Design of Infrared Sensor Based Measurement System for Continuous Blood Pressure Monitoring Device

by

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Abstract

The objective of this project is to develop a prototype for a portable system that detects the blood volume pulsation by optical radiation and then displays photoplethysmograph (PPG) signals. The prototype comprised primarily of infrared (IR) LED sensors, both high and band-pass filters, an amplifier, and voltage followers (unit-gain buffers). An oscilloscope displays PPG signal. In this project, we used TCRT1000 (IR LED sensor) to convert the fluctuating reflected light intensity into electrical signals (voltages). The high-pass op-amp filter with cutoff frequency of 0.01Hz removes the DC component of the incoming PPG signals. The closed negative-feedback loop system with the filter drives a DC offset level to near zero value (29.3 mV). A single stage operational amplifier (LT 1167) increases the incoming signal (1-3 mV) 100 times (100- 300 mV). A band-pass filter to pass signals between 0.1 Hz and 20 Hz was built to avoid the output signal DC level drift. Two voltage followers minimize the effects when the input voltage suddenly changes; for example, when a sudden pressure change occurs on the LED sensor. Finally, Infrared AC PPG signals were obtained and displayed on the oscilloscope. The prototype successfully reduces power consumption in the handing of the AC PPG signals, reducing the power supply set to 5 volts without losing signal quality. In addition, this prototype produces clean dual PPG signals in real time such that PPG from different body locations can be used for PTT-based blood pressure estimation.

1.0 Phoenix Senior Design project Background

1.1 Introduction

The Twin Cities IEEE Phoenix Project has been seeking for a prototype system for effective blood pressure monitoring that is non-intrusive, inexpensive, and can be worn twenty-four hours a day for a week or more. By monitoring a patient's blood pressure changes over an extended period of time, healthcare professionals will be able to identify, predict, and diagnose various cardiovascular diseases.[1] Photoplethysmography(PPG) is a non-invasive technique for measuring relative blood volume changes in the blood vessels close to the skin using infra-LED sensors.[2]

The design project group (spring, 2012) built a prototype system to produce PPG signals, providing those three lessons. First, their design explained the process in converting blood pressure changes into PPG signals, using an infrared LED and phototransistor sensor. Second, the inbuilt PCB demonstrated the way to eliminate DC components and increase AC components of the PPG signals. Finally, the design also introduced the process of filtering out noise component of the PPG signals, using digital filters. However, there were significant limitations and future improvements until the design is perfect. For instance, the size was too large to be a compact. It took high dc supply voltage and required a micro-controller. Also, this design failed to solve an output signal offset problems.

We tested the old prototype and thoroughly redesigned the board. We developed the idea for another PCB: blood pressure could be extracted from PPG signals using pulse Transit Time (PPT) method.[3] The new prototype consists of four channels. Each channel input connects to IR-LED sensor, and the output connects to an oscilloscope. This board can handle dual PPG signals detected from the tips of the both hands; therefore, we were able to compare the signals simultaneously. The connected oscilloscope provides waveform details, including edges, noise, and transient periods. Hence, their relative phase difference can be extracted for PPT calculation. Tracking the pulse measures of blood pressure is also possible.[4] In addition to improving the process of PPG signals, we also focused on designing a small portable device that offers solid performance and to make it easy-to-use.

The test results, analysis, and newly designed PCB provide the basis for future exploration

[1] Imholz B P M, Wieling W, van Montfrans G A and Wesseling K H 1998 Fifteen years experience with finger arterial pressure monitoring: assessment of the technology *Cardiovascular Res. 38 605-16*

[2] Murray A andMarjanovic D Z 1997 Optical assessment of recovery of tissue blood supply after removal of externally applied pressure *Med. Biol. Eng. Comput. 35 425-7*

[3] Drinnan M J, Allen J and Murray A 2001 Relation between heart rate and pulse transit time during paced respiration *Physiol. Meas. 22 425-32*

[4] Payne R A, Symeonides C N, Webb D J and Maxwell S R 2006 Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure *J. Appl. Physiol. 100 136-41*

projects. If the following project group improves the original design using the PCB we made, then these issues will be exceptionally informative milestone to start. First, design any instrumental operational amplifier with high common mode rejection ratio (CMMR); then, evaluate whether it eliminates the dc offset from the incoming signals. Second, calculate blood pressure data using PPT method with given dual PPG signals from the tips of index fingers on both hands.

1.2. PREVIOUS DESIGN

The previous design group used a LED sensor as a way to obtain a digital (pulse) signal from the heart to be used for blood pressure measurement. Figure 3 (left) shows the *Block Diagram* of the Heartbeat Monitor of the previous group. The system consists of a LED sensor, a differential amplifier, and two potentiometers for adjustment of gain and DC offset. .

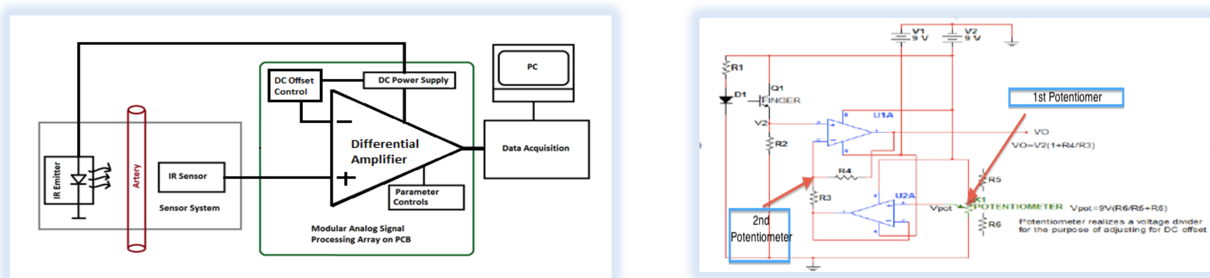

Figure 3: block diagram of spring 2012 senior design group

The first stage is a LED sensor, TCRT 1000. The sensor illuminates a tissue, the tip of a finger, with light, and the photo-detector measures the slight variations in light intensity associated with volumetric change in blood in the tissue. It converts the light into a corresponding voltage signal. The second stage is a differential op amp with a gain of 100. To avoid output saturation, the voltage from "DC offset control" is fed back into the differential amplifier's inverting input. The amplifier's non-inverting input is supplied with incoming PPG signals which include the DC components (average light intensity) and the AC components (a small varying signal caused by changing blood pressure). At the third stage, the output signal from the amplifier connected to an analog-to-digital converter (ADC). Being connected to the ADC, a microcontroller eliminates noisy components and then transmits the PPG signals to an oscilloscope. The figure on the right of Figure 3(right) shows the schematic of the block diagram of the system and the two variable potentiometers. The first pot cancels the DC offset from the incoming signal. The second pot adjusts the gain of the amplifier so that the amplifier would not be saturated. Trimming the knob stabilizes the operation of the circuit. The trimmer should be readjusted whenever we run the circuit, which was extremely difficult and frustrating.

2.1. OBJECTIVE/ SYSTEM DESIGN

We were recommended to improve those following items:

- Test different optical type sensors and find the particular type of senor, which is best suitable in converting the small variations in light intensity with volumetric change in blood.
- Build a simple circuit by eliminate the analog-to-digital (A/D) converter and a micro-controller with analog filters; instead, use an analog filter.
- Design a high performance circuit, using op amp handling the output signal within 1-2 volts p-p, a 5V single supply is preferred.
- Reduce the DC drift and output saturation, which is transient. The saturation appeared for a shot while then went again.

To achieve those desired goals, we designed entirely new circuit board (PCB). The signal conversion is implemented on seven stages as shown in the block diagram on figure 4. The first step is the LED illumination on the tip of a finger. The sensors used in this project were both optical sensors type TCRT1000 and HOA 0708. After the illumination on the tip of the finger, the LED sensor converts reflected IR light with slight variations into electrical signals (voltages). The second step is the first voltage follower (a buffer amplifier), which isolates the input (the LED sensor circuit) from the output (the high pass filter circuit). We used a conventional unity gain-inverting amplifier, which carries the same amount of voltage between the input and the output, avoiding "loading" effects. The third step is a passive RC high-pass filter for the incoming PPG signal, which contains a DC offset (the average infrared light intensity incident on the sensor) and small AC signal caused by changing blood pressure. This filter eliminates the DC offset, and as a result, the DC bias closely becomes to a ground level. The fourth step is an active non-inverting amplifier with voltage gain of 100, such that incoming PPG signal with 1-5 mV increases up to 100-500 mV. The fifth step is another voltage follower (non-inverting buffer amplifier) to reduce the output impedance. The sixth step is a passive band-pass second-order Bessel filter, with cutoff frequencies 0.1 Hz and 10 Hz.At the final stage, the output was then displayed on an oscilloscope. Both an A/D converter and a microcontroller are not necessary for the signal filtering. The figure 4 and 5 shows the corresponding block diagram and schematic diagram of the newly designed circuit. And the following section will discuss the details of each sub-circuit (component) shown in figure 5.

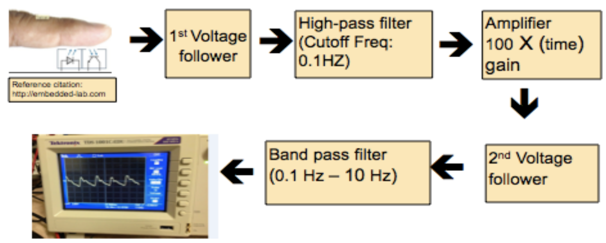

Figure 4: General Block diagram

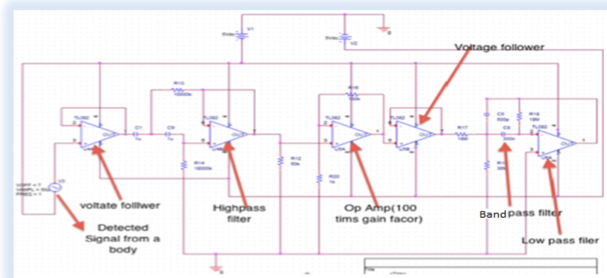

Figure 5: Newly Designed Circuit schematic

2.2. SUB-COMPONENTS

IR-LED SENSOR: Most LED sensors operate with the same principle. First, the LED light is emitted into a finger, and a detector measures the reflected light. Second, intensity of reflected light, which varies due to changes in blood volume, converts into PPG signal. Third, the PPG signal over the some periods of time, e.g. one to few minutes can be analyzed for obtaining blood pressure changes. Fourth and finally, for the PPG signal calculation, the amount of reflected light striking the sensor (detector) is inversely proportional to the blood volume at different body locations-- fingertip, earlobe, forehead, forearm, etc. However, various factors also influence this (reflected) light intensity, which we could not answer this moment. For example, as one of the critical factors, a blood vessel wall can impact on the light that gets reflected. The thickness of blood vessel wall varies within a body, like the blood volume. However, instead of considering those factors, we mainly focused on exploring the best-fit LED sensor for the tip of a finger. We had chosen IR-led sensor type HOA 0708, then compared it with TCRT 1000 used by the previous group. The technical comparison between them is:

	Wavelength	Best sensing distance	Max collector current	Price
HOA0708	880nm	3.8mm	40ma	$4.29
TCRT1000	950nm	4mm	50ma	$1.07

Both sensors have similar technical specifications: they are both equally small, easy to wear, expect for the price difference. They are the sensors with the infrared light emitter and phototransistor, which are placed side by side. Both emitter and sensor are enclosed inside a leaded package so that there is minimum effect of surrounding visible light. We placed them onto the same body position (the tip of a finger) and expected uniquely different PPG signals. However, the tests with HOA-0708 demonstrated that none of the transmitted IR light from emitter passing through the finger reached the detector while TCRT1000 produced varied the PPG signals. Those tests found HOA-0708 not suitable for the finger's blood pressure monitoring.

Figure6: HOA-0708

Figure 7:TCRT 1000

VOLTAGE FOLLOWER: The newly designed circuit board contains two voltage followers (unity-gain amplifier). The first voltage follower installed between the IR LED sensor and the high pass filter (HPF). It aimed to save the output (the input of the high pass filter) from swift current increases at the sensors. For the same purpose, the second voltage follower located between the operation amplifier and the band-pass filter (BPF). Ideally, those voltage followers separate two different stages, which are input and output circuits, by connecting a source (the input circuit) with high impedance to a low impedance load (the output circuit). This helps the filter and the sensor-circuit work in a much stable condition, by avoiding errors from unexpected voltages at the amplifier input due to pickup, stray currents.

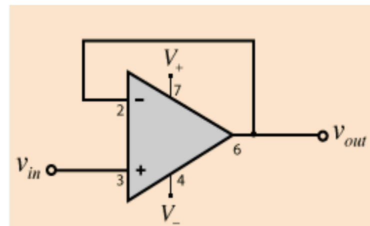

Figure 8: Unity-gain-amplifier

PASSIVE RC HIGH PASS FILTER (HPF): The voltage signal at the output of the phototransistor contains a wide quasi DC signal (the extremely low frequency component). This DC signal arises by the average intensity of infrared light, which reflected back from a body location: the tip of a finger. The essential reason for designing a high pass filter is to remove this DC signal. The previous group used the digital filter connected with the A/D convertor, but we built the analog filter because it could reduce costs and complexity. Logically, using a series capacitor (C1 and C2) will block any DC. Capacitors cannot pass DC, so the waveform will re-centre itself to ensure that there is no offset. This happens regardless of how the DC offset has been created, and is insensitive to AC waveforms. The high pass filter we designed is a simple RC circuit, comprising of two capacitors (C1 = C2 = 47 micro F) and two

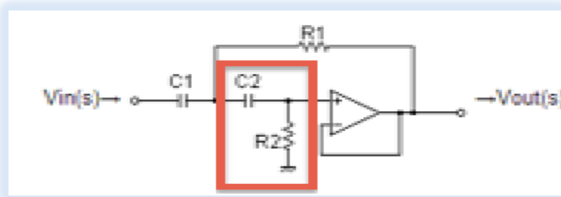

Figure 9: The Circuit design for the high pass filter

resistors (R1= 500 k ohms, and R2 = 250 k ohms), and one unity gain op amp (LM 741). The cut-off frequency sets up at 0.016 Hz because the DC offset voltage is a quasi DC signal having a particularly low frequency component. The dominant frequency component of the AC signal is about 1Hz-2Hz (approximate to person's heart beat frequency). As shown in figure 9, the DC negative feedback loop was to cancel the DC offset: the output voltage was fed into the negative input terminal. Meanwhile, the phase change around 1Hz is approximately zero, which means there will not be any group delay for the useful AC signal components. However, this filter design was found to be ineffective in eliminating the quasi DC component. On the oscilloscope, the dc level continued to move up or down for 10 to 12 seconds. This transient DC offset appeared for a shot while, caused voltage saturation, and then went away again.

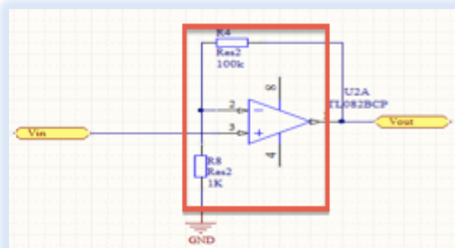

Figure 8: Non-Inverting Amplifier

NON-INVERTING AMPLIFER (GAIN OF 100): The single stage differential amplifier increases the input signal to a high level. We aimed to have the op amp with low dc supply (single power) voltage because it could save costs and take advantage of the widely available power source (a battery power). More specifically, we designed the amplifier with +5 single supply voltage, which covers the 1-2 volts p-p output voltage, dramatically reducing volts supply from the previous design (+- 15 volt supplies).

Based on the calculation, a single +5 single supply voltage was the smallest value we could reduce because a conventional amplifier requires fixed "head-room" of from 1.5 V to 3V. Here are the following reasons. First, observing the outputs signal without any distortion within the full-sweeping ranges is essential. The operational amplifier has fixed headroom. If we reduce supply voltage lower than 5 volts, the entire sweeping ranges would severely be limited. Second, as the voltage supply reduced, trimming the offset input will become problematically sensitive because output signal saturation occurs whenever the output hits the rails of the amplifier. Third, the reduced AC swinging is hardly distinguishable from noise floor. As such, we concluded that 1-2 volts p-p output voltage was sufficient to observe the key characteristics of PPG waveforms. Since the magnitude of the raw PPG signal is about 5- 8 mV, the gain of 100 is sufficiently covered with 1-2 volts p-p voltage. The amplification with the gain of 100 was built with a single op–amp difference amplifier and resistors: R4 (100K) and R8 (1K). The non-inverting amplifier with a gain of approximately 100 (i.e.: Av = 1 + R4/R8) generates the output signal at 2-volt scales in an oscilloscope. R8 is a mean of adjusting the DC level of output and compensates for any output DC offset voltage of the amplifier.

BAND-PASS FILTER: The amplified PPG signal contains high frequency noise components to be eliminated. We preferred the band-pass filer, which has two cut-off frequencies, over a low pass filter because it might be useful in somehow in solving the DC offset problem; in addition, it will filter out the high frequency noise components. We selected a second order Sallen-Key band pass filter with a pass band 0.01Hz-10Hz after considering following reasons:

- The heart rate is the leading characterizing feature of the PPG waveform;
- An average person's heart rate is between 60 and 80 bpm (1 Hz to 1.2 Hz), which is must be saved from the filter;
- We assumed quasi DC signal having AC frequency of 0.01 Hz (0.6bpm);
- We concluded that the upper cutoff frequency (10 Hz (600 bpm)), which is 10 times higher than the average heart rate, is a good balancing point

As figure 9 indicates, for setting up those frequency ranges, both R1 and R3 have the resistance value of 20MΩ. Resistor R2 has the resistance value of 40MΩ. Also, capacitor C1 has a capacitance of 500 pF and C 2 has a capacitance of 300nF. The phase bode plot demonstrates that the phase is almost stable between 1Hz and 5 Hz.

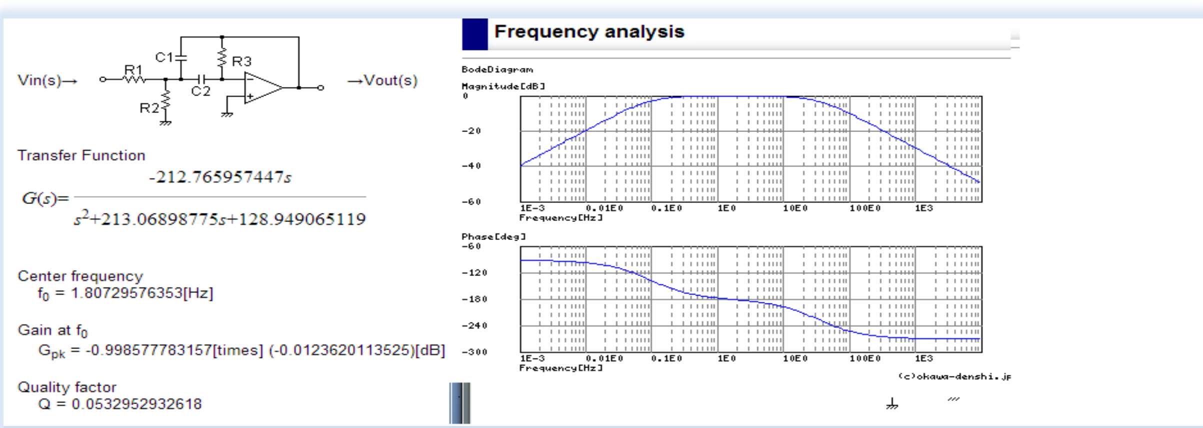

Figure 9:Seond order band pass Sallen-Key filter

3.1 SAMPLE RESULTS & DISCUSSION

3.1.1. *Old prototyped PCB board and the pulse PPG signal measured from a finger*

The following pages in this section provide printed circuit boards (PCB) and the test results. The left image in Figure 10 shows the old PCB with a total of eight sensor channels, being operable with +-9 DC voltage power supply. Two potentiometers are positioned on the top of each channel (a black rectangular box) for adjusting the AC gain and DC offset control. For the noise reduction, the PCB must be connected to an analog digital converter (ADC) and a micro-controller (digital filters). The right image in Figure 10 demonstrates the inverted pulse PPG signals coming out from the one of the circuit board, once optical sensor (TCRT 1000) detected the signal from a finger.

Figure 10: The old PCB (left) and PPG signal from the old circuit (right)

3.1.2. *Four-channel PPG monitoring device and the pulse signal measured from a finger*

As shown in Figure 11, we built up a portable four-channel PPG monitoring device, and the each of them comprised of analog filters and an amplifier; therefore, it does not require both an A/D convertor and digital filters. It is also operable with a single 5 volts supply. Each channel is independently operable and can be connected to an IR-LED sensor as well as an oscilloscope. An optical sensor can be wired to the board through header pins and jumpers, and we put TCRT 1000 onto the pins instead of using the jumpers. The operation of the prototype is remarkably easy and simple. First, place the tip of an index finger hands gently over the sensor on its face. Second, the finger should be still and should not be pressed too hard on the sensor. Within a couple seconds, the circuit stabilizes, and the detected PPG waveforms will appear in an oscilloscope in real time.

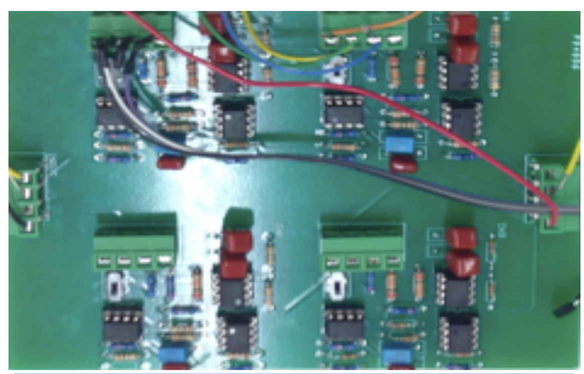

Figure 11: Newly designed PCB

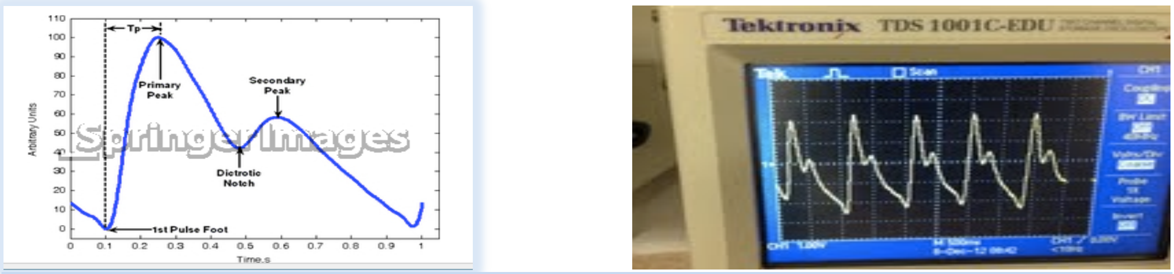

Figure 12: typical type of PPG signal (left-side) and the measured PPG waveforms (right-side)

At figure 12, the left side image is about the desired sample PPG signal measured from the tip of a finger. Also, the right side picture describes the detected PPG waveforms from a finger, produced by the currently designed PCB. We set up the vertical sensitivity to 2V/division to see the outputs on “Channel 1.” The coupling mode set up as “DC coupling,” and as a result, the oscilloscope would take the PPG signal biased with a DC voltage; therefore, if DC offset is properly working, the DC voltages should be filtered out, and we will see the entire AC PPG waveforms with ground reference. Amplitude set up as 2V/ division. The time base set up as 250 ms/ division. Clearly, the DC offset clearly improved, driving into about 30 mV (nearly ground reference). On the oscilloscope, the output neither distorted nor hit the rails of the amplifier. Also, the firm "head-rooms" did not limit the sweeping ranges.

3.5. *DUAL CHANNEL PPG MEASUREMETN ON TWO INDEX FINGERS WITH DIFFERENT*

Because we built 4 identical channels, the prototype was able to perform simultaneous pulse signals from different sites of a human body. We operated two channels, and the dual channel PPG offers two main advantages: (1) dual PPG signals can be recorded, compared with each other, and analyzed in real time; (2) PPT technique can be utilized by phase shift value between the PPG signals. As shown in figure 13, the dual signals measured from the tip of index fingers of both hands. The image from the left side picture describes the dual PPG when the DC voltage power was 3 volts. The image from the right side describes the dual signals with the increased dc voltage power, from 3 to 5 volts. The dual channel signal processing is properly working. The waveform (yellow colored) detects from the right hand’s index finger’s tip. The waveform (blue colored) detects the left hand's index finger's. The obvious fact is the performance tradeoffs as we reduced dc volts supply for the op amp (from 5 volts to 3 volts). With a single 3 DC voltage supply, the AC waveforms appears be slightly compressed by the firm "head-room" problems I have earlier mentioned. Compared to the 3 DC voltage supply, the amplifier with 5 DC voltage supply provided complete PPG waveforms as shown in the right side image at figure 13.

Figure 13: Dual PPG signal with DC power supply 3 volt (left) and 5 volt (right)

5. CONCLUSIONS

We built a new compact size PCB board. The improvements are following:

- We eliminated the potentiometers with a high pass filter. We used a couple of resisters to maintain constant gain, and eliminated the need of trimming the potentiometers. This makes the PCB easy to control.
- We significantly reduced the power supply to 5 Volts (single supply) from +-15 Volts, and as a result, the PCB need not be connected to an electrical outlet. Also, output could be displayed on 500mV level with 5 V power supply.
- The proposed two-channel PPG signals operate well, measuring pulse signal from the tip of the index fingers from both hands.
- The dual PPG signal detected at two different body sites is a useful reference for obtaining PTT (pulse transit time method) for blood pressure assessment.

Problems need to be fixed in Future work

- **Eliminating the DC drift**

  We designed the sub-circuit to achieve zero input offset before the incoming signal would be amplified. The input offset was an extremely low frequency signal: voltage of ± 15mV AC sine wave. The output-offset voltage increases by the closed loop gain (100 times), which was then gradually increased close to the supply rails (± 3 Volts). When the input offset (voltage) was higher than ground reference level, the output saturated to the positive supply rail. When the input offset (voltage) was lower than ground reference level, the output saturated to the negative supply rail. In addition, even if the magnitude between the voltage between the inverting input and the non-inverting input is about the same, difference in phase (due to the time delay) might produce output saturation. Regarding this DC offset problem, we discussed ideas that might be useful for future teams to fix this problem. First, use an instrumental amplifier with a high CMRR ratio. In theory, it helps the circuit to get rid of the quasi DC (very low frequency component) drift.

- **Reducing setup time for operating the device.**

  Currently we spent 1 minute for the capacitor to charge and discharge to get to steady state. We tried to reduce this time constant by using the small capacitors. However 1 minute is still too long.

6.References

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