A REPORT

ON

Design and Development of a Blood Pressure Monitor

BY

Mihir Shete 2006A8PS241G B.E.Hons (Electronics and Instrumentation)

Prepared in partial fulfillment of the

Lab Oriented Project Course

AT

BITS, PILANI

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(APRIL, 2010)

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ACKNOWLEDGEMENTS

We are indebted to our project guide and instructor Ms. Sarita Kumari for her valuable suggestions and for the motivation she provided. We thank her for the guidance she offered us in making the project a success.

We would also like to than Mr. Aditya Yadav, the Coordinator of The PSoC Club at BITS-Pilani Goa Campus, for providing us with PSoC1 kits to conduct our experiments on and lending a helping hand whenever needed.

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1.1 Introduction

"Prevention is better than cure", and one way to tackle the problem of healthcare is through development of cost efficient electronic gadgets capable of accurate diagnosis. The problems bio-medical electronic design has posed in front of engineers have resulted in overall development of electronics and development of reliable instruments for diagnosis and patient monitoring.

Today the Medical Electronics market is divided in three categories:

1. Home Diagnostics
2. Imaging
3. Diagnostics and Therapy

The table below shows the medical electronics market forecast done by Databeans:

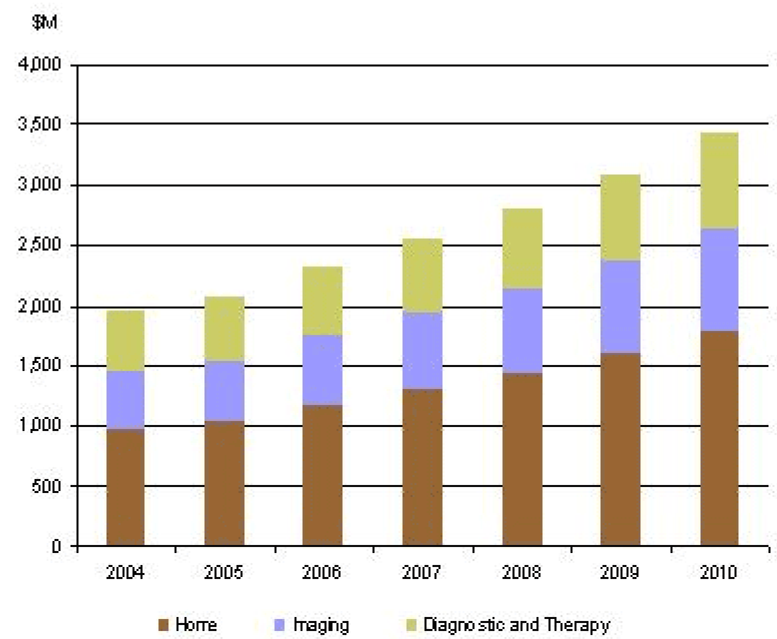

Figure1.1: Global Semiconductor Revenue Forecast by Medical Market Segment[1]

As can be seen from the forecast the trend in the coming years will be proliferation of portable medical electronics equipment capable of household use. And accordingly medical electronics is advancing rapidly with the goal of improving patient care.

1.2 The Future Of Medical Electronics

With the advancement of medical electronics healthcare is going personal and here is a preview of where all this is headed:

- Bathroom fixtures with embedded devices that can detect potential problems, such as a toilet that analyzes urine to identify kidney infection or progression of chronic condition such as diabetes and hypertension. Another example is a bathroom-scale which determines sudden change in weight or body fat. These devices could directly upload data to patients' physician and schedule appointments according to physician's predetermined criteria.[2]
- Connected diagnostic devices such as retinal scanners could be coupled with patients' existing consumer electronics products, such as digital cameras to provide digital diagnosis and treatment options and make information available to proper medical personnel. Sensors in home could measure how a person is walking to determine if he or she may be a candidate for a medical episode, such as a seizure. This is another example of how healthcare can be preventative and move deeper into the home without significant tradeoffs in quality of care.[2]
- Portable blood pressure monitors could be manufactured as accessories to popular consumer devices like iPods, these devices using internet connectivity of the parent devices could alarm the user's physician if some discrepancies are found in the measurements.

These advances will make healthcare more user friendly and patient centric and someday soon technology will be able to predict our diseases, manage our chronic diseases and help us live our life to the fullest.

2. Blood Pressure Monitoring

2.1 Introduction

Blood pressure (BP) is the pressure exerted by circulating blood on the walls of blood vessels, and is one of the principal vital signs for keeping track of human health. During each heartbeat, BP varies between a maximum (systolic) and a minimum (diastolic) pressure. The mean BP decreases as the circulating blood moves away from the heart through arteries, and hence the point of measurement of BP is important.

The techniques used to measure blood pressure are broadly classified as

- Invasive BP monitoring techniques
- Non-Invasive BP monitoring techniques

Invasive BP monitoring techniques are far more accurate than the non-invasive ones but invasive procedures are more complex to setup and hence only non-invasive techniques are used in portable household BP monitors.

Figure below lists the non-invasive techniques of BP measurement.

Method	Non-invasive Principle
Palpatory (Riva-Rocci)	Palpable pulse when cuff pressure equals systolic pressure (SP).
Auscultatory	Based on sound waves generated from artery
Ultrasonic	Based on frequency difference between transmitted and reflected ultrasound wave when passed through arteries
Tonometry	When the blood vessel is partly collapsed, the surrounding pressure equals the artery pressure. Measured using an array of pressure sensors and the cuff is around the wrist.
Oscillometric (Popular and widely used)	The intra-arterial pulsation is transmitted via cuff to transducer (e.g. piezo-electric). SP and DP are estimated from the amplitudes of the oscillation by using a (proprietary) empirical algorithm. Oscillometric method is quite popular and it is used in almost all portable blood pressure monitors. this application note is also based on this method

Figure2.1: Non-Invasive Techniques of BP Measurement

Oscillometric method is the most popular and widely used non-invasive technique of blood pressure measurement. This is because it is more suitable for automation as compared to auscultatory method, it is more accurate than the Palpatory method and cheap as compared to Ultrasoinc and Tonometry.

2.2 Oscillometric Method

In Oscillometric method the blood pressure is judged through establishing relationships between the Systolic pressure, Diastolic pressure and the Sleevelet pressure because there is steady relativity between pulse pressure wave and blood pressure.[3]

Following are the steps in which Oscillometric blood pressure measurement is made:

- A cuff is worn around the upper arm and it is inflated beyond the typical systolic pressure. There are various algorithms to determine the maximum inflation pressure, maximum pressure should not exceed the levels set by AAMI standards for safety reasons.
- The cuff is then deflated .The pressure starts decreasing ,resulting in blood flow through artery which makes artery to pulsate.
- The pressure measured on the device at the time of onset of pulsations defines the systolic blood pressure.
- Then the cuff pressure is reduced further. The oscillations will become increasingly significant, until they reach maximum amplitude.
- The pressure at the maximum amplitude of these oscillations is the average blood pressure.
- The oscillations will start decreasing as the cuff pressure reduces. The pressure at this point will define the minimal blood pressure or diastolic blood pressure.

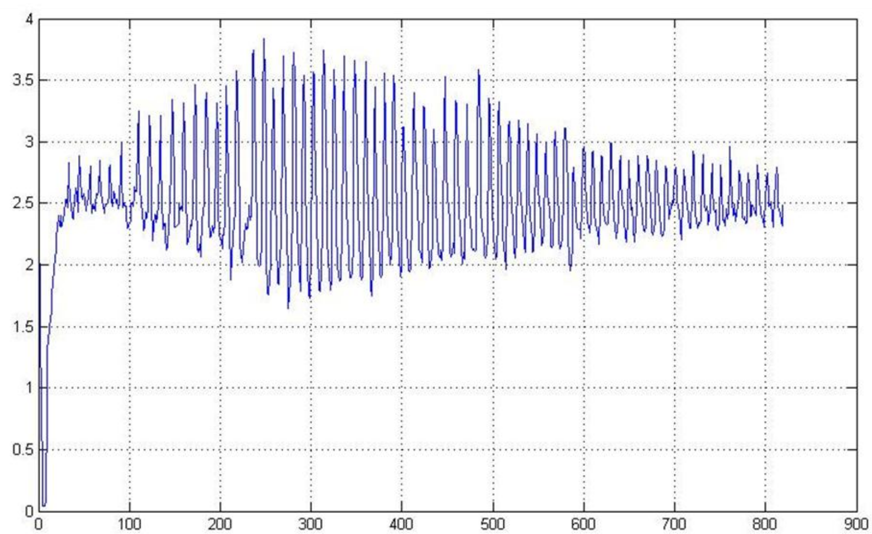

Figure2.2: The Oscillation wave

2.3 The Hardware

Figure below shows the block diagram of the portable blood pressure monitor:

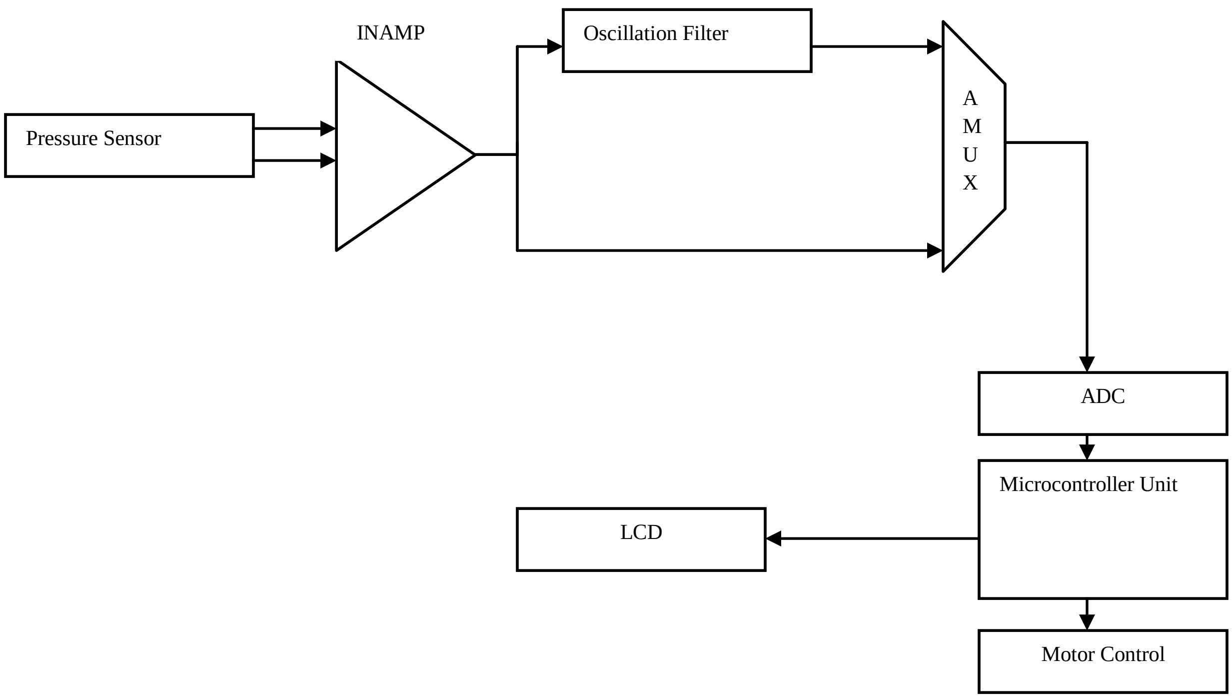

Figure2.3: Block Diagram of BP Monitor

2.3.1 Pressure Sensor

A variety of pressure transducers are available for medical purposes, the transducers to be used for blood pressure measurement should have the following characteristics:

- Should be linear within pressures from 0mmHG(0 Kpa) to 300mmHg (40 Kpa).
- Should be gage type because blood pressure is measured with respect to atmospheric pressure.

The pressure sensor chosen for our application is Freescale's MPX2053. It is ratiometric and gives differential output with maximum measurable pressure range of 50Kpa. It has a transfer characteristic of (20mV/50Kpa) 0.4mv for every 1 Kpa change in pressure or 53µV per mmHG with Vs=5V shown in the following figure:

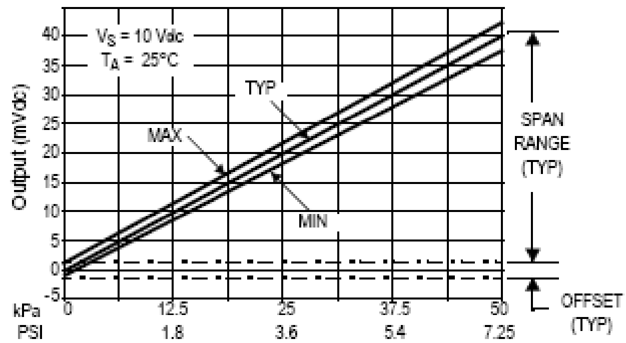

Figure2.4: Output versus Pressure Differential[4]

2.3.2 Instrumentation Amplifier

Instrumentation amplifier is a differential amplifier; it amplifies the differential signal applied at its inputs and blocks the common mode signal. Instrumentation amplifiers have very large CMRR and are easy to setup.

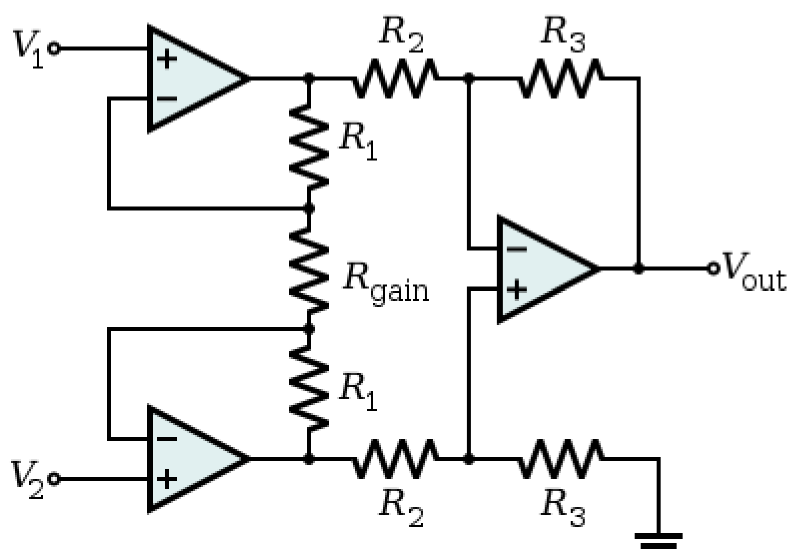

Figure2.5: Instrumentation Amplifier[5]

The transfer function of the Instrumentation amplifier shown in Figure2.4 is as given below:

$$\frac{Vout}{V2 - V1} = (1 + \frac{2 \times R1}{Rgain}) \times \frac{R3}{R2}$$

2.3.3 Oscillation Filter

As can be seen from Figure2.1 the pulse oscillation ride on a DC signal, we use the oscillation filter to remove the DC component from the oscillations. Oscillation filters can be constructed in many ways, so these filters have to be analyzed and the most suitable filter is to be used.

Circuit1[6]:

The circuit in the Figure2.5 is a 2-pole high pass filter designed to block the DC signal before amplification of the oscillation signal.

The filter consists of two RC networks that determine 2 cutoff frequencies:

$$f_1 = \frac{1}{2\pi R_1\, C_1}$$

$$f_2 = \frac{1}{2\pi R_3\, C_2}$$

The cutoff frequencies are chosen so that the oscillations are not distorted or lost.

The transfer function of the circuit is

$$\frac{V_o}{V_i} = \frac{R_3 C_2 s}{R_3 C_2 s + 1} \times \frac{(R_1 + R_2) C_1 s + 1}{R_1 C_1 s + 1}$$

The frequency response of the circuit is shown in Figure2.6 [refer Appendix for the Matlab script for analyzing the transfer function and simulation using NI Multisim].

The frequency range of interest is from 1-15Hz and as seen from the bode plot, phase response is almost linear in that frequency range so that there is no distortion. Also since the circuit amplifies all the Oscillation frequencies we need a low pass filter stage after the circuit to attenuate the gain for frequencies greater than 15Hz.

The Oscillation amplifier in Figure2.5 can be easily constructed using an Opamps IC and a few passive components but it is difficult to construct using only internal PSoC1 blocks.

Hence we require another circuit which can be easily integrated in PSoC1 without using external active components. Circuit2 solves our problems.

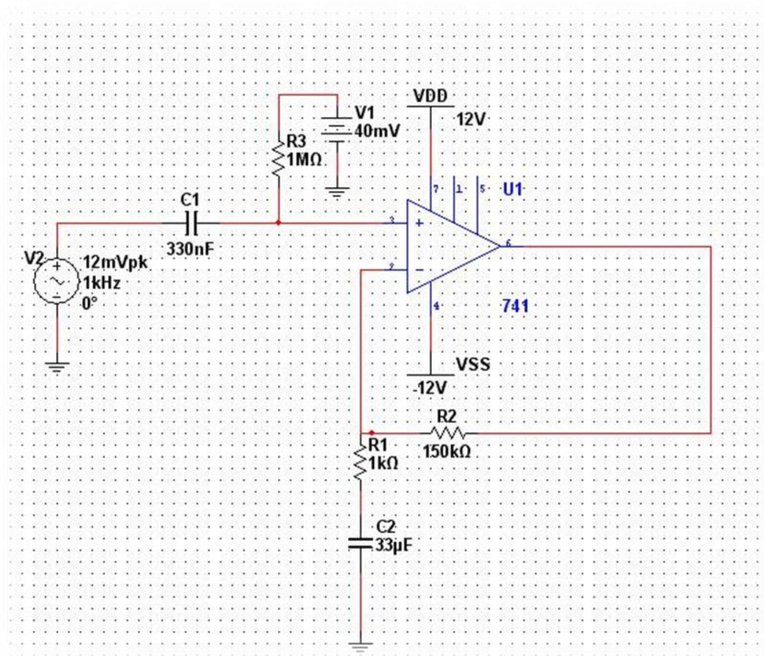

Figure2.6: Oscillation Amplifier Circuit1

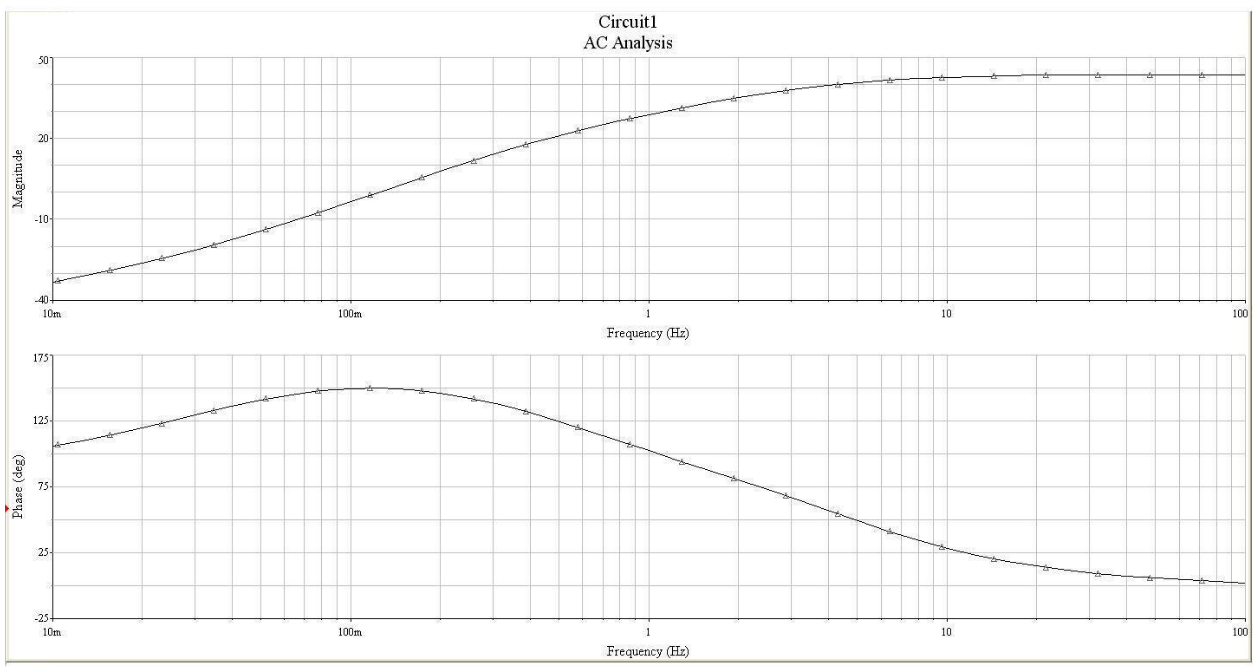

Figure2.7: AC Sweep Analysis of Circuit1

Circuit2[7]:

Figure2.7 shows another high gain oscillation amplifier, this topology of an oscillation amplifier is used to amplify small AC signals riding on DC component.

The transfer function of the circuit is:

$$K(s) = -\frac{a_2 s^2 + a_1 s}{b_2 s^2 + b_1 s + b_0}.k$$

Where,

$$a_2 = C_1C_2(R_2R_3 + R_2R_4 + R_3R_4)a_1 = C_1(R_2 + R_3)b_2$$
$$= C_1C_2R_3(R_1 + R_2) + C_1C_2R_4(R_1 + R_2 + R_3 + kR_1)b_1$$
$$= C_1(R_1 + R_2 + R_3) + C_2R_3 + KC_1R_1 + (1 + k)C_2R_4b_0 = k + 1$$

The transfer function of the circuit describes a combination of high pass filter and low pass filter for the same roll off frequency ω_r.

$$\omega_r^2 = \frac{b_0}{b_2}$$

For the circuit to be stable the roll off frequency should not be increased beyond 1-2 kHz.

As can be seen from the Figure2.7 this circuit uses 2 Opamps, 1 more as compared to Circuit1 but from the frequency response of the circuit it can be seen that we can achieve greater amplification at the desired 1-4 Hz frequency range as compared to other frequencies and Circuit2 can be easily constructed using internal PSoC blocks.

The frequency response of the amplifier calculated using NI Multisim simulation software is shown in Figure2.8. Refer appendix B for Matlab script to obtain the frequency respsonse of the circuit.

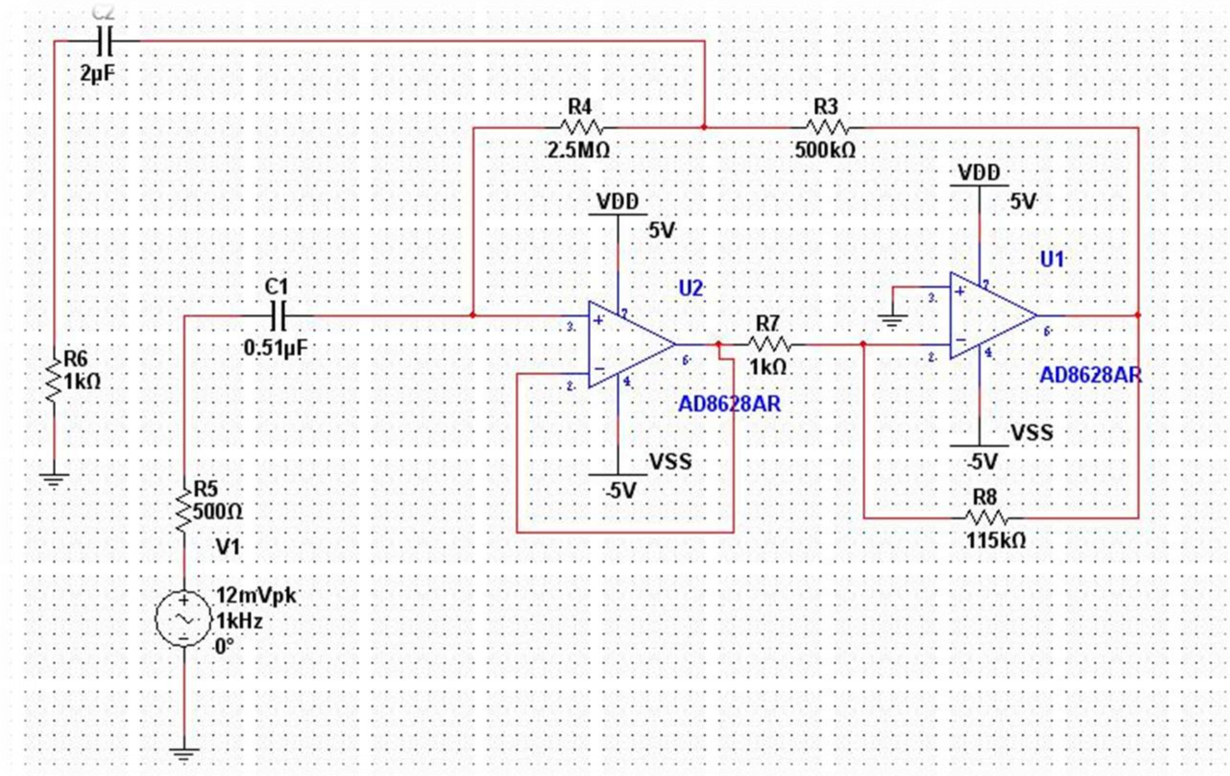

Figure2.8: High Gain Oscillation Amplifier Circuit2

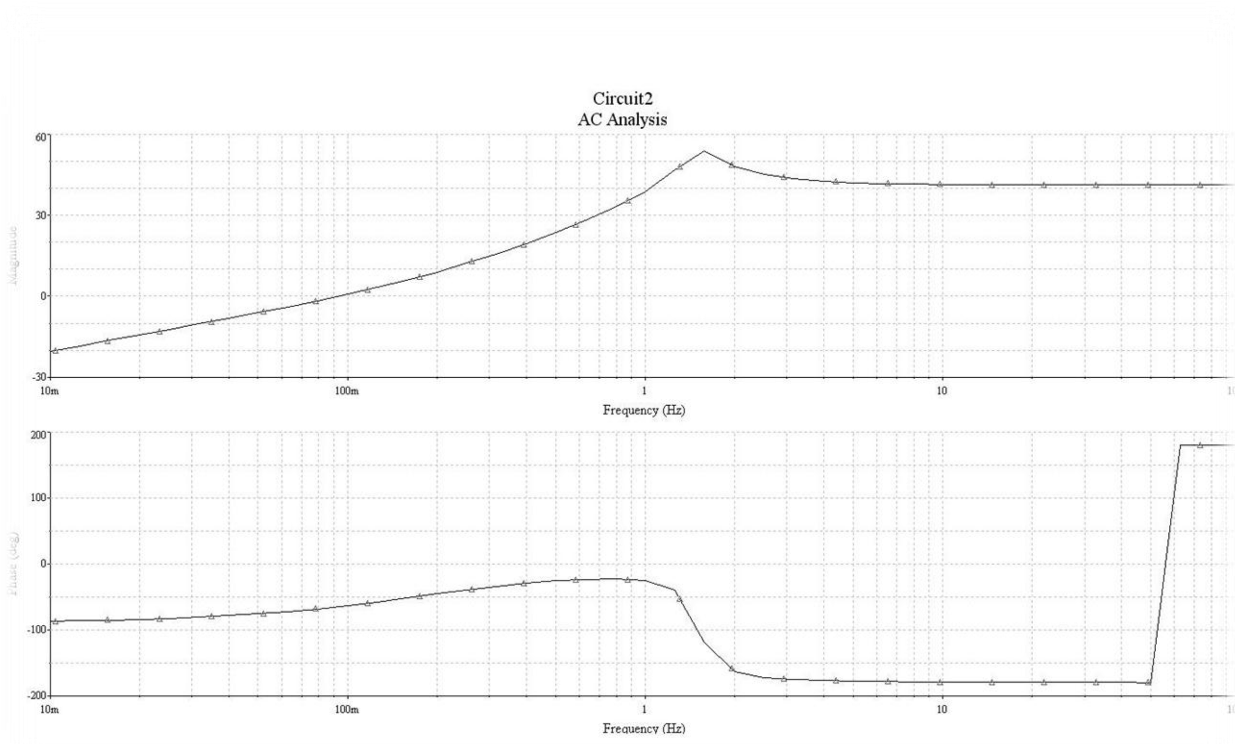

Figure2.9: AC Sweep Analysis of Circuit2

2.3.4 Low Pass Filter

The Low pass filter is used so that only the frequencies of interest i.e. 1-20Hz are passed through to the ADC unattenuated.

The PSoC switched capacitor LPF2 module is used for this purpose, we can also use the sallen key topology but it would require external amplifiers hence its use is not considered.

The LPF2 user module is a 2-pole low pass filter whose parameters can be adjusted by varying the values of capacitors connected to the module.

Figure2.9 shows the topology of the LPF2 user module,

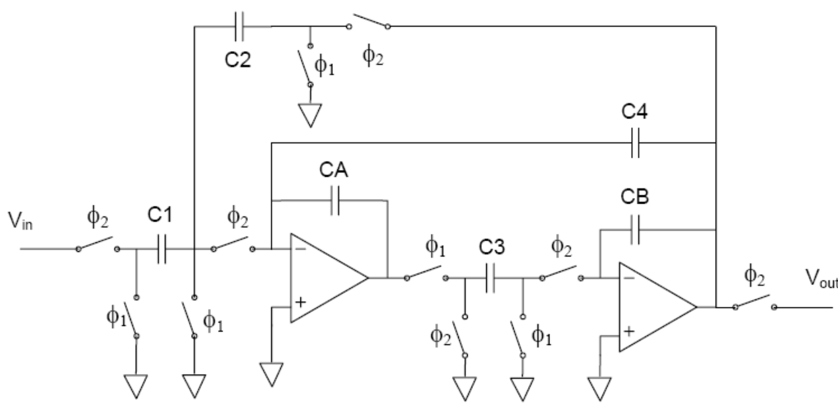

Figure2.10: PSoC1 LPF2 Topology

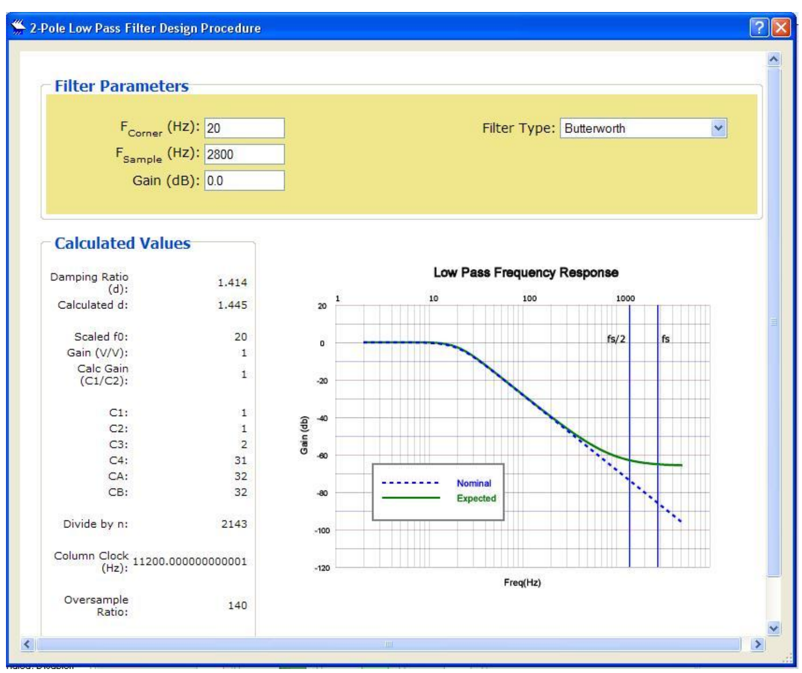

Figure2.11: LPF2 Configuration Wizard

2.3.5 Analog Multiplexer and The ADC

The analog multiplexer is used to switch between the pressure signal and the oscillation signal, which is then converted into digital domain by the ADC to be further processed by the microcontroller unit. In PSoC ADC is inbuilt and we do not need to worry about interfacing an external ADC.

The Figure2.11 shows the plot of Oscillation pulses with time, it can be seen here that even though the signal has passed through a filter stage considerable amount of noise is present, and this noise can result in miscalculation of SP and DP. The noise is clearly seen in Figure2.12.

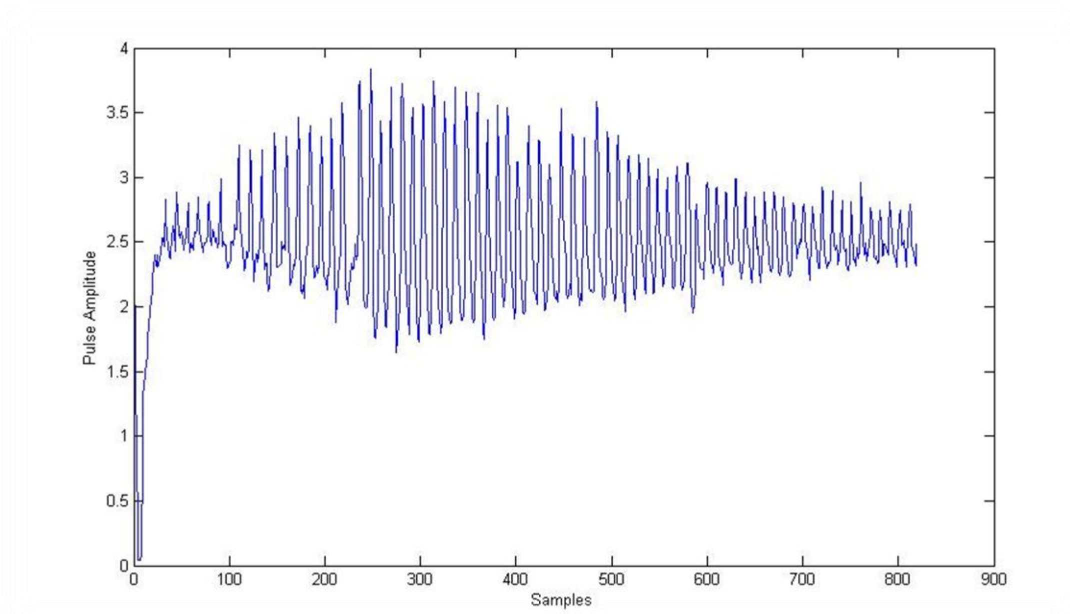

Figure2.12: Oscillation Pulses

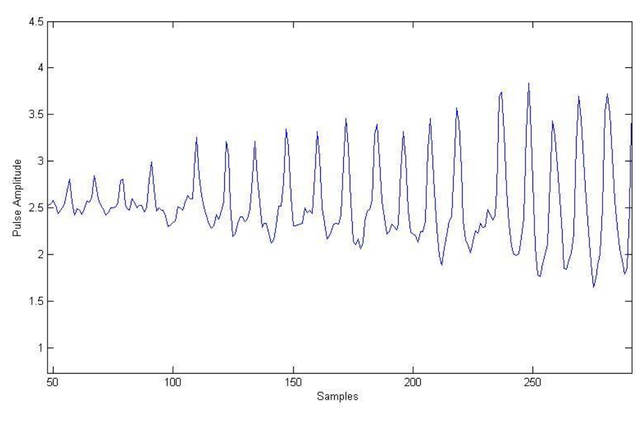

Figure2.13: Noise in The Oscillation Pulses

This noise has to be removed, and for this purpose we have to filter the signal in digital domain. The disruptions are caused mostly by 1/f noise [8] and for this purpose we use a low pass filter, a single pole low pass filter is enough to remove the noise as was seen in the simulations.

The topology of the low pas IIR filter is shown below:

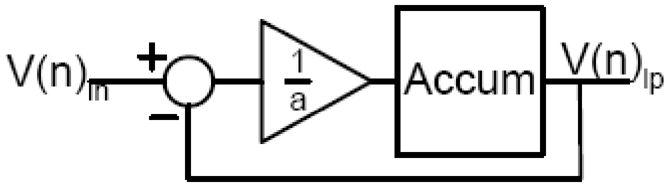

Figure2.14: IIR Low Pass Filter[8]

The transfer function of the filter is

$$\frac{V(n)_{lp}}{V(n)_{in}} = \frac{1}{1 + a(z - 1)}$$

And the roll off frequency is given by

$$f_0 = \frac{f_s}{2\pi a}$$

Where f_s is the sampling frequency and a is the attenuation value.

The ADC data after being operated upon by the IIR filter of the above equation is as shown in the Figure .The matlab script to simulate the IIR Low pass filter is given in the Appendix

It can be clearly seen from the figure that all the high frequency noise has been removed and the waveform data is smooth and ready to be processed further for determining SP and BP. It should be noted here that the data is to be stored in memory for processing as we require the complete data for calculation of blood pressure, we can also preprocess the data before going to the next algorithm stage so that only the values required [i.e the local maximas] to calculate BP are stored and other values are omitted, the firmware takes care of this [it should be noted that this technique has not been tested by us yet].

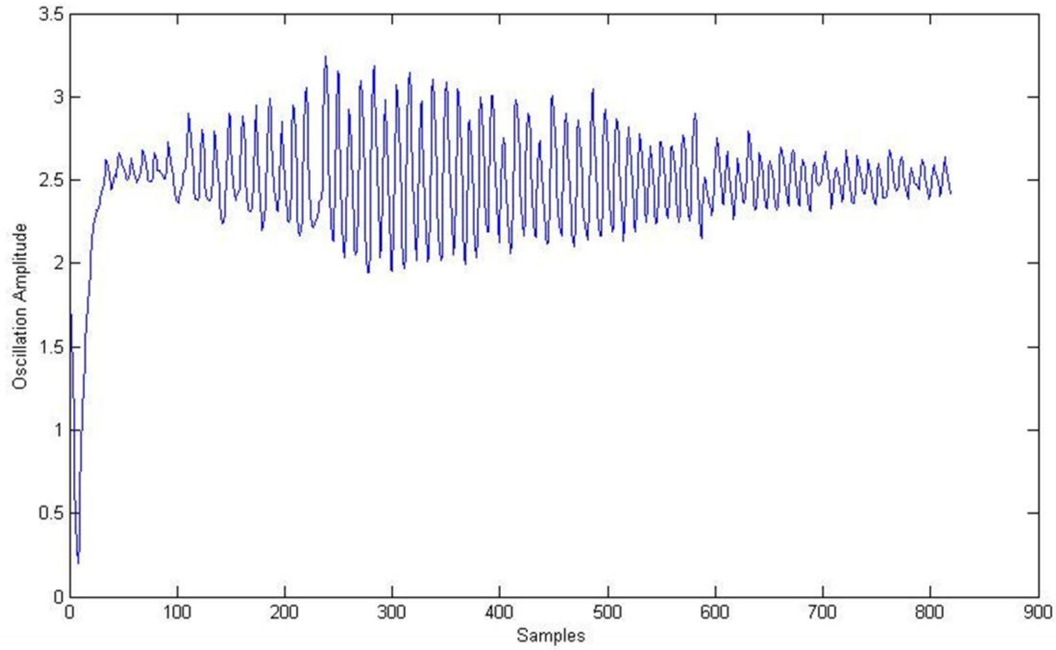

Figure2.15: Filtered Oscillations

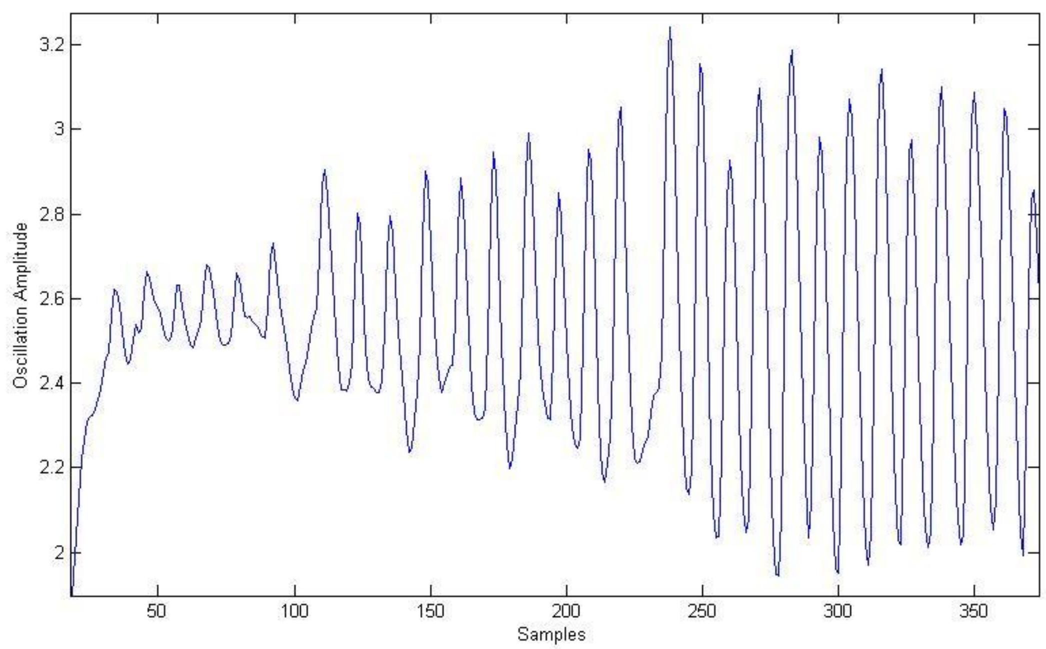

Figure2.16: Zoomed View of Filtered Oscillations

As compared to Figure2.12, the Oscillation wave in Figure2.15 is free of noise.

2.4 The Algorithm

For the data obtained from pulse oscillations, there are two types of approaches to calculate the SP and DP,

1. The height approach
2. The slope approach

In the approach by height the systolic and diastolic pressure values are calculated as fractions of envelope curve with respect to the maximum value. Some authors have proposed to take the values of 40% and 60% for the evaluation of SP and DP respectively but, the idea is strongly opposed because of the wide set of factors affecting the oscillation amplitude including the cuff, the pneumatics.

In approach by slope criterion of maximum and minimum index pulse change value is used, though the method may seem foolproof there is a catch; pulse oscillations are different for different people and sometimes peaks may appear two times which may affect the calculation of SP and DP.

To overcome these problems a new approach combining the above two approaches was developed[9], according to studies the ratio of pulse amplitude corresponding to SP and DP and the biggest amplitude has a regularity for SP the ratio lies between 0.4-0.7 and for DP it lies between 0.4-0.8; taking these facts into account the new algorithm was developed and its flowchart is as given in the Figure2.16

In Figure2.16

d = peak[i] – peak[i-1]

rd = (peak[i] – peak[i-1]) / peak[i-1]

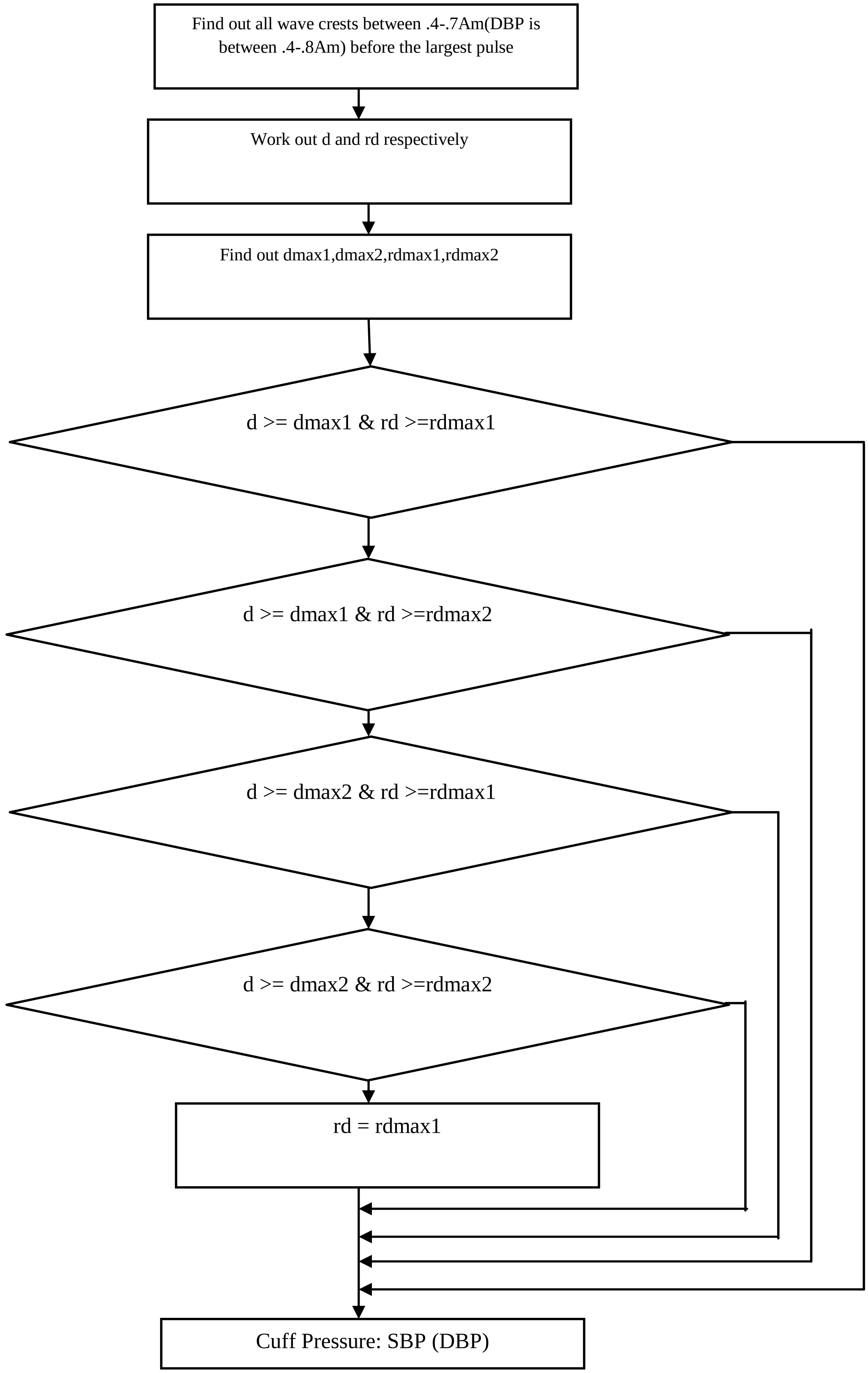

Figure2.17: Algorithm to Calculate Blood Pressure[9]

The algorithm requires only the crests or the local maxima from the oscillation pulses to find the systolic and diastolic pressure as can be seen from Figure2.16.

The flowchart in Figure2.17 expounds the algorithm used to find out the peaks from the oscillation pulses.

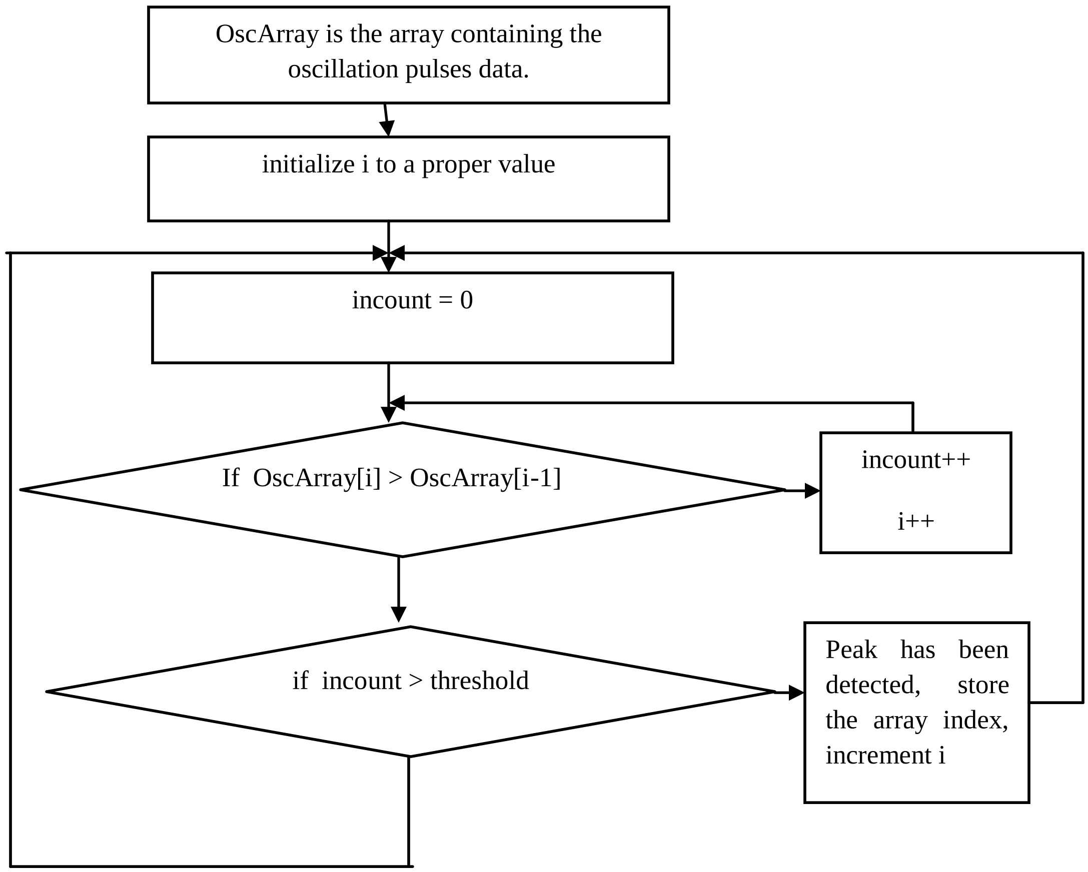

Figure2.18: Algorithm To Find The Peaks

The threshold should be set to an appropriate value depending on the sampling rate, the threshold value and the sampling rate determine the cutoff frequency of a low pass filter, all the frequencies falling above the cutoff are not considered for determining the peaks.

Threshold = ***t***

Sampling rate = ***n*** sps

Cutoff frequency = 4*(***n/t***)

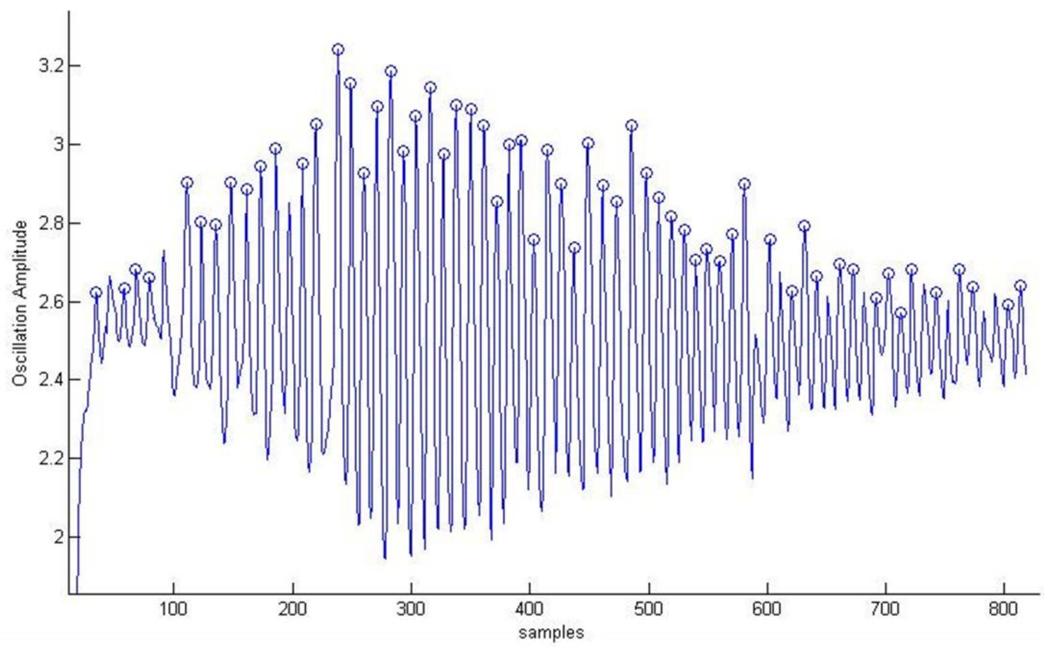

Figure2.19: The Peaks in The Pulse Oscillation Wave

As can be seen from the Figure2.18 peaks are efficiently detected by the above algorithm.

After finding the array containing the peaks, we can use the algorithm expounded in Figure2.16 to find the systolic and diastolic pressure. The algorithm can easily be implemented in C or assembly language.

3. BP Monitor: PSoC Implementation

3.1 Introduction To PSoC

PSoC is a device with built in flash memory and SRAM, the PSoC1 core is a powerful core that supports a rich feature set.

There are essential system resources that include:

- Sleep timers and watchdog timers that are hard coded into the PSoC. They are easy to hook up and can be disabled. Over 90% of designs will use a watchdog timer, so a hard coded watchdog timer is provided to save space and time.
- PSoC includes multiple clock sources that include a Phase Lock Loop. The clock sources can be set up to operate anywhere from 24MHz down to 9.3 KHz. To go even lower, an internal digital block can be used.

There are a very large number of clocking combinations available with PSoC.

- Two Internal oscillators can be accessed: main and low-speed. The low-speed oscillator is used primarily for sleep mode; the main oscillator for normal operation. External systems can access this internal PSoC oscillator by assigning one block and pin on the PSoC. This can save on component cost, labor, and footprint space. (Just in case someone asks you, the internal oscillator on the M8 core PSoC is accurate to 2.5% at a 5 supply voltage, without the use of an external PLL, or Phase Lock Loop. There is a dedicated location for connecting a PLL to the PSoC internal oscillator.)
- For greater precision, an external crystal oscillator can be attached to one pin. An external oscillator will also provide clock programmability.

PSoC devices can be configured to have up to two MACs (Multiply-and-Accumulate). This is helpful for creating a faster computation system, especially useful for applications with a DSP (digital signal processor.) PSoC devices can have up to 2 decimators for DSP applications. PSoC can implement I2C communications for slave or master functionality. And a full-speed USB 2.0 compliant interface is also integrated into select PSoC devices.

Configurable Analog and Digital Blocks*:* Using configurable analog and digital blocks, designers can create and quickly change advanced mixed-signal embedded applications. The digital blocks are 8-bit resources that designers can configure using pre-built digital functions or, by combining blocks, turn into 16-, 24-, or even 32-bit resources. The analog blocks are composed of an op-amp circuit, allowing complex analog signal flows.

3.2 Implementation

1. Instrumentation Amplifier: The output from the pressure sensor is in the order of few mV so we use a 3 Opamp Topology Instrumentation amplifier to amplify the incoming signal, the overall gain selected for this amplifier is 93.
2. Fliter: The output of the pressure sensor consists of two signals, the cuff pressure signal and the pulse oscillation signal riding on it, the oscillation signal has frequency components from 0.3-20Hz, a 2 stage filter is used to filter out this oscillation signal.
   - Stage1 consists of the filter described in Circuit2, section 2.3.3
   - Stage2 consists of 2 pole LPF implemented inside PSoC using the switched capacitor blocks, its cutoff is set to 40Hz.
3. Multipexer and A-D Conversion: The amplifier and the filter signal are muxed inside PSoC using the Analog multiplexer, it selects 1 of the signals to be routed to the 13bit incremental ADC, which works at 60sps.
4. Display: The display used is a 16x2 character LCD with built in controller. We can also use a segment LCD if Emerald family of PSoC1 is used, but the functionality of BP monitor + Segment LCD driving has not been tested on it yet.

4. LabVIEW VI to Capture Data

4.1 About LabVIEW

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine the order of program execution, LabVIEW uses dataflow programming, where the flow of data through the nodes on the block diagram determines the execution order of the VIs and functions. VIs, or virtual instruments, are LabVIEW programs that imitate physical instruments.

We have created a LabVIEW Virtual Instrument to capture the Data generated by our BP monitoring apparatus and then process it on the computer, it also stores the data in an excel sheet, so that it can be used later as well.

4.2 The VI

Figure 4.1 represents the front panel of the VI and Figure 4.2 gives us the block diagram. We have used RS232 cable to establish a connection between our MCU and the PC for the purpose of data transfer.

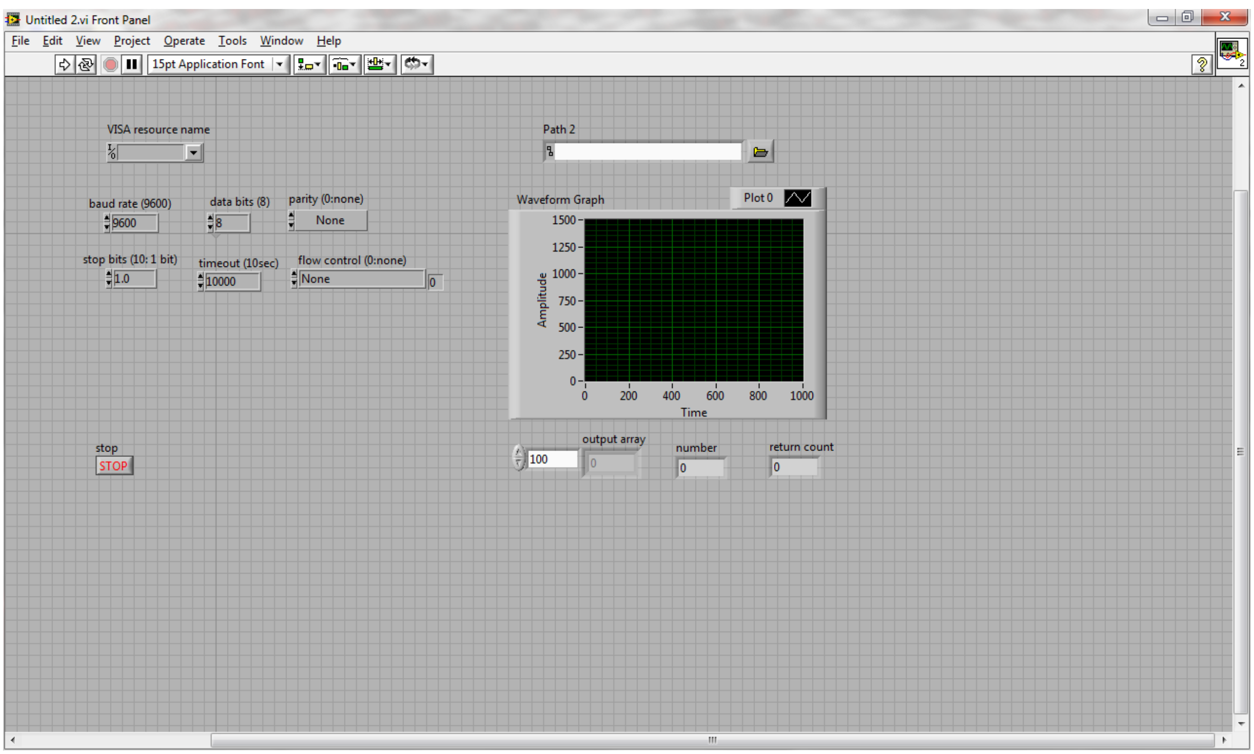

Figure4.1: The Front Panel

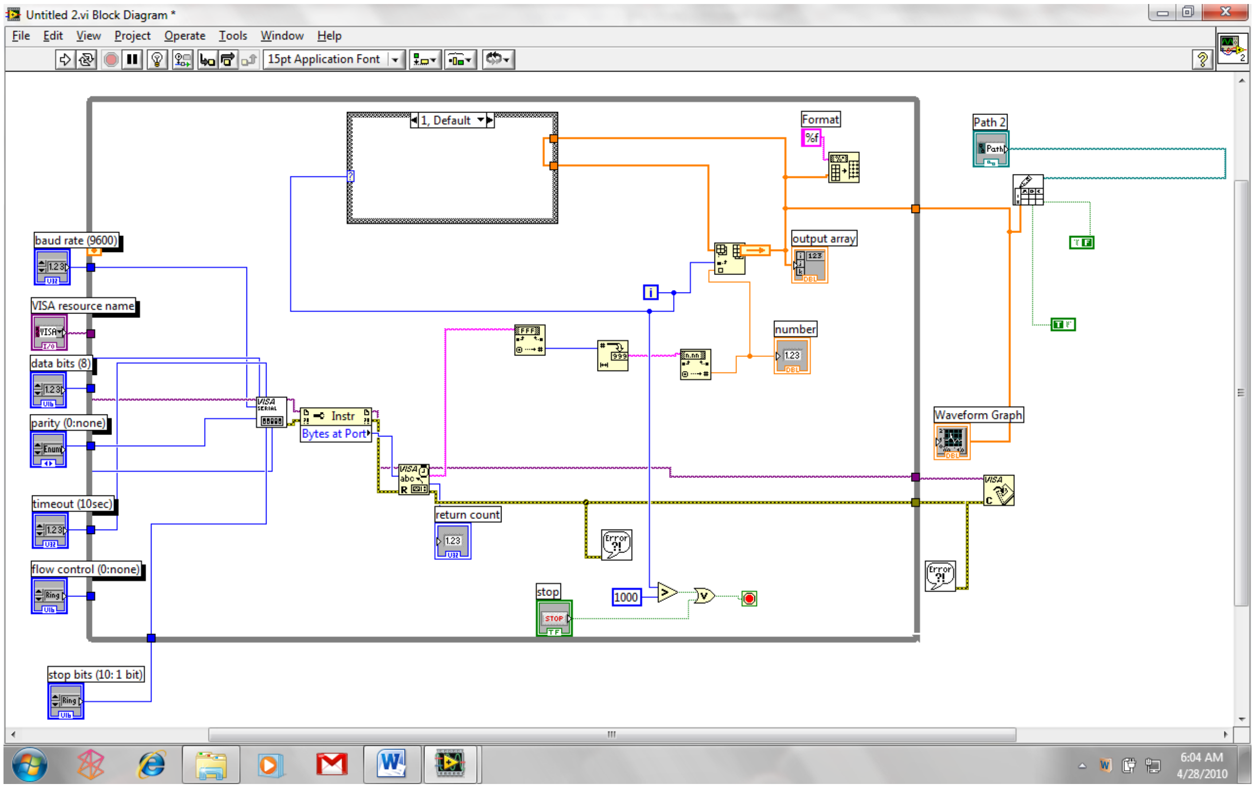

Figure4.2: The Block Diagram

5. Future Work

Medical Electronics is a developing field and new innovations can always be brought about in the existing products. As far as the device we have developed is concerned, we haven't used the analog filtering mentioned in the report due to financial constraints, but instead we use digital filters in Matlab, the resolution of ADC is not enough and hence we don't get accurate enough readings, so as a future development we can use the analog filters. Further work can also be done to improve the algorithms and make them suitable to be used in the microcontrollers.

6. Conclusion

Medical electronics is a challenging and a very interesting field. Our work in developing the BP monitor required development of skills in different domains and we gained lot of knowledge in the process.

The work we did was really challenging and very fulfilling.

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APPENDIX A

The matlab script to plot the frequency response of circuit1 is given below:

```
r1 = 1000;

r2 = 150000;

r3 = 10^6;

c2 = 330*(10^(-9));

c1 = 33*(10^(-6));

n1 = [r3*c2 0];

d1 = [r3*c2 1];

n2 = [(r1+r2)*c1 1];

d2 = [r1*c1 1];

n = conv(n1,n2);

d = conv(d1,d2);

sys = tf(n,d);

bode(sys);
```

APPENDIX B

The Matlab script to plot the frequency response of circuit2 is given below:

```
r1 = 500;

r2 = 2.5*(10^6);

r3 = 500000;

r4 = 1000;

c1 = 2*(10^(-6));

c2 = 0.5*(10^(-6));

k = 115;

a2 = c1*c2*(r2*r3 + r2*r4 + r3*r4);

a1 = c1*(r2 + r3);

b2 = c1*c2*c3*(r1 + r2) + c1*c2*r4*(r1 + r2 + r3 + k*r4);

b1 = c1*(r1 + r2 + r3) + c2*r3 + k*c1*r1 + (1 + k)*c2*r4;

b0 = k + 1;

n = [-a2 -a1 0]*k;

d = [b2 b1 b0];

sys = tf(n,d);

bode(sys);
```

APPENDIX C

The Matlab script to implement a first order iir filter is given below:

```
input('Enter the name of csv file: ',"s");

array=csvread(ans);

i = 1;

accum = 0;

a = 2;

while(i<length(array))
	tmp = (array(i,1)-accum)/a;

	accum = accum + tmp;

	outarray(i) = accum;

	i = i + 1;
end

plot(outarray);
```

To get a second order filter all we need to do is call the script twice and pass the output of the first run as the input to the second run.

APPENDIX D

The Matlab script to find the peaks is given below:

```
IncCount = 0;
LMxCount = LMxCount + 1;
else
IncCount = 0;
end
DecCount = DecCount+1;
end
i = i+1;
end
LocMaxArray = LocMaxima1;
%plotting
hold off
%subplot(3,1,1)
plot(array(:,1))
%subplot(3,1,2)
hold on
stem(LocMaxima1,"1")
%subplot(3,1,3)
%stem(LocMinima1)
% algo to find peaks
clear
clc
input('Enter the name of csv file: ',"s");
array=csvread(ans);
%find local Maxima and Minima
i= 1;
LMxCount = 1;
LMnCount = 1;
IncCount = 0;
DecCount = 0;
while(i+1<rows(array))
pData = array(i,1);
pData1 = array(i+1,1);
if(pData1>pData)
%IncCount = IncCount+1;
if(DecCount > 3)
LocMinima(LMnCount) = pData ;
LocMinima1(i) = pData;
DecCount = 0;
LMnCount = LMnCount + 1;
else
DecCount = 0;
end
IncCount = IncCount+1;
end
if(pData1<pData)
%DecCount = DecCount+1;
if(IncCount > 3)
LocMaxima(LMxCount) = pData;
LocMaxima1(i) = pData;
```