LABORATORY MANUAL

PLETHYSMOGRAPH
DATA ACQUISITION SYSTEM

CE3002: SENSORS, INTERFACING AND CONTROL

2021 SEMESTER 1

SCHOOL OF COMPUTER SCIENCE AND ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Blood pulse wave is one of the most important physiological parameters for the noninvasive diagnosis and monitoring of cardiovascular diseases. In many cases, such as during surgery as well as in Intensive Care Unit (ICU), there is a need to monitor the continuous blood pulse wave in real time. Blood pulse wave continuously monitored in real time by direct catheter insertion. However, catheter insertion always brings lots of risks of embolism, arrhythmia, heart attack, and certain percent of mortality. Therefore, noninvasive monitoring of blood pulse wave is preferred.

Continuous and noninvasive arterial blood pulse wave monitoring is desirable for patient monitoring, especially in ICUs. The existing methods to measure arterial blood pulse wave non-invasively include cuff sphygmomanometer, arterial tonometer, etc.

Cuff sphygmomanometer is the most standard manual technique used to monitor blood pulse wave for blood pressure measurement [1]. This method takes advantage of the Korotkoff sounds and presents two parameters, namely the systolic and diastolic pressure. However, with periodic cuff inflation and deflation, it cannot provide continuous beat-to-beat measurement of blood pressure. On the other hand, arterial tonometer is able to offer a continuous beat-to-beat pressure waveform but it is subject to motion artifact caused by the high sensitivity to sensor position and wrist movement [1].

A new method of continuous blood pressure monitoring was attempted by Penaz using photoelectric technique of detecting blood flow [2], using a transparent inflatable cuff controlled by a servo control system and placed on the human finger. This method is based on the idea that if an externally applied pressure in the cuff is equal to the arterial pressure at any instant, the arterial walls will be unloaded (zero transmural pressure) and the arteries will not change in size. In this condition, the blood volume will not change.

These abovementioned principles provide the motivation to design and implement a simple, low-cost, and stable continuous blood pulse wave monitoring system to facilitate the study of patients' clinical condition through observation of blood flow (related to changes in volume).

1.2 Objective and Scope

Based on the background and motivation discussed in Section 1.1, the project objective is to design and implement a noninvasive continuous blood pulse wave monitoring system that consists of transducer, data acquisition, and post processing. The signal obtained from a test subject (using a transducer) is passed through a signal conditioning circuit, digitized, and transferred to the computer. Signal post processing is performed to extract useful information about the test subject using appropriate algorithms in software.

The main goals of the project are:

1) To design and implement blood pulse wave monitoring hardware (employing transducer, operational amplifiers (op-amps) and other electronic components for signal conditioning, and an analog to digital converter, i.e., ADC for quantization).
2) To interface the digitized signal with the PC and to improve the quality of the digitized signal by performing digital filtering in software, if required.
3) To display the digitized signal on the computer and to perform post processing for extracting clinical information about the test subject.

1.3 Resources

The two tables below enlist all the resources needed for the project, for hardware as well as software part.

No.	Type	Description	Use	Quantity
1	1020FC	PPG Finger Clip transducer from UFI	Transducer	1
2	AD625	Instrumentation amplifier (IA) IC	Amplification	1
3	IC 741	Operational amplifier IC	Analog Signal Conditioning – in lowpass filter and level shifter.	2
4	Trimmer	Variable Resistor 5KΩ, 64W	IA gain adjustment	1
5	Potentiometer	Potentiometer 10KΩ, Round Metallic, 3-terminal	Non-inverting Adder in Level Shifter	1
6	Resistor	Resistor 1.2MΩ, 1/4 W	Capacitive coupling for transducer	1
7	Resistor	Resistor 150Ω, 1/2 W	Voltage Divider for transducer supply	2
8	Resistor	Resistor 100kΩ, 1/4 W	IA gain adjustment	2
9	Resistor	Resistor 1.6KΩ, 1/4 W	Lowpass Filter	1
10	Resistor	Resistor 1kΩ	Non-inverting Adder in Level Shifter	4
11	Resistor	Resistor 240Ω	Attenuator pad, useful for simulating	1

			signals from function generator	
12	Resistor	Resistor 62Ω	Attenuator pad, useful for simulating signals from function generator	2
13	Capacitor	Capacitor 220nF, 35V, tantalum	Capacitive coupling for transducer	1
14	Capacitor	Capacitor 10uF, 16V, electrolytic	Lowpass Filter	1
12	Mini Clips	To connect sensor wires	Transducer	3
15	Breadboard	For building the circuit (available in lab)	-	1
16	Single Strand Wires	For building the circuit (available in lab)	-	1
17	Dual power supply	For Opamp 741 and AD625 IC (available in lab)	Analog Signal Conditioning	1
18	Function Generator	With probes (available in lab)	-	1
19	DSO	With probes (available in lab)	-	1
20	Arduino Uno R3 with USB cable	Microcontroller board	Interfacing with computer	1

Table 1.1: Table of components used.

No.	Software	Use	Publisher
1	MATLAB R2015a	Data Acquisition and Signal Processing	MathWorks Inc.
2	Arduino	Data Acquisition	Arduino

Table 1.2: Table of software used.

CHAPTER 2: RELATED WORK AND THEORY

2.1 Plethysmograph as a Volume Change Detection Transducer

The monitoring of blood flow using plethysmograph is the measurement of volume changes that result from the pulsations of blood occurring with each heartbeat. Such measurements are useful in the diagnosis of arterial obstructions as well as for pulse-wave velocity measurements. Instruments measuring volume changes or providing outputs that can be related to them are called *plethysmographs*, and the measurement of these volume changes and the consequent pehnomena is called *plethysmography* [3].

2.2 Infra-Red Pulse Plethysmograph [4]

In this project, an infra-red pulse plethysmograph (PPG) is used as a transducer. It uses an infra-red photoelectric sensor to detect and record changes in tissue blood volume from fingers, toes, ear, forehead, etc. Fig. 2(a) shows PPG model 1020 FC manufactured by UFI.

Figure 2(a): PPG model 1020 FC manufactured by UFI.

2.2.1Specifications

The model 1020 infra-red PPG has the following specifications:

Size	15 × 15 × 6.3 mm
Weight	28 g (approximately)
Excitation	20 mA at 6 to 9V DC nominal
Output	5 to 50 mV (typical finger application)
Output Impedance	1 KΩ nominal

2.2.2Description

The UFI model 1020 PPG is a compact, flexible PPG transducer. It uses a matched semiconductor infra-red Emitter and Receiver pair to detect small changes in the reflectivity of the subject's skin (these changes are due to the inflow and outflow of blood associated with the beating of the heart). The use of the infra-red light spectrum helps minimize artifacts resulting from changes in ambient light.

2.2.3Use

The study of blood pulse wave in this project is conducted through observation of blood flow (which is related to volume changes measurement) in a finger. For a comfortable use, the 1020FC ("Finger Clip") type which is built into a finger clip fixture is chosen. A built-in spring maintains clip pressure, which also helps hold the finger inside the clip. The clip itself is made of Aluminum, which further reduces the effects of changes in ambient light. The 1020FC should be attached to the end of any finger firmly but not in such a fashion that the blood flow is restricted. The amplitude of the pulsatile signal depends primarily on the volume of blood in the capillary bed directly beneath the sensor, so it may be necessary to move the sensor around to find the best signal. It is important to realize how the application of the transducer will affect the blood flow through the area being monitored and the resultant pulsatile signal quality. In general, if the transducer feels tight to the subject, or the area being monitored exhibits signs of low blood flow (becomes pale or begins turning blue), it should be adjusted to be slightly looser. It may be necessary to move the Finger Clip around to obtain the largest or best signal at the chosen site. Fig. 2(b) shows various pulsatile signals as the transducer is applied with various degrees of tightness.

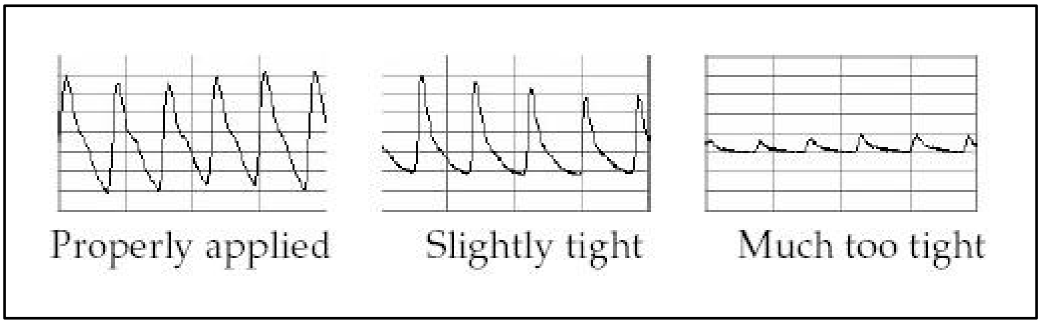


Figure 2(b): Various pulsatile signal qualities.

2.3 PPG Model 1020 Output Signal Component

The signal generated by the 1020 PPG has two components, i.e.: [4]

a) A DC "baseline" or average component corresponding to the average amount of light reflected by the tissue under the transducer.

b) A much smaller "pulsatile" component which normally increases following the flow of blood into the tissue under the transducer, followed by the resulting decrease as blood flows out. This pulsatile blood flow correlates predominantly with the beating of the heart.

The primary application for the 1020 PPG is to measure pulsatile blood flow/volume changes in the skin of human subjects. Therefore, the average DC voltage component of the 1020 output needs to be eliminated, in order to supply just the pulsatile signal for further analysis. Fig. 2(c) shows an example of pulsatile signal output by 1020 PPG (the pulse rides on a slowly varying DC level). In this report, *"PPG signal"* term is used to refer to pulsatile signal.

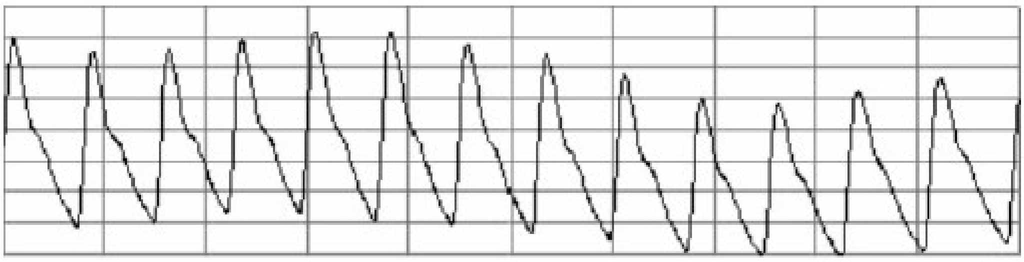


Figure 2(c): Output "pulsatile" signal of 1020 PPG.

2.4 Interface – Analog to Digital Conversion and Serial Communication

In this project, after the signal conditioning stage, data is fed to the Arduino board that contains a number of components that allow many options for on-board post processing as well as communication with other devices. The board has an Atmega328P microcontroller [6]. The on-board Atmega8U2 USB-to-TTL serial chip communicates with a computer using the USB interface, via the Universal Synchronous/Asynchronous Receiver/Transmitter (USART) protocol. To send and receive data, the computer creates a virtual COM port. The COM port is a name given to serial port interface on all IBM-PC compatible computers. Nowadays, the serial port is rarely seen on computers, so the operating systems create virtual COM ports, transmitting and receiving data through the USB port.

When the board is connected to the computer (which has the Arduino software installed on it), it will install the necessary drivers. Then, the virtual COM port can be seen in the list of devices connected to the computer, using the Device Manager in the Computer Management tool. It will appear as COMx where x may be any integer, as designated automatically by the operating system. **Note that 'x' may be different every time the board is re-connected to the computer. Hence, it is important to check and note down the exact COM port before using the board for Serial communication.**

The Arduino board has both digital input/output (IO) and analog I/O pins to communicate with other devices. There are a total of 6 analog pins (numbered

A0 through A5) which are connected to a 10-bit analog to digital converter (ADC). This means that it is capable of mapping 0 – 5 V to 1024 levels. In other words, it has a resolution of 0.0049 volts (4.9 mV) per unit. For the purpose of this project, we connect the output of the 741 op-amp to one of the analog pins (say, A0). The input to this pin will thus be mapped to one of the 1024 levels (from 0 to 1023).

The Arduino software comes with an inbuilt Serial Monitor which allows us to view the incoming data from the board, on the computer. It can also be used to send data to the board. To enable communication using USART, one has to use the Serial library while programming the microcontroller. A sample program is given in the appendix which can be used to program the microcontroller to read and sample data on one of its analog pins and send it to the computer. The programmer needs to specify the rate of data transmission between the board and the computer in terms of the baud rate. Arduino offers a number of options for the baud rate, namely 300, 600, 1200, 2400, 4800, 9600, 14400, 19200, 28800, 38400, 57600, or 115200. Thus, both devices at either end of the communication need to communicating at the same baud rate. (For this project, a Baud Rate of 1200 may be used.)

Thus, to summarize, the Arduino board is used to convert the data from analog to digital and send it to the computer for visualization. On the computer, MATLAB is used to read the data sent by the board. Note that, at one time only one program can have access to the COM port. Hence, one cannot use the Serial Monitor in the Arduino software and MATLAB to communicate with the board simultaneously.

CHAPTER 3: DATA ACQUISITION SYSTEM

3.1 System Architecture

Fig. 3(a) summarizes the entire data acquisition system (DAS) designed and implemented in this project.

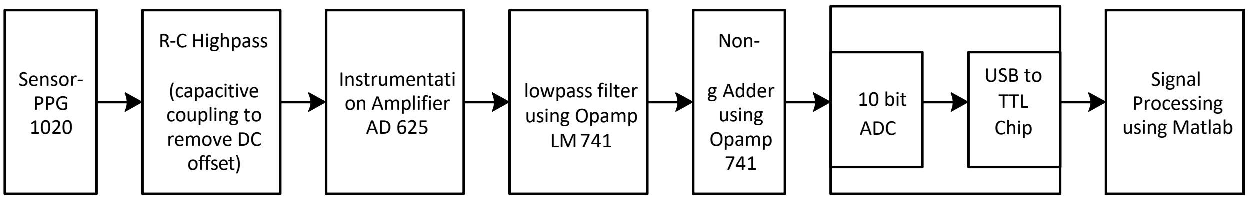


Fig. 3(a) Block Diagram.

3.2 Input Signal

Input signal in the analog signal conditioning circuitry is the pulsatile signal obtained from an infra-red pulse transducer; model 1020FC (Finger Clip). This transducer is used to record changes in pulsatile blood volume from fingers.

The amplitude of PPG signal obtained from the 1020FC PPG is 5 to 50 mV peak-to-peak, typically for a resting subject. In order to make the PPG signal appropriate for further analysis, analog signal conditioning is performed.

3.3 Analog Signal Conditioning

3.3.1Capacitive Coupling

The 1020FC produces 1 to 2 V DC offset component in addition to the PPG signal. Capacitive coupling is used to eliminate the average DC voltage component of the 1020FC output, in order to supply just the PPG signal to the amplifier. This approach involves connecting a capacitor between the 1020FC output and the amplifier input. A resistor is added between the amplifier input and ground to keep the signal ground referenced.

The circuit shown in Fig. 3(b) shows the capacitive coupling which supplies a low frequency roll-off of 0.6 Hz (see equation 3.1 for the fairly low frequency PPG (finger pulse) signal. The average 1 to 2 V DC offset present on the output of the 1020FC is removed due to the highpass characteristic of the R-C circuit. The power supply of the PPG transducer is obtained using a voltage divider circuit.

$$fc = \frac{1}{2\pi RC} = \frac{1}{2\times 3.14\times 1.2M \times 0.22\mu} = \frac{1}{1.658} = 0.6 \text{ Hz.} \qquad \textbf{\textit{(eqn.3.1)}}$$

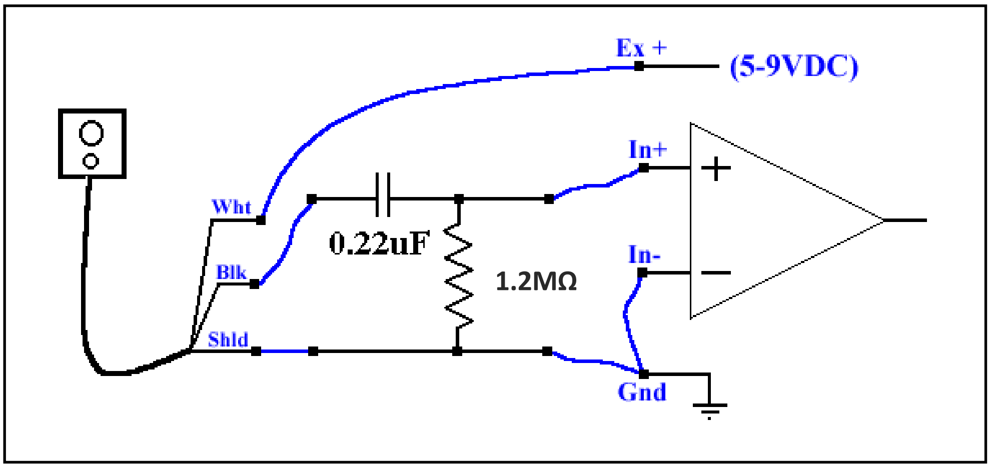


Figure 3(b): 1020FC interface for pulse sensing (capacitive coupling method).

Impedance considerations

Care has to be taken to make sure that the resistor chosen is greater than 100 times the output impedance of the 1020FC transducer (which is 1KΩ nominal) in order to prevent attenuation of desired PPG signal due to loading effect.

3.3.2Amplification

The signals obtained from transducers are usually too small to be used directly for post processing, so an amplifier is required to raise the signals to the appropriate level. Since the 1020FC supplies only one output signal, it is not necessary to use a differential amplifier to amplify the signal. A single-ended amplifier is usually sufficient. However, a differential amplifier can be used, since it is much more common, with the unused (inverting) input of the amplifier is connected to ground.

An Instrumentation Amplifier (IA) is used because it has high and balanced input impedance, high adjustable gain with low offset problem, and a high common mode rejection ratio (CMRR) which does not depend on matching of the resistors. The very high input impedance of the IA minimizes input signal loading effects from the finite source impedances. The gain of IA is easy to adjust by selecting appropriate external resistors R_f, R_g (see equation 3.2 below).

The IA used in this project is AD625. As the output signal from 1020FC is about 5 to 50 mV peak-to-peak, the amplifier circuit is designed to give gain of approximately 100. This output is suitable and sufficient for further analysis. Based on the gain equation of the IA, the resistors values for obtaining a gain of 100 can be calculated as follows:

$$Gain = \frac{2Rf}{Rg} + 1 \qquad \textbf{\textit{(eqn.3.2)}}$$

$$100 = \frac{2 \times 100K}{Rg} + 1$$

$$99 = \frac{200K}{Rg}$$

$$Rg = \frac{200K}{99}\Omega = 2.02\ \mathrm{K}\ \Omega.$$

A variable resistor of 5KΩ can be used to provide Rg ≈ 2.02KΩ. Fig. 4.2 shows the configuration of the IA. Fig. 3(c) shows the configuration of the IA circuit using AD 625.

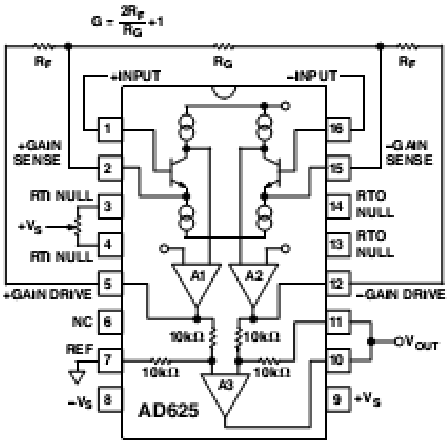


Figure 3(c): Configuration of instrumentation amplifier AD 625.

3.3.3Filtering

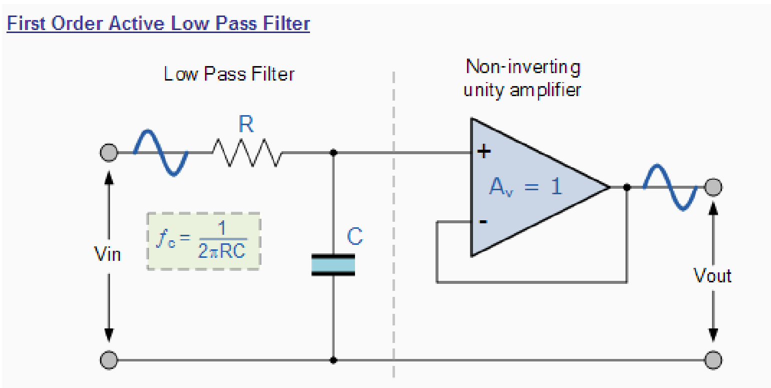


Figure 3(d): Low-pass filter

In this project, the bandwidth of the PPG signal is from 0.6 to 10 Hz. For low frequency filtering, this corresponds to a fairly high respiration rate of 36 breaths/minute, and for the high frequency filtering, the maximum heart rate might be 240 beats/minute, which corresponds to 4 Hz. So, filtering the PPG amplified output signal with a lowpass filter that rolls off at 10 Hz is more than sufficient. A highpass filter that rolls-off at 0.6 Hz has been designed in the capacitive coupling for DC offset removal, using a highpass RC filter as described in part 3.3.1. An opamp is used to design an active lowpass filter that rolls off at 10 Hz. The corresponding circuit is shown in Fig. 3(d).

We choose the closest standard capacitor value C = 10uF and the closest standard resistor value R=1.6KΩ to obtain the cutoff frequency of approximately 10Hz using $f_c=1/(2\pi RC)$.

3.3.4Level Shifter using Non-Inverting Adder

In this DAS, the ADC used has a reference voltage range 0-5V DC. Hence, to shift the dual polarity filtered and amplified PPG signal to the positive domain, a non-inverting adder is designed using an opamp. Fig. 3(e) shows the circuit of the non-inverting adder wherein $V_{out} = V_1+V_2$. R is chosen as 1KΩ. V_1 is the amplified and filtered PPG signal and V_2 is set to be an appropriate fixed DC voltage using a voltage divider circuit.

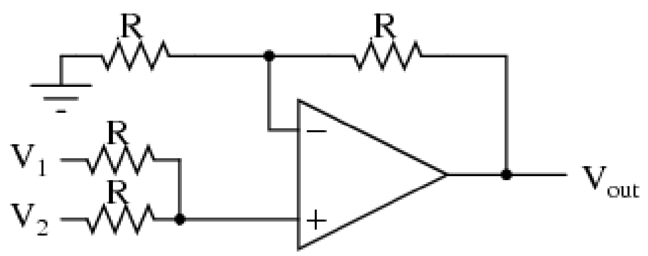


Figure 3(e): Non-inverting adder circuit diagram

3.4 Signal Acquisition and Post Processing in Matlab

Matlab is used as a tool for building the interface between the ADC and the computer, and to control the access to the (virtual) COM port. The data read from COM port is further processed and analyzed to get the clinical data of the test-subject. The acquired samples of the PPG signal are filtered if required. Fig. 3(f) shows an example of the acquired signal.

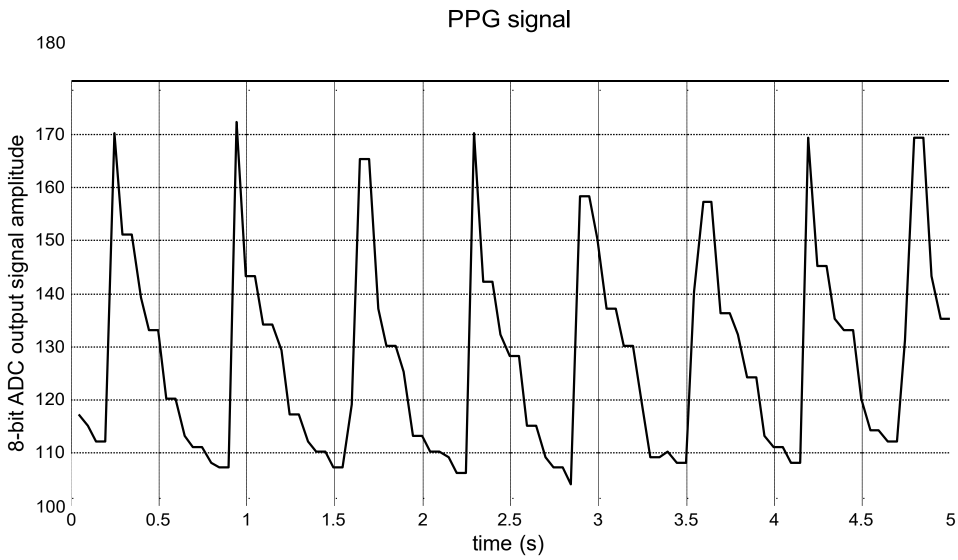
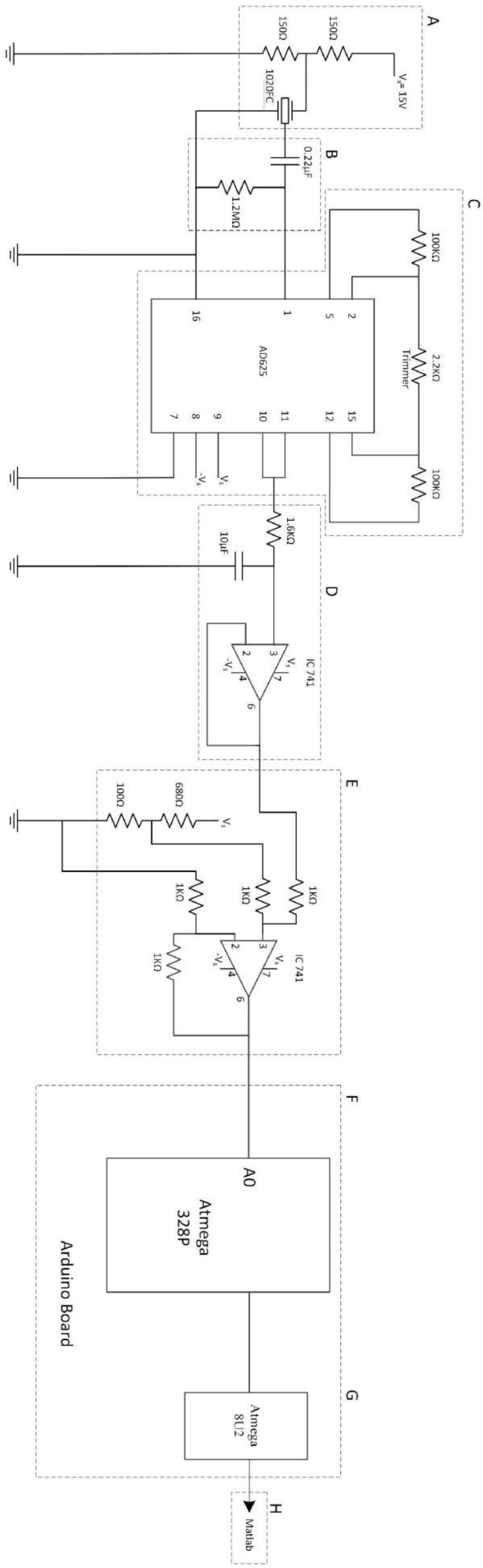


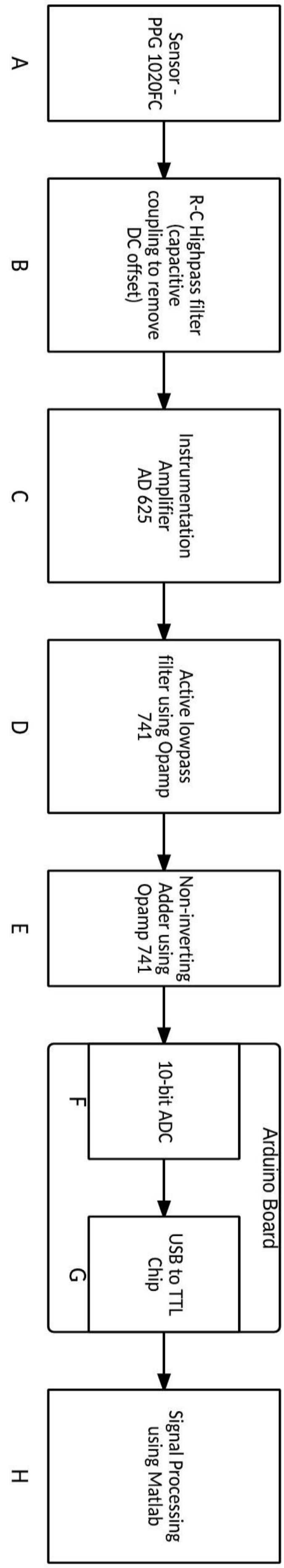
Figure 3(f) Acquired PPG signal

3.5 Schematic Diagram

The following figure shows the different sections in the plethysmograph data acquisition system and the corresponding schematic diagram.



Plethysmograph Data Acquisition System – Schematic Diagram

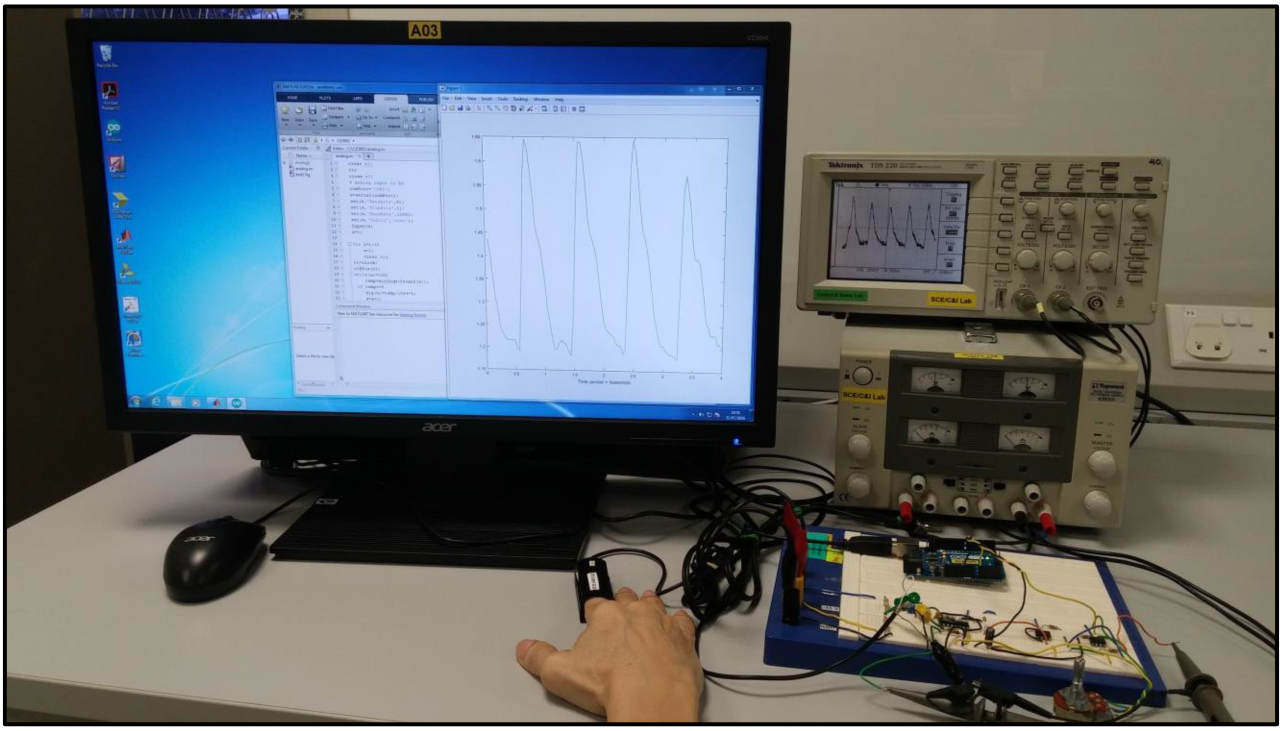


3.6 Photograph of prototype Data Acquisition System

The following figure shows the photograph of the working prototype of the plethysmograph data acquisition system and the different sections in it.

The circuit comprises of the following main parts:

- Finger-clip transducer.
- Circuit assembled on breadboard - comprising of two operational amplifier, one instrumentation amplifier and one ADC ICs.
- Oscilloscope – to check and analyze waveforms at different stages in the circuit.
- Power supply – to provide dual 15V and single 5V supply.
- Computer – to acquire data and process it.



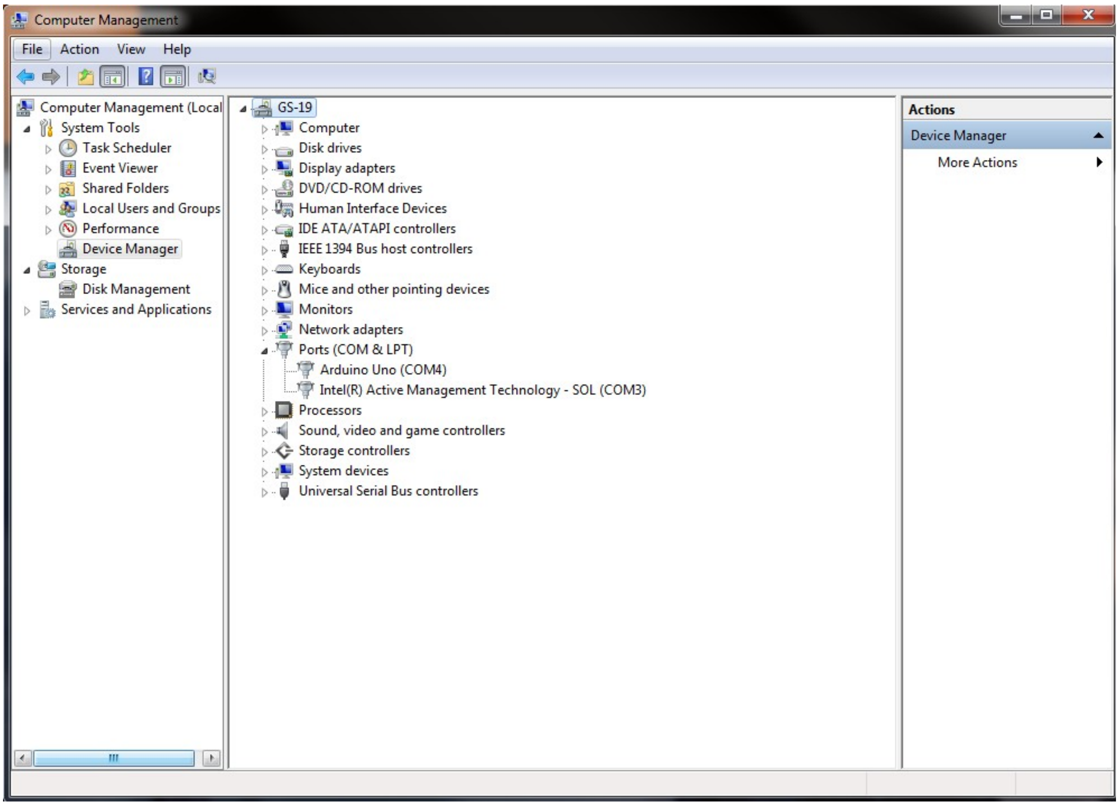
CHAPTER 4: CONCLUSION

This project has both hardware and software sections in it. The combination of both sections is the whole system termed as “PPG Data Acquisition System (DAS)”. For hardware part, signal conditioning circuit and data quantization circuits are designed and implemented. Data transfer circuit that performs communication with the PC is designed and controlled using Matlab. A Matlab code is written to display the digitized signal on the computer. To improve the quality of the signal acquired, digital filtering can be performed in Matlab. The obtained signal is analyzed to extract the available clinical information about the test subject such as his heart rate.

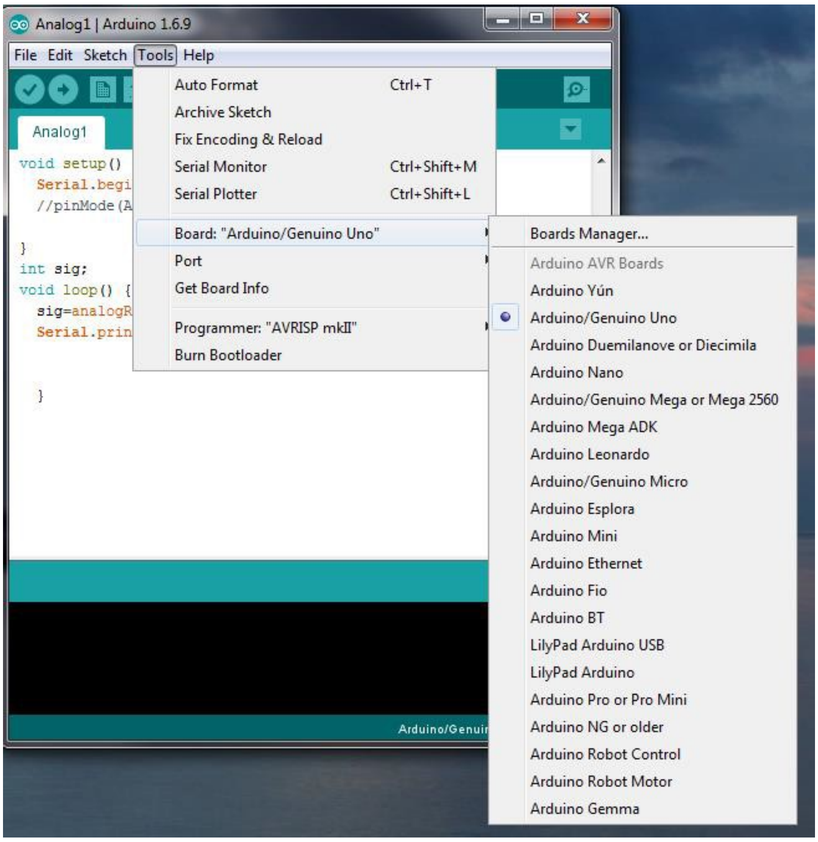
APPENDIX

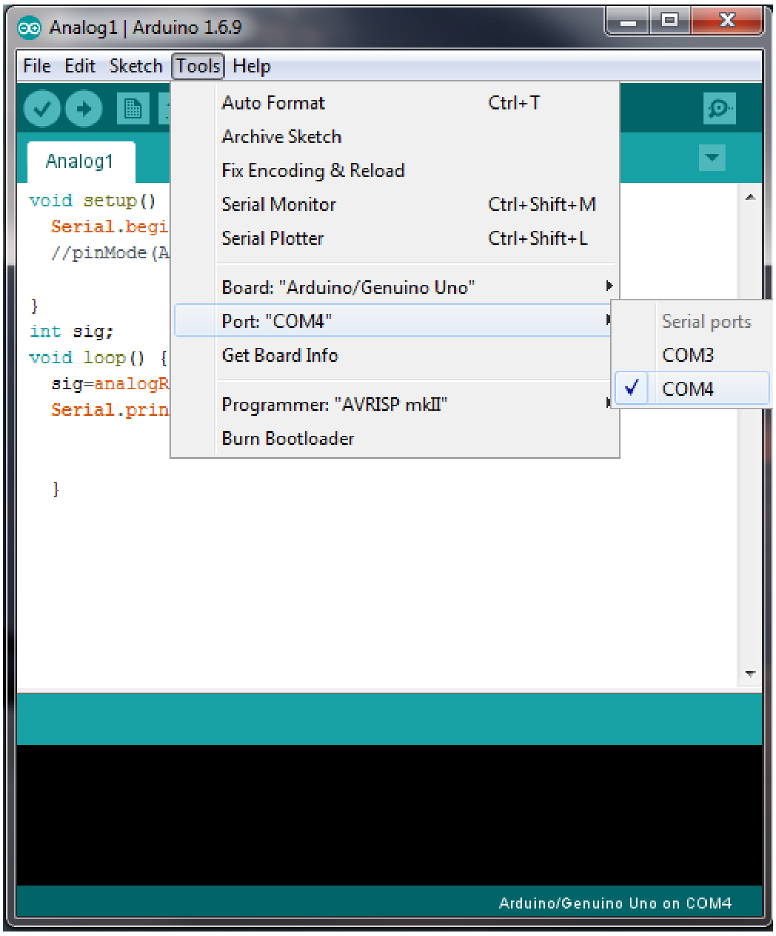
Steps to Configure and Use the Arduino Uno Board

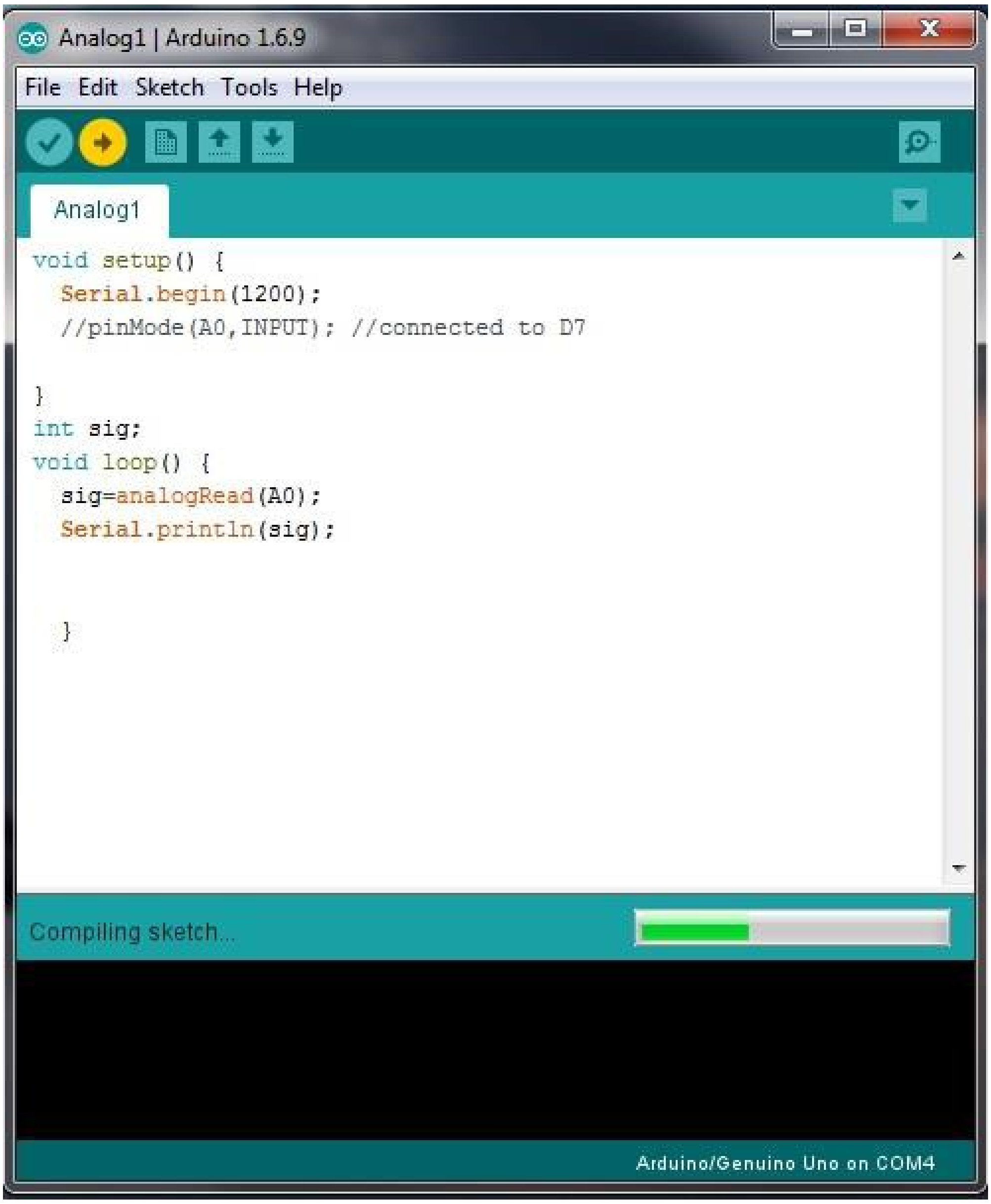
1. Check the COM port assigned by the operating system after the Arduino board has been connected. Here, it is COM4 as can be seen in the screenshot below.



2. When the board is used *for the first time*, it needs to be programmed to read analog values. We do that by opening the Arduino software, selecting the correct board and port from the Tools menu, writing the program and then uploading it on the board. Refer to the images below.


Analog1 | Arduino 1.6.9
File Edit Sketch Tools Help
Auto Format Ctrl+T
Archive Sketch
Fix Encoding & Reload
Serial Monitor Ctrl+Shift+M
Serial Plotter Ctrl+Shift+L
Board: "Arduino/Genuino Uno"
Port
Get Board Info
Programmer: "AVRISP mkII"
Burn Bootloader
Boards Manager...
Arduino AVR Boards
Arduino Yún
Arduino/Genuino Uno
Arduino Duemilanove or Diecimila
Arduino Nano
Arduino/Genuino Mega or Mega 2560
Arduino Mega ADK
Arduino Leonardo
Arduino/Genuino Micro
Arduino Esplora
Arduino Mini
Arduino Ethernet
Arduino Fio
Arduino BT
LilyPad Arduino USB
LilyPad Arduino
Arduino Pro or Pro Mini
Arduino NG or older
Arduino Robot Control
Arduino Robot Motor
Arduino Gemma


Analog1 | Arduino 1.6.9
File Edit Sketch Tools Help
Auto Format Ctrl+T
Archive Sketch
Fix Encoding & Reload
Serial Monitor Ctrl+Shift+M
Serial Plotter Ctrl+Shift+L
Board: "Arduino/Genuino Uno"
Port: "COM4"
Get Board Info
Programmer: "AVRISP mkII"
Burn Bootloader
Serial ports
COM3
COM4
Arduino/Genuino Uno on COM4



The above image shows a sample program for reading data from pin A0 and sending it serially to the computer.

3. After performing the above, **Arduino needs to be closed**. Then one can use MATLAB to directly read the data being sent by the board. A sample program is shown below. Care must be taken to mention the same COM port and Baud Rate as mentioned in the Arduino program.

C:\Users\tushar006\Downloads\analog.m

```matlab
clear all
clc
close all
% analog input to A0
comPort='COM4';
s=serial(comPort);
set(s,'DataBits',8);
set(s,'StopBits',1);
set(s,'BaudRate',1200);
set(s,'Parity','none');
fopen(s)
a=1;

for l=1:10
    a=1;
    clear sig
c1=clock;
c1=fix(c1)
while(a<=100)
    temp=str2num(fscanf(s));
 if temp>=0
    sig(a)=temp/1024*5;
    a=a+1;
 end
end
c2=clock;
c2=fix(c2)
tp=c2-c1;
tp=tp(5)*60+tp(6);
plot((1:length(sig))*tp/100,sig)
xlabel(['Time period = ' num2str(tp) 'seconds'])
pause(0.01);
end

fclose(s);
delete(s)
disp('Done')
```

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[5] Manufacturer datasheets of:
i) IC 741
ii) IC AD 625
iii) IC AD 0820

[6] https://www.arduino.cc/en/Main/ArduinoBoardUno