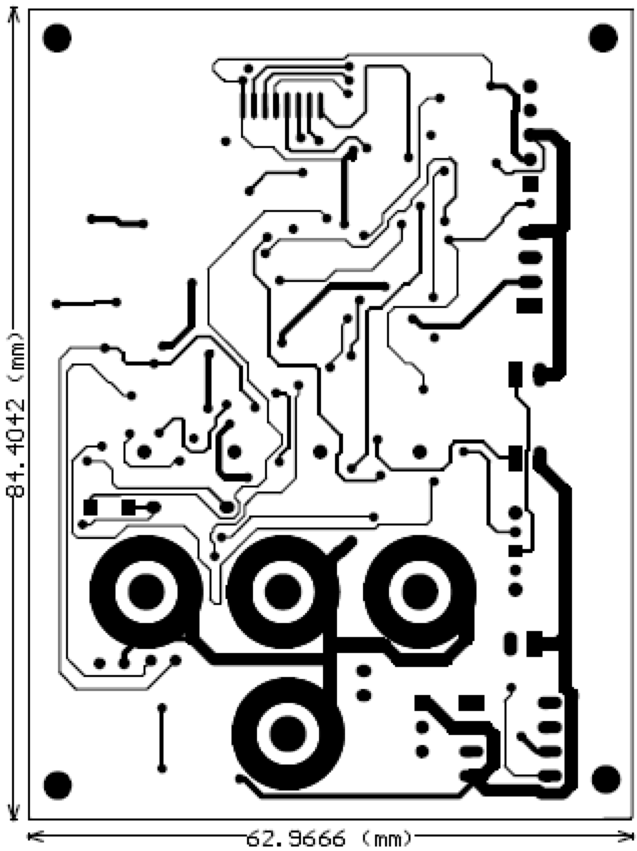


Figure C.10 Bottom side of the arm simulator PCB (62.966 mm X 84.402 mm) circuit schematic as given in Figure C.2

Appendix D
COMMERCIALLY AVAILABLE BP SIMULATORS

The information on some of the commercially available arm simulators is briefly reviewed here and summarized in Table D.1.

1. Fluke Biomedical "Cufflink Noninvasive Blood Pressure Analyzer" [8]: This Analyzer provides BP simulations using oscillometric method. It generates different type of BP waveforms with arrhythmias and settable heart rate over the full physiological range of normal, hypotensive, and hypertensive adult or neonate patients. An internal pump pressurizes the NIBP system under test. It has an internal digital manometer. It facilitates overpressure testing of NIBP monitors by automatically detecting and displaying the overpressure point. It can also be used for leakage testing and relief valve testing.

2. Fluke Biomedical "BP Pump 2 Non-Invasive Blood Pressure Simulator and Tester" [8]: This simulator is a multi-purpose test instrument for use with oscillometric NIBP. It provides dynamic blood pressure simulations, static calibration, automated leak testing, and pressure relief valve testing. The models available includes the basic model BP Pump 2L and high accuracy model BP Pump 2M. The key features are pressure leak testing on cuff, tubing, and connections, relief valve testing on the patient monitor, pressure gauge measurements, pressure source capability, NIBP simulations including adult, neonate, arrhythmias, and respiratory artifacts, internal adult and neonatal cuff simulation, ECG synchronization with non-invasive output, and external wrist cuff simulations.

3. NASCO "Life/form Blood Pressure Simulator (LF03204U)" [9]: The NASCO Life/form BP simulator can be used for the demonstration of the 5 Korotkoff phases including an auscultatory gap. This simulator produces digitally recorded sound with settable pulse rate and volume. Its main features are calibration of simulator, setting of palpation, extra speaker to hear Korotkoff sound, and settable systolic pressure, diastolic pressure, pulse rate, and pulse volume.

4. Pronk Technology "Simcube NIBP Simulators" [11]: It is a compact, hand-held instrument for simulating the oscillometric pulses by varying both the size and shape of the wave as cuff pressure changes. Its main features are digital manometer, 12-lead ECG- 10 different heart rates synchronized with NIBP**,** respiration- 3 rates, plus a sequence of 7 different rates, pacer simulation, leak test mode it measures leak rate of a NIBP monitor, cuff, and hose automated alarm test mode**:** tests heart rate alarms.

5. Rigel "Non-Invasive Blood Pressure Simulator (311C)" [12]: It simulates oscillometric waveform for calibration of NIBP monitors. It provides graphic representation of the inflation and deflation process and it displays the dynamic NIMP cuff pressure waveform, measurement time (in s), maximum inflation pressure (in mmHg), inflation time, inflation rate (mmHg / sec), minimum pressure, deflation time, and deflation rate. It has a digital manometer that simulates oscillometric waveform for adults and neonates.

6. Simulaids "No 600 Blood Pressure Simulator Arm" [13]: This arm can be used for auscultatory method for measuring blood pressure. It also simulates the palpation of the radial pulse. The systolic and diastolic pressures can be varied over 0–300 mmHg in two mmHg increments. It has provision for varying the amplitude of the sound, sound jack for group listening, auscultatory gap setting, and heart rate setting.

7. Pinnacle Technology "BPT-001 Blood Pressure Simulator" and "BPK3-001 Blood Pressure Training Arm" [14]: BPT 001 simulates the five Korotkoff phases. Its main features are systolic and diastolic settings, on or off of auscultatory gap, adjustable volume and adjustable pulse rate. BPK3-001 is an electronic trainer for NIBP measurement. Its main features are palpable antecubital pulse, settable systolic, diastolic, heart rate, auscultatory gap, and adjustable volume. Indication of gauge reading as pressure is increased or decreased.

6. BC Biomedical "**Non-Invasive Blood Pressure Simulators (1000 series)" [15]:** This series has many compact instruments for NIBP simulation. NIBP-1020, offers ECG waveforms with full QRS and respiration waveforms. The NIBP-1030 offers temperature, arrhythmias and a leak rate test mode. The graphics display provides multiple screen display and cuff pressure in mmHg, and it also offers views of the plot of the overall pressure or a close-up of the BP waveform. The main features of NIBP (1010) are full range manometer, adult, neonatal, hypertensive and hypotensive modes, pressure envelope offset, peak pressure detect with reset, and digital calibration with flash programmable. The model NIBP (1020) also has ECG output. It provides sinusoidal respiration simulation and optional peak pressure detect with ECG alarm test. In addition to all the features model NIBP (1030) also provides static and synchronized BP outputs for invasive BP measurement.

Table D.1 Features of some of the commercially available arm simulator for BP

Sr. No	Manufacturer	Model	Cost (US $)	Features and specs.
1	Mass Group INC.	LF01095U SI- 600 10-81-BP10	US$ 780 US$ 775 US$ 1,365	Pressure range: 0–300 mmHg
2	Fluke Biomedical	BP Pump 2L(Basic Model) BP Pump 2M (High-Accuracy Model)	Not available	Pressure range: 0–400 mmHg Resolution : Basic model: 1 mmHg High accuracy model: 0.1mmHg Accuracy: 0.5% (0–300 mmHg) 2% (301–400mmHg) <0.8mmHg(High accuracy model)
3	Clinical Dynamics	Not available	Not available	Pressure range: 0.0–400.0 mmHg, Accuracy: ± 0.5 mmHg, Resolution: ± 0.1 mmHg
4	Rigel	311C	Not available	Heart rate: 1–300 bpm Integrated pump: 0–350 mmHg (user conf.) Leak test: 0–350mmHg (user conf.) Overpressure: automatic (max. 410 mmHg) Digital manometer: 0–410 mmHg Accuracy: ±0.5% FS
5	Simulaids	No 600 LF01129 LF01095 LF03204	$802.95	Pressure range: 0–300 mmHg in two mm increments
6	Pinnacle Technology	BPT001	$795	Not available
7	BC Biomedical	NIBP-1000 NIBP-1010 NIBP-1020 NIBP-1030	$1,995	Pressure range: 0–500 mmHg Accuracy: ± (1% of Reading + 0.5 mmHg) Heart rate: 80, 94 bpm
8	Laerdal	Not available	Not available	Pressure range: 0–300 mmHg
9	Pronk Technologies	SC-1/2 SC-3/4 SC 5 Sim Cube NIBP Simulators	Not available	Pressure range: 0–480 mmHg Accuracy: ±1% of reading Precision: 0.5mmHg Pressure range: 0–400 mmHg Accuracy: ±1mmHg Precision: 0.1 mmHg
10	Nasco	LF03204U	Not available	Not available

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I dedicate my work to my parents Mr. Mahadev Gothwal and Mrs. Rajshri Gothwal.

Pushpa Gothwal

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