EE 4951 Senior Design (Fall 2012)

Infrared Sensor Based Measurement System for Continuous Blood Pressure Monitoring

University of Minnesota

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1.0 Phoenix Senior Design project Background

1.1 Abstract

The phoenix project is in the midst of developing an ambulatory blood pressure monitor which is inexpensive, non-invasive and easy to use. This device should be able to monitor blood pressure for a week without interfering with the comfort and lifestyle of the patient. The BP monitor should also be wearable in all places that someone could be during that week. The device should continue to monitor the patient's blood pressure (BP) and record data throughout that week. The product will take measurements from separate locations of the body at different distances from the heart. In addition, data collected during that week should give doctors and other healthcare professionals useful information about the overall health of the patient. Furthermore, when this non-intrusive technique becomes widely available in the market, it will be an excellent substitute for the current BP monitoring devices. The phoenix group is a non-profit subgroup of the IEEE organization. Its goal is to develop an inexpensive, non-invasive BP monitoring device for university of Minnesota's Halberg Chronobiology center.

1.2 Background and history

Blood pressure is an important indicator of the fundamental signs of someone's overall health. The measurement of blood pressure is vital to the medical community and the health of general public. Historically, the first blood pressure measurement was done by Reverend Stephan Hales [4], who performed the procedure on a horse. He conducted the experiment by inserting water filled glass tube into the horse's arteries and compared it to the height of a column of fluid. This proved very important as it triggered a number of other experiments done by several pioneers in the following 150 years. In 1901 a Dutch physiologist Willem Eitnthoven invented the electrocardiogram (ECG) to measure heartbeats, and in 1924 he was awarded the Nobel Prize in Medicine for his work. He concluded that after each heartbeat, the cardiac tissue releases ions that depolarize the tissue. The process creates a voltage of about 1 mV that can be measured with different leads connected to the body. In spite of that cumulative effort, it wasn't until 1969 that the first automated intra-arterial blood pressure report was received from ambulant man [4]. The next four decades saw a lot of work to improve the measurement of blood pressure, and several techniques were theorized by numerous researchers in the field.

There are a number of different methods for blood pressure measurement. However, these techniques fall into two main procedures of measuring blood pressure. The first one is direct measurement also called invasive method, and the second one is indirect measurement which is called non-invasive. The direct invasive technique involves surgically inserting BP measurement device into artery; this technique is used mainly in hospitals to give an accurate uninterrupted measurement to use for the diagnosis of patients vascular situation. The common non-invasive method doesn't involve any puncturing of body parts, but rather uses cuff over arm containing the artery. This classical non-invasive method doesn't hurt the patient but it is less accurate than direct invasive method. The cuff over arm method depends on inflation by a healthcare professional or the patient, and recordings of BP are confined to those instants the procedure is done. For that, it doesn't give a continuous measurements which truly reflects the patients overall system performance.

This project falls into the second method of non-invasive BP measurement. However, instead of using cuff over arm, we use infrared sensors placed on different parts of the body to collect signals that will then be used as a reference to measure BP. The monitor process is continuous, and is supposed to collect data over a long period of time. As a consequence, our project is mainly focus on friendly, inexpensive and convenient BP method.

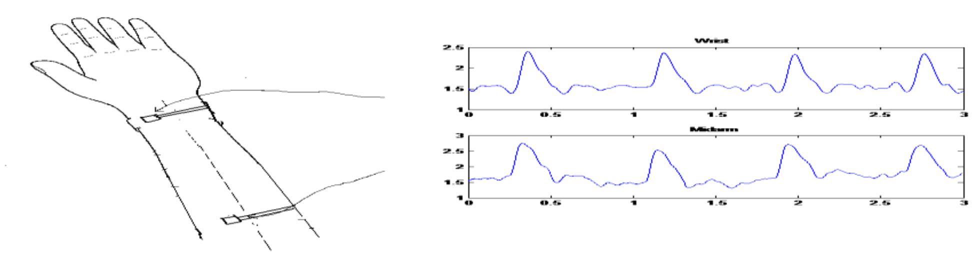


Figure 1: Pulse wave from wrist & mid-arm [1]

1.3 Medical motivation

The ambulatory blood pressure monitor is useful in a number of ways and its benefits outnumber that of traditional blood pressure monitoring done at discrete times in doctor's office or hospitals and clinics. It is useful for all people regardless of age and level of wellness. Some of these benefits include the following reference [1]:

- **Prevention of white coat hypertension**:

This type of hypertension is associated with having hypertension when someone is in the doctors' office. This occurs due to anxiety on the part of the patient. Some studies suggest that about 20 percent of patients diagnosed as having high blood pressure are misdiagnosed because they have "white coat hypertension" and as a result are prescribed drugs they don't need which could cause further unwanted side effects. Ambulatory blood pressure monitor gives doctors overall big picture of patient's blood pressure and solves this problem.

- **Diagnosis of resistant hypertension**:

Resistant hypertension is a type of hypertension that is resistant to common blood pressure drugs. It cannot be diagnosed with only single office visit because the measurement taken at the instant you are in doctor's office is not representative of your pressure for the whole day. In that sense, the ambulatory blood pressure monitor can single out this case from others, and give doctors better tool to take a well thought decision.

- **Prevention of white coat normotension**:

This means someone has low blood pressure at the instant they are in doctor's office, and the pressure rises when they leave. The ambulatory BP monitor can tell the doctor the true condition of your blood pressure and can tell the doctor if you have white coat normotension.

- **Prevention of borderline Prehypertension**:

This type is when your pressure is elevated high but not to the level of hypertension. The simple office measurement might mistakenly show a real serious hypertension as a mild borderline prehypertension. Again ambulatory BP can show some consistent measurement throughout the day and night. This can save the patient from serious conditions caused by hypertension.

1.4 Introduction

Today's medical community strives for better equipment and techniques to improve the diagnosis of a vascular disease. The type of device has to be non-invasive, portable, and perform a continuous diagnosis of the patient blood pressure for a week. The most promising solution for this type of work is using an IR sensor to measure Pulse transit time (PTT). Pulse transit time is defined as the time it takes the pressure waveform to travel through the length of arterial tree. It results from the ejection of blood from the heart through the left ventricle, and the waves propagate with a velocity that is higher than the movement of blood.

In this project we use the photoplethysmography (PPG) technology which is non-invasive method of obtaining the variations of blood in tissues. We achieved this goal using the infrared sensor, which releases light into the tissue and the reflections are collected by the detector. A PPG can be used in two modes, a reflection mode and a transmission mode. For transmission mode, light is emitted into the tissue and a detector is placed on the opposite, a good example of transmission mode is using ear lobe. For the reflection mode a light source and the detector are placed on the same side and emitted light will be reflected by a bone in the body part. A good example of reflection mode is placing the sensor on the finger tip. The intensity of reflected light depends upon the blood volume inside the finger. So, each heartbeat slightly alters the amount of reflected infrared light that can be detected by the photodiode. With a proper signal conditioning, this little change in the amplitude of the reflected light can be converted into a pulse. The values from this device are not actual heart rates. The reflected or the transmitted light both will oscillate in rhythm with the heartbeat, in other words both will give comparable results. The figure below illustrates these concepts visually.

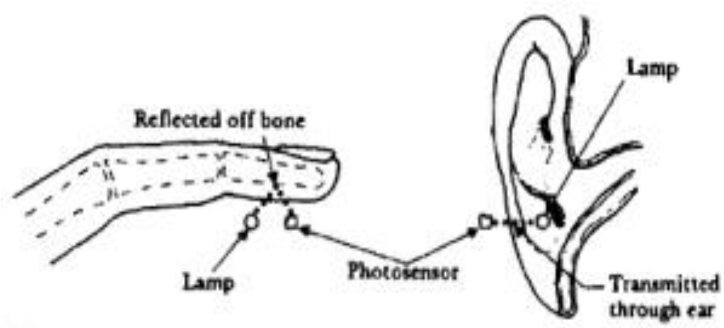


Fig. 2: The modes of reflection & transmission [1]

1.5 Previous work/problems

1.5.1 Previous work

This phoenix project (developing a prototyped system for a blood pressure monitor) was performed by two groups in the fall of 2011 and spring of 2012. The first group used magnetic sensor as a way to obtain pulse, and the second group used the TCRT1000 infrared sensor. The magnetic sensor of the first group did not attain much progress. On the other hand, the TCRT1000 together with amplifier circuit and data acquisition system showed some results. For this reason, our project is mainly based on the project of the group from Spring 2012.

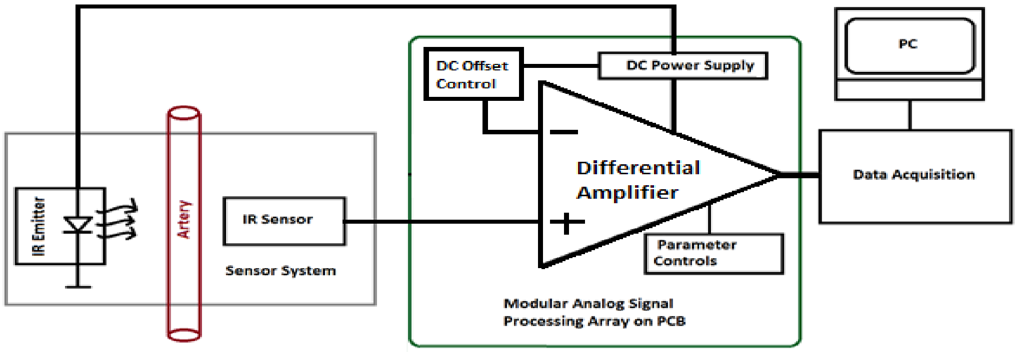


Figure 3: block diagram of spring 2012 design team [cited from spring 2012 team's figure 2-1]

The first stage was the sensor circuit. They tested several sensors to give better detection of pulse, and finally settled with the TCRT1000 sensor. The second stage was the amplifier circuit to increase the amplitude of the signal. The output of the amplifier was fed into a DAQ that performed an analog-to-digital converting and fed the data to a PC. Labview and MATLAB were then used to acquire, store, and process the data.

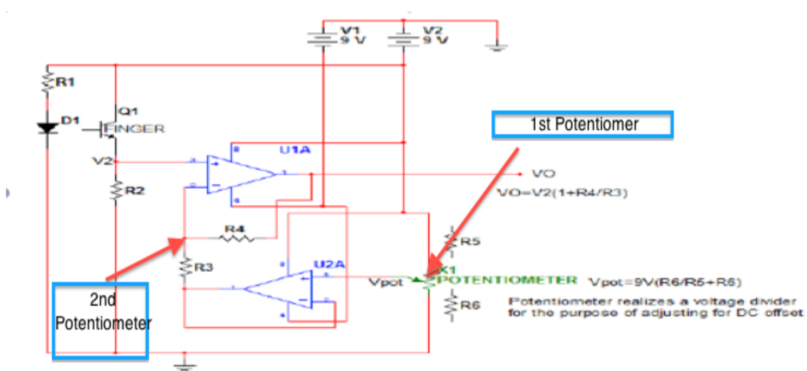


Figure 4: Previous design schematic

Figure 4 shows the schematic of one channel of last group design (the 8 channels are identical). They used two potentiometers. The first potentiometer was used for cancelling out the DC offset from the sensor. The second potentiometer was used to adjust the gain of the amplifier to ensure that no saturation occurred. In general, their project was successful, but there are still many improvements can be made which will be discussed in the following section.

1.5.2 Problems

List of improvements can be made

- Use potentiometer to adjust DC offset and gain is not acceptable in real product
- 18V (peak to peak) power supply was not an option for battery powered portable device.
- Lack of a quantitative understanding of how accurate the pulse waveforms are and whether they contain all information we need to calculate the blood pressure
- DC drift and offset before signal were fed into the DAQ.

First two problems are mainly considered for practical purpose. Since no one will buy a device that is hard to use and contain several heavy batteries. The third problem is to make sure the signal can be used in the following calculation. The fourth problem is considered to obtain clear signal stable signal that can be fed into DSP or Microcontroller for future calculation.

1.6 Client needs and objectives

- **Device that can accurately detect pulse**
- **Device must be connected between IR sensors and a newly designed circuit board, including amplifiers and filters.**
- **Rectify the previous senior design group's work.**
- **Fix DC drift**
- **Solve DC offset**
- **Solve noise problem**
- **lower down power supply**
- **Maximum design budget of $ 300**
- **The device should be safe**
- **Device must work in normal environment; handle typical pressure, room temperature, and humidity.**

In addition to the client needs, a set of design objectives were developed by the phoenix project to obtain the best possible sensor circuit. The design objectives are necessary to provide guidelines for the design of final product. These objectives include the following

- **A product that can monitor BP for a week:**

To obtain the best possible overview of person's blood pressure, the monitor should record the measurements at least every half hour for 7 days. This ensures the measurements of both systolic and diastolic pressure, and gives complete pulse waves. Furthermore, blood pressure can change from time to time; so continuous monitoring product gives a comprehensive overview of cardiovascular health.

- **Inexpensive product**:

The final product should be affordable by the average buyer to ensure healthcare improvement of average poor people around the world. The final product should be in Ball Park of 10 dollars according to phoenix project. Going from that noble cause, we tried to find the cheapest components to be used in our design. However, we made sure not to compromise cheap price for overall product quality.

- **Undisruptive BP monitor**:

The blood pressure monitor should not obstruct the patient's daily activities and not hinder their comfort. This is particularly important to make sure the patient can wear the monitor for a period of 7 days to obtain a genuine data. The phoenix project targets a product that is no more inconveniencing than a wrist- watch or similar objects.

2.0 Design approach

2.1 Design Overview

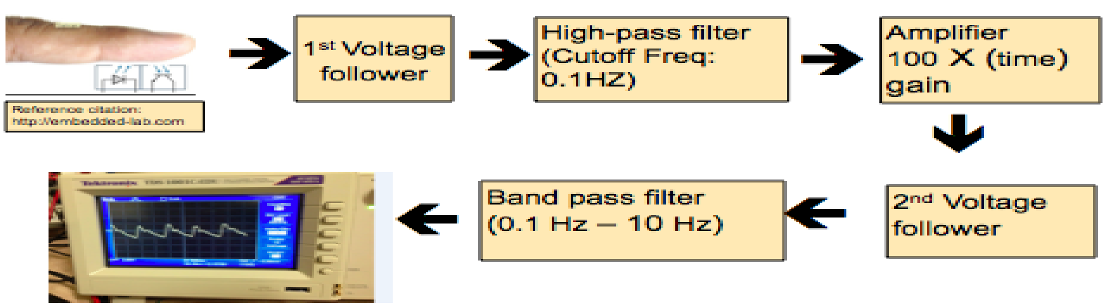


Figure 5: Block diagram for pulse detection from finger

As figure 5 demonstrates, the process starts with the LED to illuminate a person's finger with infrared wave. The light intensity changes in the finger before striking the phototransistor. The sensor then converts the changing intensity into a proportional current containing two components – a large DC signal caused by the distance between blood vessel (mainly the thickness of skin) and a small AC signal caused by the amount of blood changing in blood vessel due to the pulse. The signal is then passed through a high-pass filter to remove the DC component and then get amplified. The band-pass filtering is then applied to remove any high frequency noise before displaying the signal on an oscilloscope.

The figure 6 shows the designed circuit.

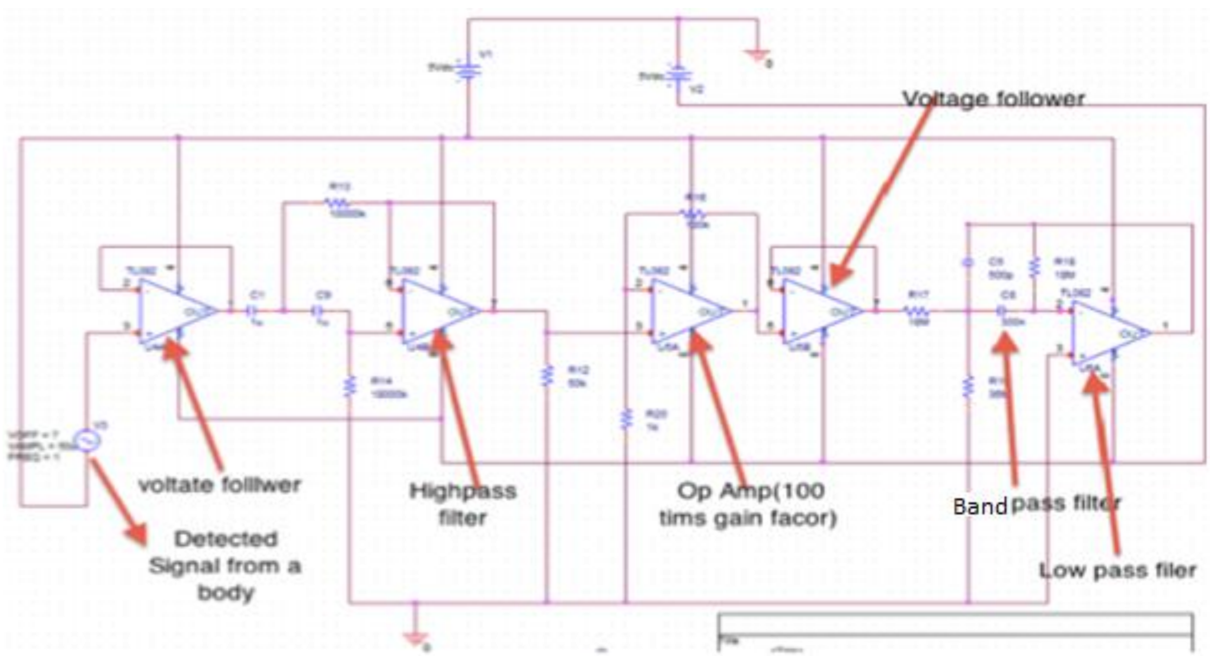


Figure 6: Overall circuit schematic

2.2 Determination of the sensor

The sensor circuit stage is the first and most important stage. In order to pick up an appropriate sensor, following characteristics need to be take into consideration

1) Obtain an accurate AC signal from pulses. The skin thickness of human finger is 3mm. The sensor should be most sensitive at this distance. The wavelength of sensor should also be sensitive to the amount of blood. In this way an infrared sensor will provide an accurate signal for future BP calculation.

2) High collector current. This ensures we have enough current for following stages to amplify. Also it will be more representative to the actual pulse.

3) Sealed emitter and collector in one sensor: when collector and emitter of sensor are separate, there is a good chance that the surrounding ambient light would affect the sensor performance. Hence, the best performance is obtained when they are sealed in one sensor.

4) The cost of sensor: the cost of the sensor should be low so that the overall BP monitor device will cost less and product can get commercialized easily

5) Sensor should be easy to wear, so that it won't affect daily life of the patient.

	Wavelength	Best Sensing distance	Collector current max	Price
HOA0708	880nm	3.8mm	40ma	$7.01
TCRT1000	950nm	4mm	50ma	$1.07

Table 1. Detailed data for HOA 0708 and TCRT 1000

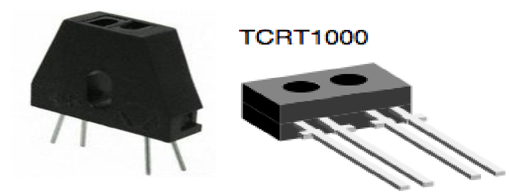


Figure 7: HOA-0708 vs. TCRT 1000

After searched carefully, we found another infrared sensor HOA0708 manufactured by Honeywell which is comparable and similar to TCRT1000. Both sensors fulfilled the requirement of combining the emitter and collector in one chip. Meanwhile both sensors are small and easy to wear.

Comparing TCRT1000 and HOA-0708 functionalities, we first tested HOA-0708 to see how it works, and whether it performs better than the TCRT1000. The simple test circuit is the same as the sensor circuit in previous group but with different resistor value so that HOA -0708 can work under a normal voltage. We adjusted our finger positions and observing the output however, we haven't obtained consistent signal as we predicted. When we pressed our finger on the sensor, the output current became nearly 0 which means that the 880nm wave can't pass through our skin and reached our blood vessel. So despite HOA-0708 has a better sensing distance, it can't be adopted to our project.

We replaced TCRT1000 with HOA-0708, and performed the same test. With the TCRT1000 we obtained a result that showed it was the better sensor. A consistent waveform was observed at the oscilloscope. The output was varied as we changed the finger positions to reflect changes in pressure waveforms inside the finger. With these results, we showed HOA-0708 is not the IR sensor suitable for our project and hence abandoned it for good.

2.3 Voltage follower

Now our design included two voltage followers: the first one was inserted between the sensor and the high pass filter and the second was installed between the amplifier and the band-pass filter. Both followers are designed to separate two different stages, so the two separated stages won't affect each other. Meanwhile, the voltage followers increase the input impedance of the following stage and decrease the output impedance of the previous stage. This helps the filter and sensor circuit work in a better condition.

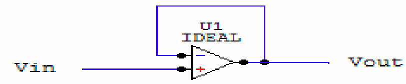


Figure 8: Voltage follower

2.4 High-pass filter

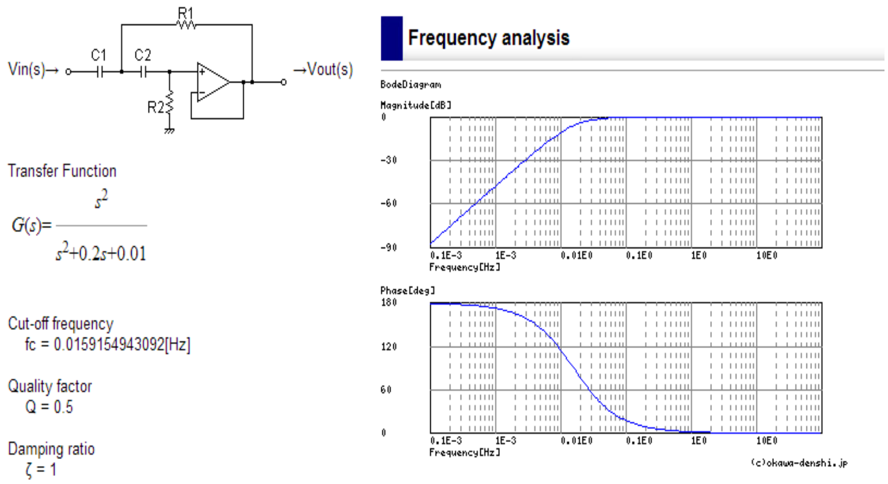


Figure 9: Second order Sallen-Key High Pass filter R1=10MΩ, R2=2R1=20MΩ, C1=C2= 1μF.

The PCB board from the last project team was built with two potentiometers (P1, and P2). (See the figure 4). P1 was designed to cancel out the DC component of the signal coming out of the IR sensor so the amplifier won't be saturated. The potentiometer was extremely sensitive and hard to adjust. So our team built a second order Sallen-Key high pass filter to remove the DC component from the signal.

Then the cut-off frequency is set up to 0.016 Hz, so that 0Hz DC component can be filtered. Meanwhile, as we can see from the phase bode plot, the phase change around 1Hz is approximately 0, which means that there won't be a group delay for the useful AC signal.

2.5 Operation Amplifier

The single differential amplifier(s) were installed to increase the input signal to a high level. In order to be properly monitored, we used 100x (times) gain factor for the operational amplifier, generating the output signal is visible at 2 volt ranges in oscilloscope. We made a great progress with the gain factor, since the signal from last group can only be captured on 200mV range.

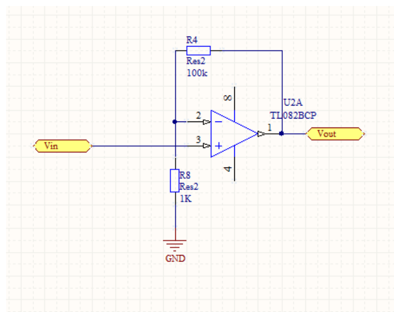


Figure 10: Operation amplifier

2.6 Band-Pass filter

As the client would like us to build up an analog filter to replace the digital filter from previous group, we came up a second order Sallen-Key band pass filter with a pass band 0.1Hz-10Hz. (Figure 10)

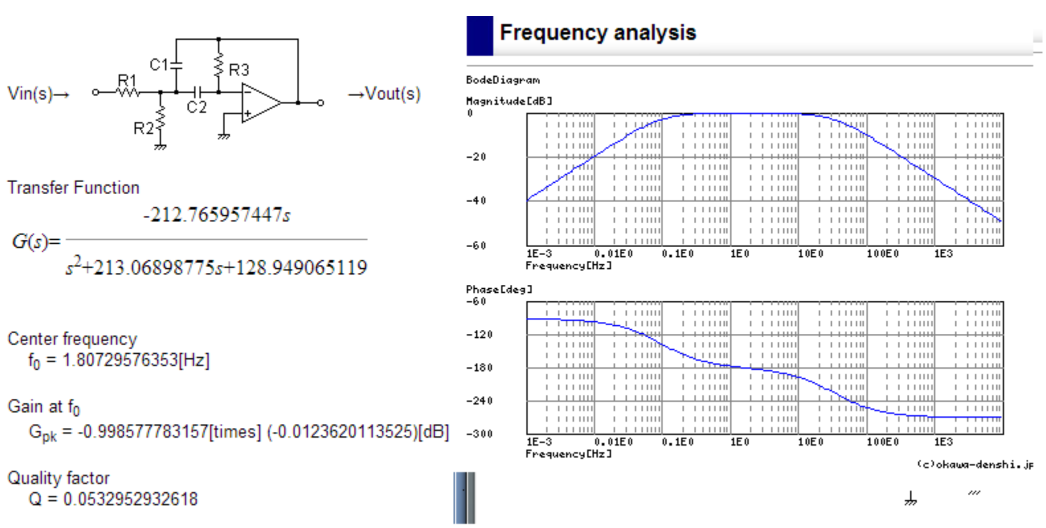


Figure:11 Second order band pass Sallen-Key filter

R1=R3=20MΩ R2=40MΩ C1=500pF C2=300nF

This filter can help us to eliminate the remained DC offset that has been amplified by the amplifier and also eliminate the high frequency noise that may come from other components of the circuit. As we can also see from the Phase bode plot, the phase is approximately stable between 1Hz and 5Hz. This ensures the no group delay will be generated to the pulse signal.

3.0 Results

3.1 Improvements overview

We were successful in designing a complete brand new circuit, providing more stable and precise output signals. In this project, we eliminated the potentiometers, reduced the DC offset, increase the gain factor, lower down the power supply, and established an analog filter.

3.2 Elimination of potentiometer

The PCB board from previous senior design group had a design made up of an amplifier with feedback loop and the feedback loop was controlled by a potentiometer. We eliminate this potentiometer by our high pass filter. And we use a pair of resisters to generate constant gain for the amplifier, which eliminate the second potentiometer from previous team. This makes the product more practical for an ordinary patient to use.

3.3 Power supply

The previous senior design team powered their circuit with 18V peak to peak voltage. Our client needs our group to lower down the power supply such that it can be battery powered and low power consumption. And we successfully achieved. Our circuit is normally powered by 10V peak to peak voltage which is a solid improvement from last semester, however further improvement is needed to achieve a goal of using small battery size power for BP monitor. Also, in our testing we used the 6V peak to peak voltage. The functionality of the circuit remains, but the gain factor reduced rapidly (under 6V condition, the signal can be captured on 500mV level).

This blood pressure monitor device is expected to take automatic measurements for a week without changing the battery or even needing to recharge in that duration. Thus, we need to design low power consuming device. In addition, since our goal is to design smaller device which doesn’t compromise the patient’s comfort level, we need to eventually have smaller size batteries.

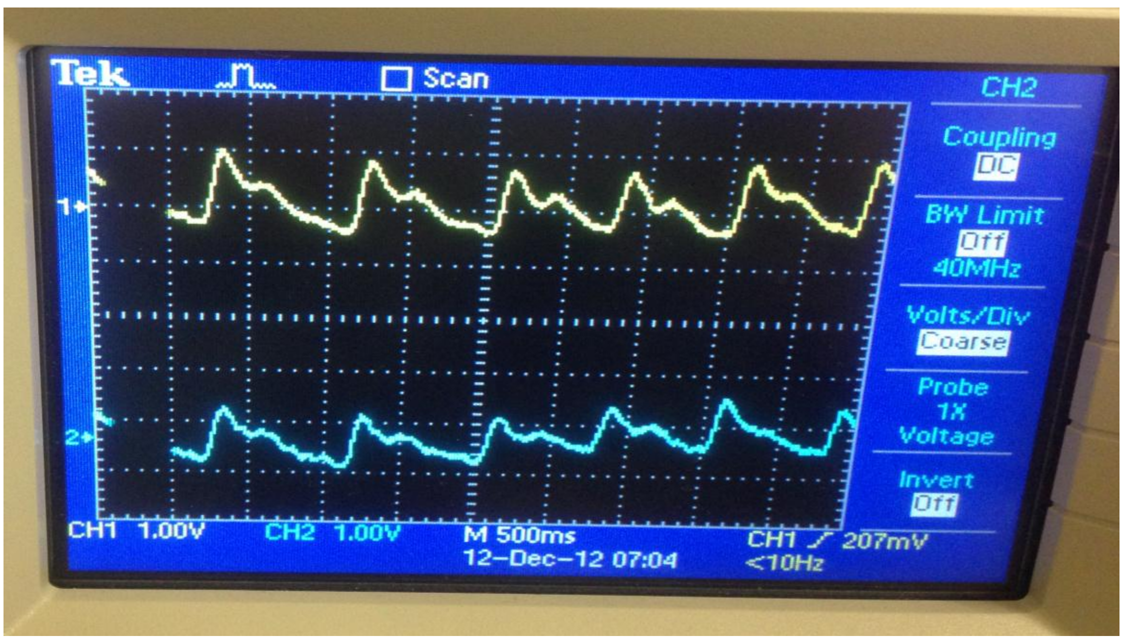
3.4 Multiple channel testing

In this project we built 4 identical channels to obtain pulse signal from different place of a human body at the same time. Previous group built 8 channel device but never test with two channels at the same time. We did a simultaneous test from one person's two fingers. And the results are shown in the next section.

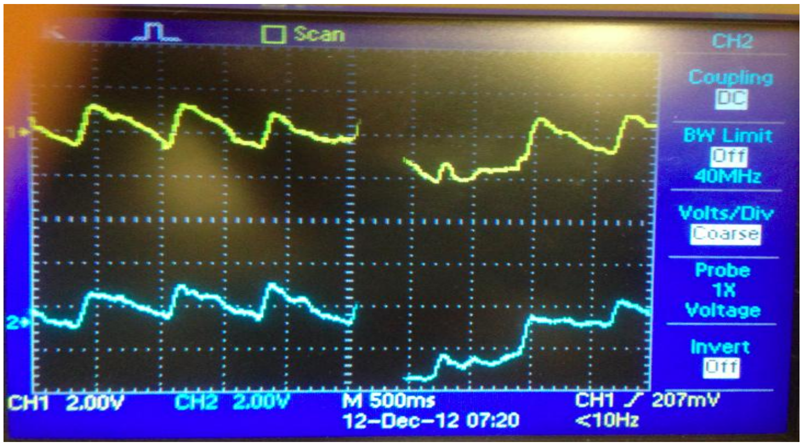
3.5 Sample results

The following pages in this section display a notable sample dates. They were taken from all group members, as well as the project advisor. These images illustrate the effectiveness of the system in obtaining pulse waveforms. At those pictures, the yellow curve was the pulse collected from a left finger and the blue curve was the pulse collected from a right finger.

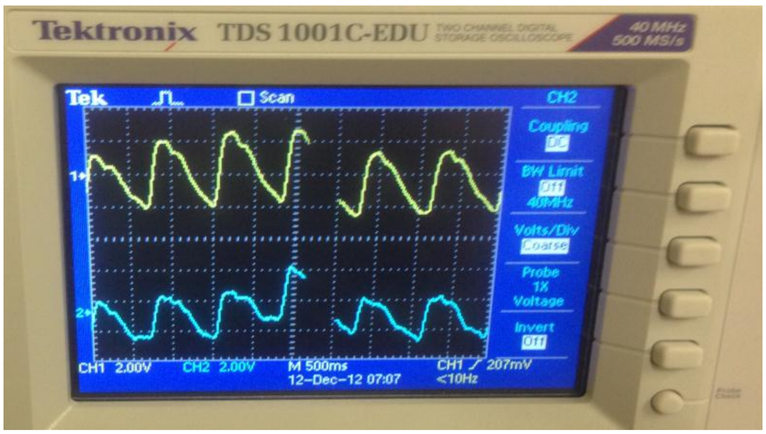
3.5.1. Jialiang Wang both index fingers



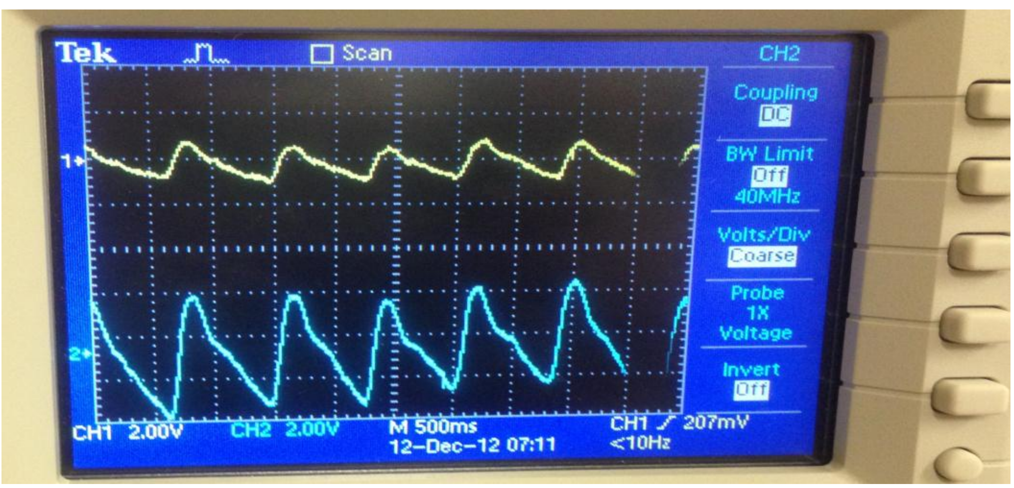
3.5.2Mohammed Hassan’s both index fingers



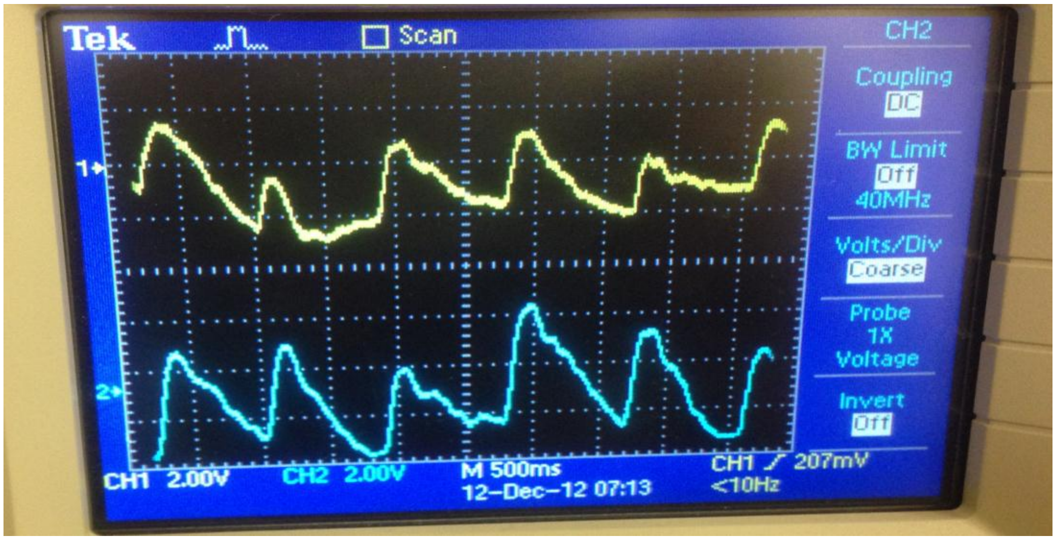
3.5.3 June-young Kim’s both index fingers



3.5.4. Osman Elmi both index finger



3.5.5. Larry Beaty both index fingers



3.5.6 Tong Chang’s Result

The following results were collected from Tong Chang’s finger under different circumstances.

3.5.6.1 The pulse signals from the previous circuit board.

The below (left-side) was the signal collected by the old-circuit board (PCB) (right-side). The old circuit board contained total eight black boxes and each of them was equipped with two potentiometers. As earlier mentioned, the PCB board from last design is extremely hard to use due to the potentiometers. They need to be adjusted by the customers themselves. Also as we can see from the picture the output signal is tiny.

Figure 12: previous output signal and PCB board

3.5.6.2. *Our product and the pulse signal measured from Tong's finger*

The below (left) picture was about the output signal from one channel of our product. Clearly, the dc offset was successfully eliminated (around 30 mV) and the gain is pretty high.

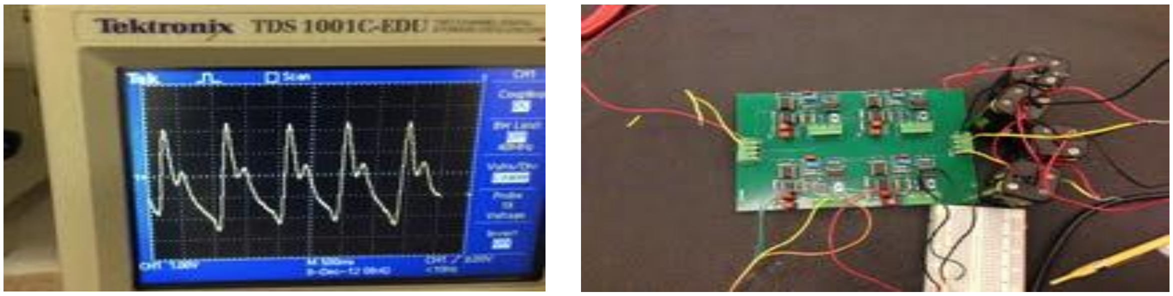
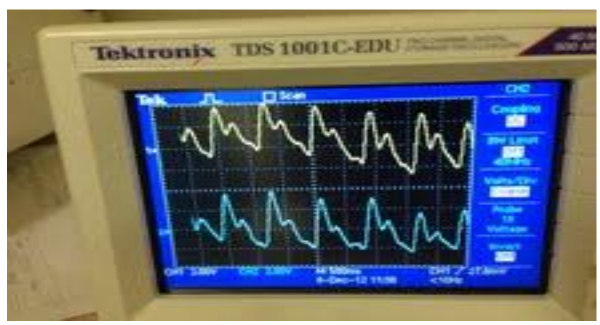


figure 13: our output signal and PCB board

3.5.6.3 *Tong's two index fingers from two channels under3 Volt and 5 Volt.*

Those below pictures indicate how well our product was running with low voltage power. The left side picture was about the pulse waves from Tong's finger while the circuit was powered by 3 volts. The right-side picture describes when the board was running with 5 volt. It is clear that under both circumstance, the circuit is working. The only thing changed here is the gain factor.



4. Budget

From the department we obtained a maximum of $ 300 budget, which we used almost half for our project. The individual components such as sensors, resistors, OP-AMPs are pretty cheap. The most expensive part was the PCB that costs about $100 to fabricate. This cost can be reduced by large amount fabrication.

Item	**Item Code (Digikey)**	**Quantity**	**Sales Price $**	**Total Price $**	**Date Received**
TCRT1010	751-1032-ND	10	0.825	8.25	10/3/2012
TL082	296-1780-5-ND	20	0.176	3.52	10/3/2012
HOA-0708	480-3542-ND	4	5.72	22.88	10/24/2012
ELECTRICAL TAPE	782-1001	1	5.42	5.42	11/6/2012
TCRT1010	751-1031-ND	10	0.798	7.98	11/8/2012
CAP 1000 pf	308-1029	10	0.036	0.36	11/15/2012
RESISTOR 18M	201-1177	5	0.06	0.30	11/15/2012
RESISTOR 10M	201-1174	30	0.06	1.2	11/15/2012
QUICK BRAID ANTSST	731-1002	1	2.697	2.697	11/15/2012
CAP 0.33 uf	309-1001	15	0.65	9.75	11/16/2012
CAP 470 pf	308-1028	15	0.22	2.2	11/16/2012
RESISTOR 3.9M	201-1077	5	0.06	0.3	11/16/2012
CAP 1.5 uf	308-1083	5	0.3872	1.94	11/16/2012
CAP 1 uf	P4675-ND	15	0.41	6.15	12/5/2012
RES 20K	CF12JT20K0CT	20	0.081	1.62	12/5/2012
TERM BLOCK 4POS	A98370-ND	10	0.916	9.16	12/5/2012
SW SLDE DPDT	401-2001-ND	6	0.34	2.04	12/5/2012
Solder	733-1002	2	5.71	11.42	12/6/2012
RESISTOR 2K	200-1196	10	0.04	0.4	12/6/2012
RESISTOR 1K	200-1167	14	0.3715	0.52	12/7/2012
RESISTOR 100K	200-1359	20	0.04265	0.43	12/7/2012
Battery AA	740-1003	24	0.245	5.88	12/11/2012
Battery holder	740-1003	4	0.915	3.66	12/11/2012
PCB		1	100.00	10.00	12/1/2012
Grand total				**$ 214.88**	

5. Conclusion/future work & acknowledgement

5.1 Conclusion of significant improvements

- DC offset was effectively removed.
- No Potentiometer was needed anymore
- Low power supply with 6V peak to peak value.
- Multi-channel working
- High gain factor so the signal is visible on 2V range.

In general we make some great improvements to meet the client need. Especially reduce the power supply and remove potentiometer, which makes the product way more practical than the last group. However there are still a lot can be developed in future work.

5.2 Problems need to be fixed in Future work

- Test other different IR sensor or even other type of sensors to determine the best one.
  We only pick HOA-0708 for our testing, which proves the wavelength 880nm is not working that well. Future work can be made to determine whether the 950nm is the best wavelength for this project.
- Lower down the power supply to +-2V or even +-1V.

  +-3V is a great improvement but is not good enough yet. In realistic, the portable medical device should be powered by very low voltage battery. However, there are two main things need to be considered before lowering down the power supply. First is TCRT-1000 might not work at that low voltage (the nominal working voltage for TCRT is 5V). Future team may need to pick up other low power sensors. Second amplifier may suffer more saturation if DC drift is not solved.
- Eliminating the DC drifting

  Due to time limitation, our product didn't meet this client need. However, we list two ideas here that might be helpful for future teams to fix this problem. First is use instrumental amplifier which has a high CMRR ratio. In theory, it can help the circuit to get rid of the DC drifting. Another simpler way is to use digital filter such as connecting microcontroller or DSP chip after the amplifier stage. This method is proved to be applicable by previous team, the disadvantage is it costs a little bit more.

- Reduce setup time for the device.

  Right now it will need 1 minute for capacitor to charge and discharge to get to steady state. We tried to reduce this time constant by using small capacitors. However 1 minute is still too long.

5.3 Acknowledgement

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6.References

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