Using Photoplethysmography to Monitor Vitals for Patients with Arrhythmia and Hypertension

By: Cole Wener, JD Russo, Mohak Patel, Zaira Adrianwala

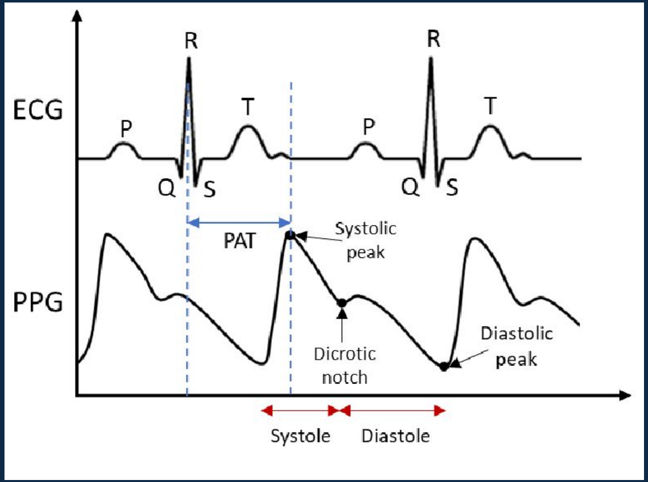
What is Photoplethysmography?

- Abbreviation is PPG
- Non-invasive
- Optical technique that uses a light source and a photodetector to measure the blood volume variations in arteries over time
- Also known as Pulse Oximeter Waveforms
- Heart rate monitoring
- Heart rate variability
- Blood pressure measurement by estimation
  - Either in conjunction with an ECG, relating speed of a pulse through fluid and pressure, or using machine learning to analyse the PPG wave morphology. We chose an ECG
- Pulse Oximetry: non-invasively calculate the arterial Oxygen saturation (SpO2)
- Accuracy of: 93.7+/-10%

https://global.samsungdisplay.com/29237/

PPG vs. ECG (Electrocardiogram)

- Both are non-invasive
- PPG is relatively inexpensive
- User friendly, also is mobile
- ECG is more accurate but PPG is also very reliable (ECG considered as the gold standard)
- PPG sensors use ECG signals as a reference for static heart rate
- For ECG you must put on the leads near the heart for most accurate reading
- PPG device can be placed anywhere that has adequate access to skin vessels



https://www.sciencedirect.com/science/article/abs/pii/S0169260722000621?via%3Dihub

Arrhythmia & Hypertension

- Arrhythmia: irregular heartbeat
  - Too fast, too slow, or just irregular
- Hypertension: high blood pressure
  - Pressure in blood vessels is too high
  - 140/90 mmHg or higher
- Can come from coronary heart disease, coronary artery disease, previous heart surgery
- Can also come from lifestyle choices, medications, and previous health conditions

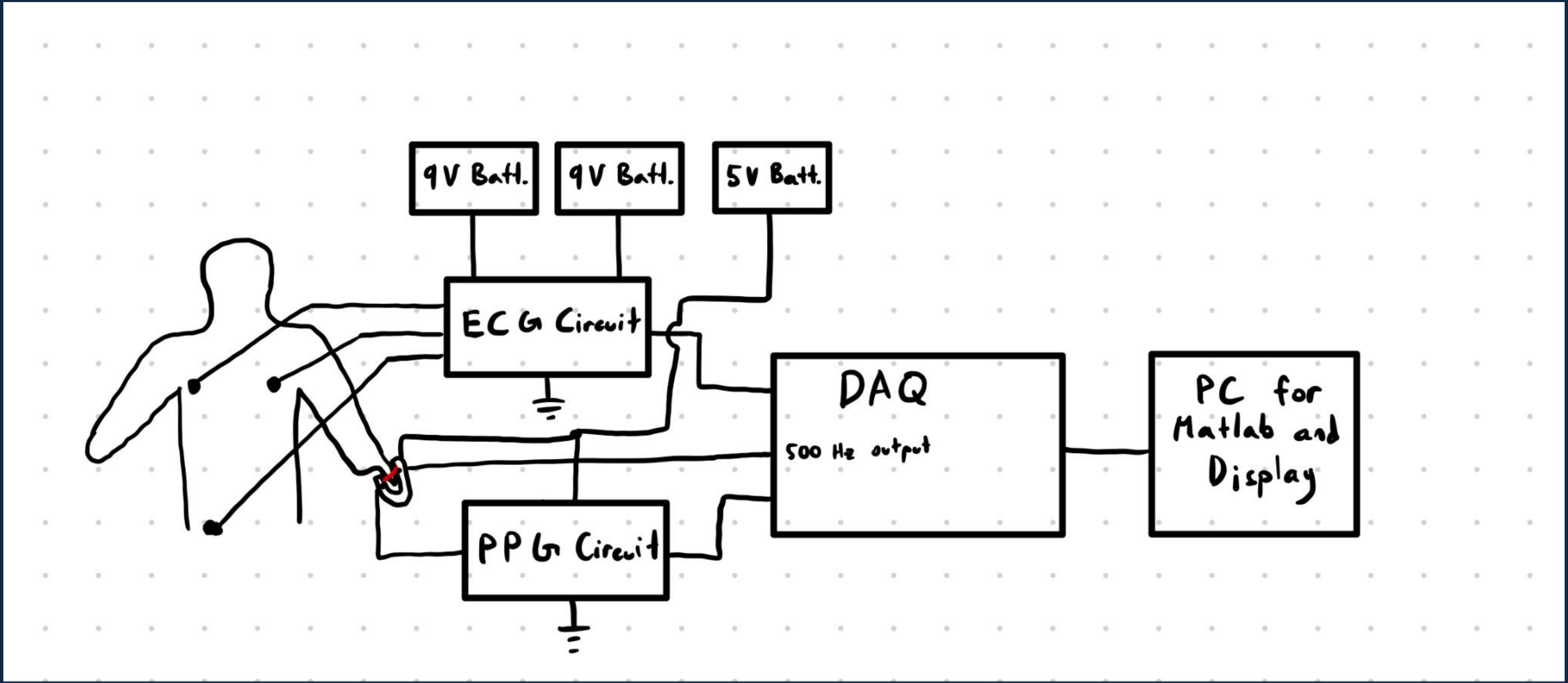
RESTING HEART RATE
BY AGE AND GENDER

AGE	ATHLETE	VERY GOOD	ABOVE AVERAGE	AVERAGE	BELOW AVERAGE	POOR
20-39	47-54	55-60	61-68	69-75	76-83	84-94
40-59	46-54	55-60	61-67	68-76	77-84	85-94
60-79	45-53	54-59	60-66	67-74	75-83	84-97

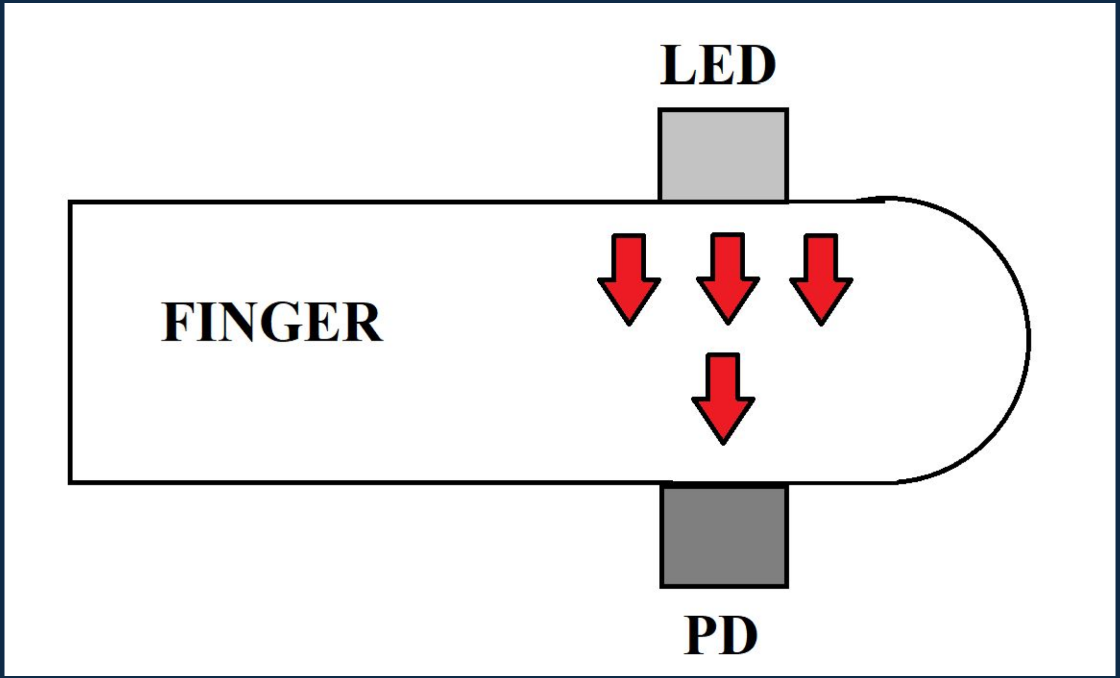
AGE	ATHLETE	VERY GOOD	ABOVE AVERAGE	AVERAGE	BELOW AVERAGE	POOR
20-39	52-59	60-65	66-73	74-81	82-88	89-98
40-59	51-58	59-63	64-70	71-78	79-85	86-96
60-79	52-58	59-63	64-69	70-77	78-85	86-95

https://www.whoop.com/us/en/thelocker/whats-a-normal-heart-rate-for-my-age/

Sensor Setup and General Block Diagram For Entire Device



Sensor Setup and General Block Diagram For Entire Device



Modes of setting up PPG sensors:

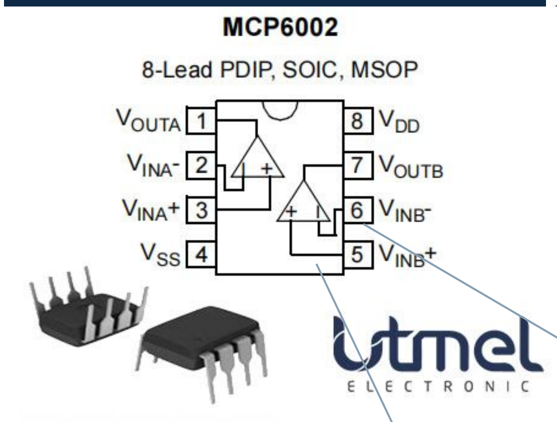
- Transmissive: source and sensor on opposite sides of tissue
- Reflective: source and sensor on the same side of tissue

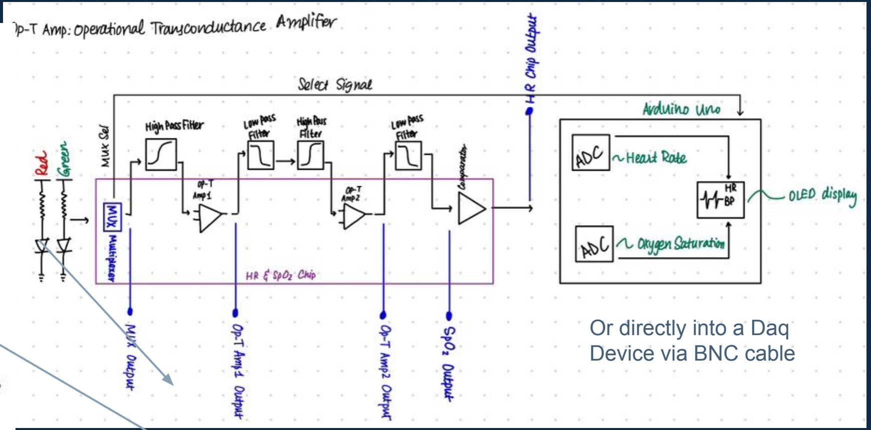
We chose to implement our PPG to sense via transmissivity, with an LED and photodiode on opposite sides of the finger with the intention of optimizing accuracy

PPG General Circuit Diagram

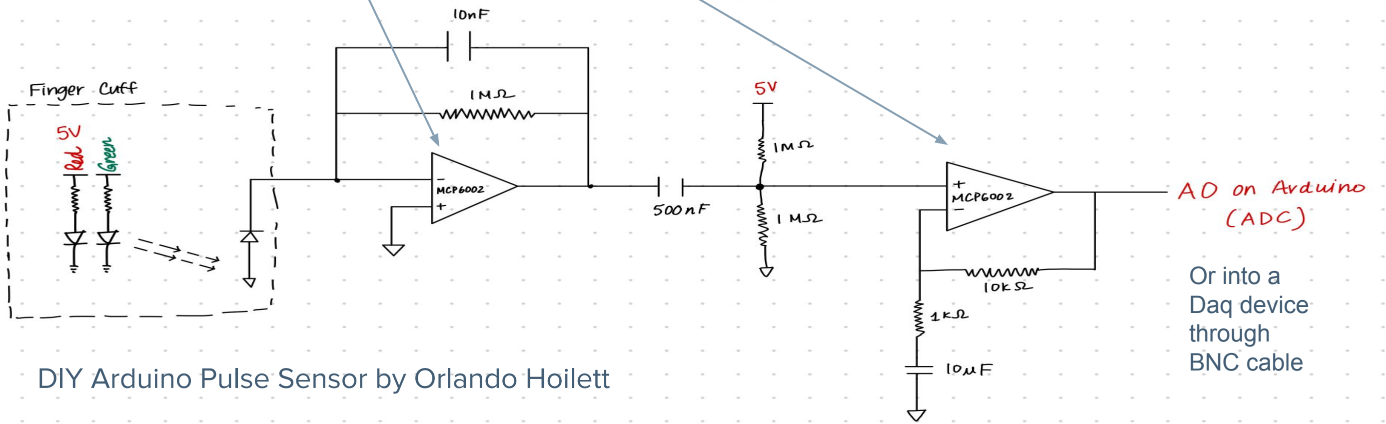
MCP6002 Applications

- Automotive
- Portable Equipment
- Photodiode Amplifier
- Analog Filters
- Notebooks and PDAs
- Battery-Powered Systems





Or directly into a Daq Device via BNC cable



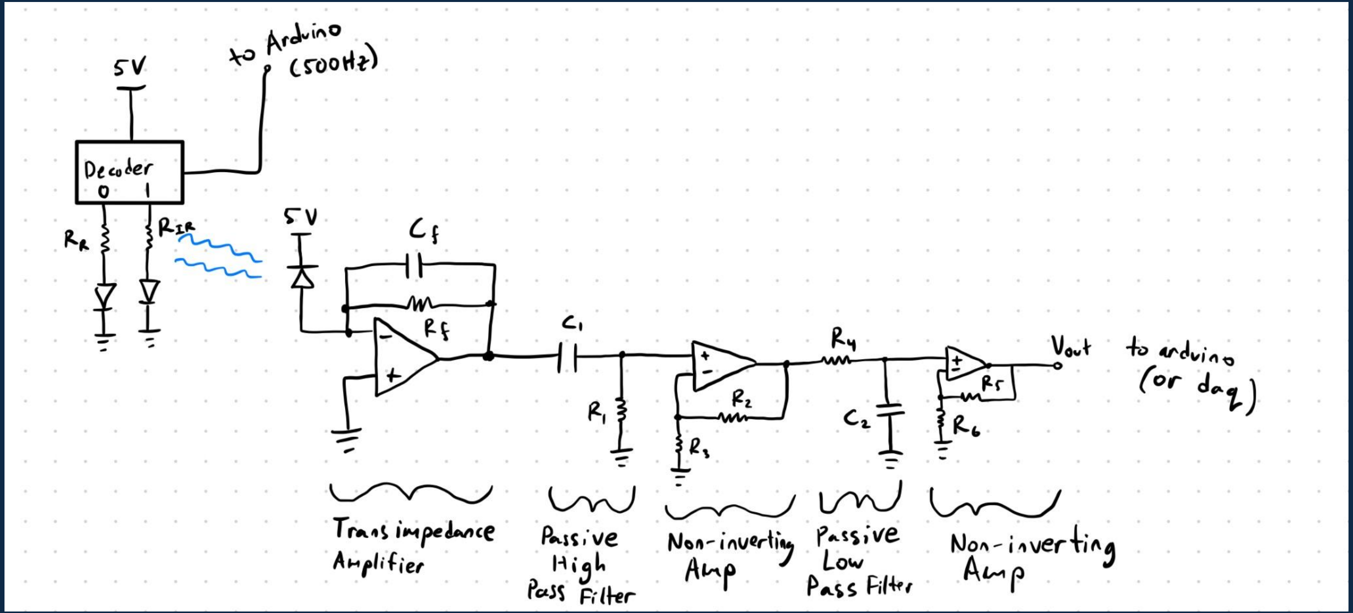
DIY Arduino Pulse Sensor by Orlando Hoilett

Or into a Daq device through BNC cable

ECG With PPG Using Arduino By Peter Balch (2014)

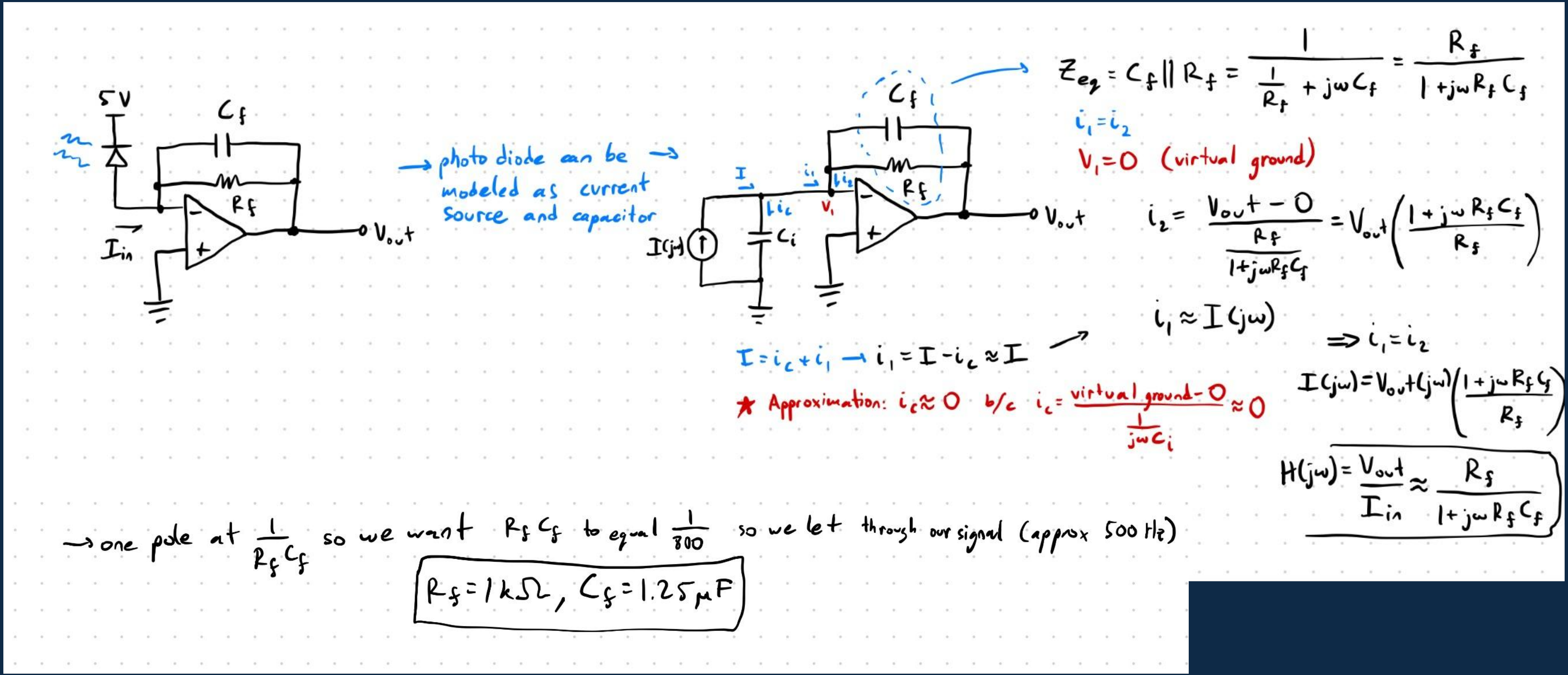
Utmel Electronic- MCP6002 Op-Amp Circuit, Printout, Datasheet

Designed circuit



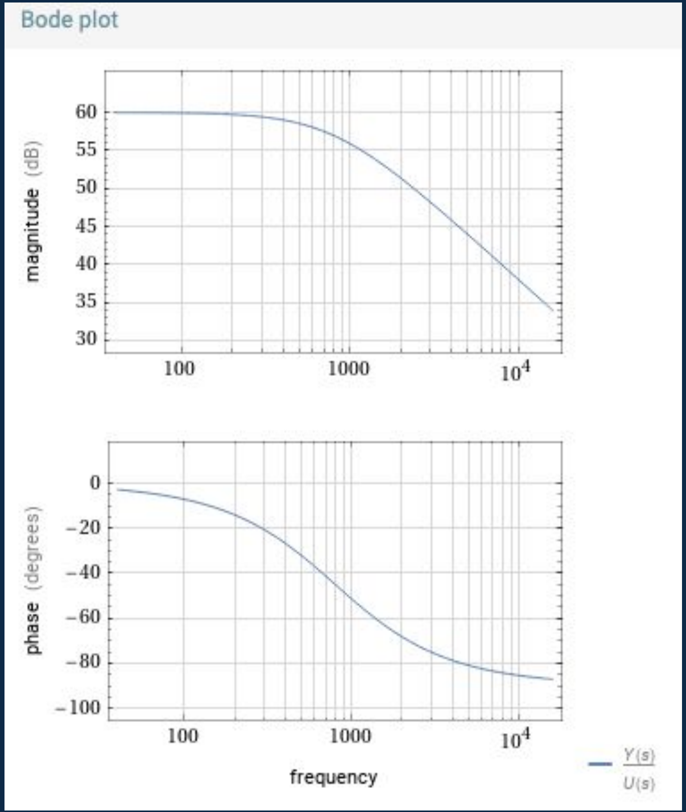
The circuit is designed to have a Gain of 3720, which is approximately the 3700 typical for PPG's (Langereis). Vout will go port A0 on the Arduino.
Also, our photodiode is reverse-biased with a positive voltage of at the cathode.

Transimpedance Amplifier

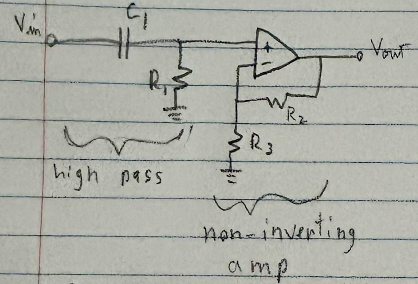


A transimpedance amplifier here is used to convert the current produced by the photodiode operating in photoconductive mode to a voltage for the rest of our circuit. The op-amp is inverting.

Transimpedance Amplifier Bode Plot



High Pass Filter and Amp



$R_1 = 10\,\Omega$ $\quad C_1 = 0.04\,F$

$R_2 = 636.2\,\Omega$

$R_3 = 10\,\Omega$

input signal ≈ 1 Hz

target f_c for high pass = 0.4 Hz

target gain = 60

$$f_c = \frac{1}{2\pi R_1 C_1} = 0.4\,Hz$$

$$C_1 = \frac{1}{2\pi (0.4\,Hz) R_1} \qquad \text{set } R_1 = 10\,\Omega$$

$$C_1 = \frac{1}{2\pi (0.4\,Hz)\,10\,\Omega} = 0.040\,F$$

$$A_F = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_3}$$

$$\text{Gain} = \frac{A_F \left(\frac{f}{F_c}\right)}{\sqrt{1+\left(\frac{f}{F_c}\right)^2}} = 60$$

$$1 + \frac{R_2}{R_3} = \frac{60\sqrt{1+\left(\frac{f}{F_c}\right)^2}}{\left(\frac{f}{F_c}\right)}$$

$f = 1\,Hz$

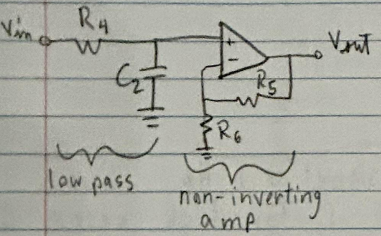
$F_c = 0.4\,Hz$

$$\frac{R_2}{R_3} = \frac{60\sqrt{1+\left(\frac{f}{F_c}\right)^2}}{\frac{f}{F_c}} - 1 = 63.62$$

$R_2 = 63.62\,R_3$ $\qquad$ set $R_3 = 10\,\Omega$

$R_2 = 636.2\,\Omega$

Low Pass Filter and Amp



$R_4 = 10\ \Omega$ $C_2 = 0.796\ mF$
$R_5 = 610.8\ \Omega$
$R_6 = 10\ \Omega$

input signal ≈ 1 Hz
target f_c for low pass = 20 Hz
target gain = 62

$$f_c = \frac{1}{2\pi R_4 C_2} = 20\ Hz$$

$$C_2 = \frac{1}{2\pi (20 Hz)(R_4)}$$ set $R_4 = 10\ \Omega$

$$C_2 = \frac{1}{2\pi (20\ Hz)\, 10\ \Omega} = 0.796\ mF$$

$$\text{Gain} = \frac{A_F}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = 62$$

$$A_F = \frac{V_{out}}{V_{in}} = 1 + \frac{R_5}{R_6}$$

$$1 + \frac{R_5}{R_6} = 62 \cdot \sqrt{1+\left(\frac{f}{f_c}\right)^2}$$

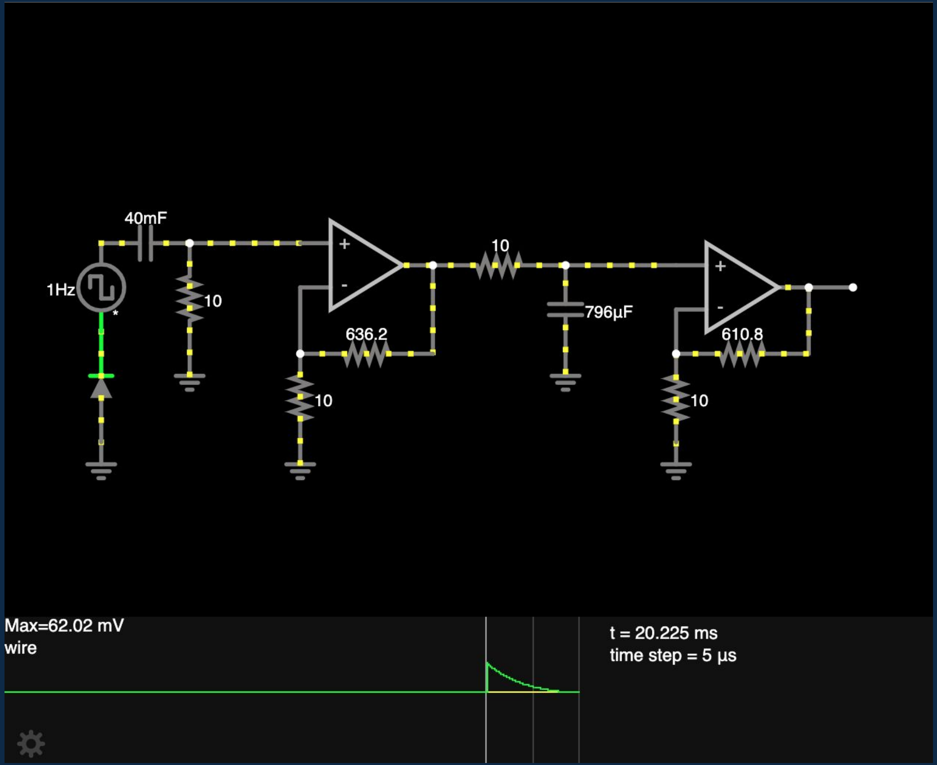
$F = 1\ Hz$ $f_c = 20\ Hz$

$$\frac{R_5}{R_6} = 62 \cdot \sqrt{1+\left(\frac{f}{f_c}\right)^2} - 1 = 61.08$$

$R_5 = 61.08\ R_6$ set $R_6 = 10\ \Omega$

$R_5 = 610.8\ \Omega$

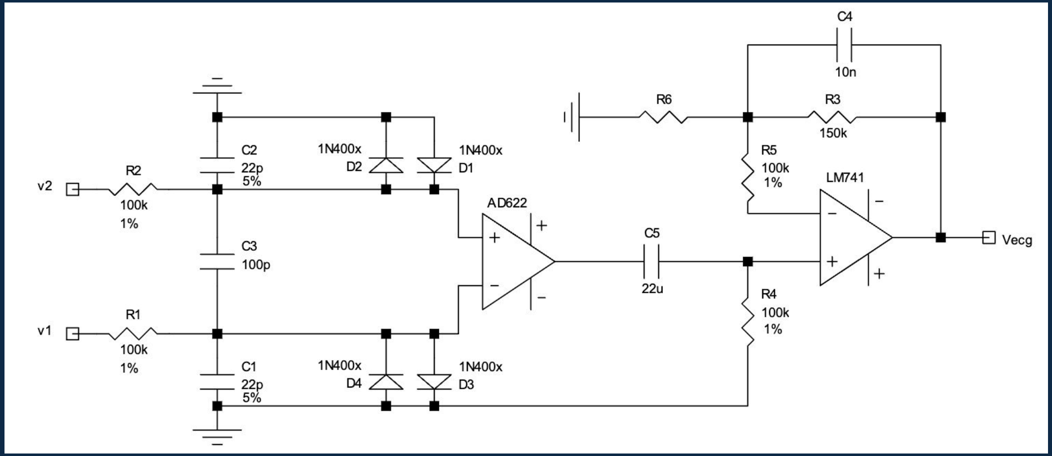
Designed Circuit Simulation (PPG)

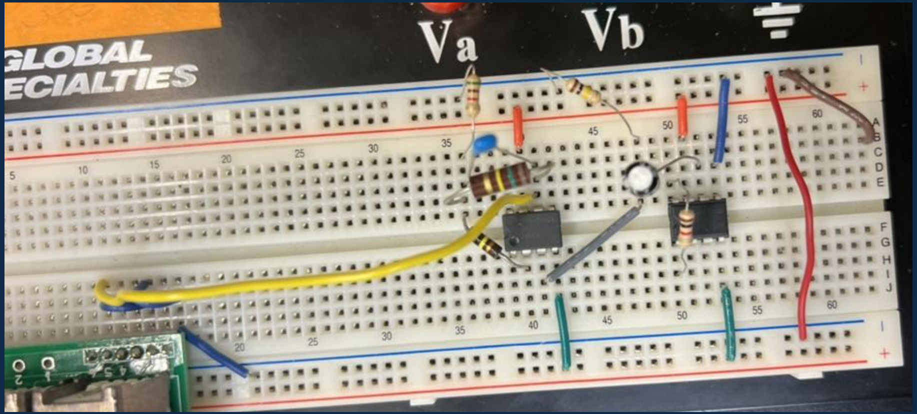


The simulation to the right shows the previous slide’s PPG circuitry. The square wave is used to mimic the signal of heartbeat pulses, and the output can be seen on the graph at the bottom.

We used this circuit for the simulation because the software does not contain the MCP6002 chip that we wanted to use in our ideal design.

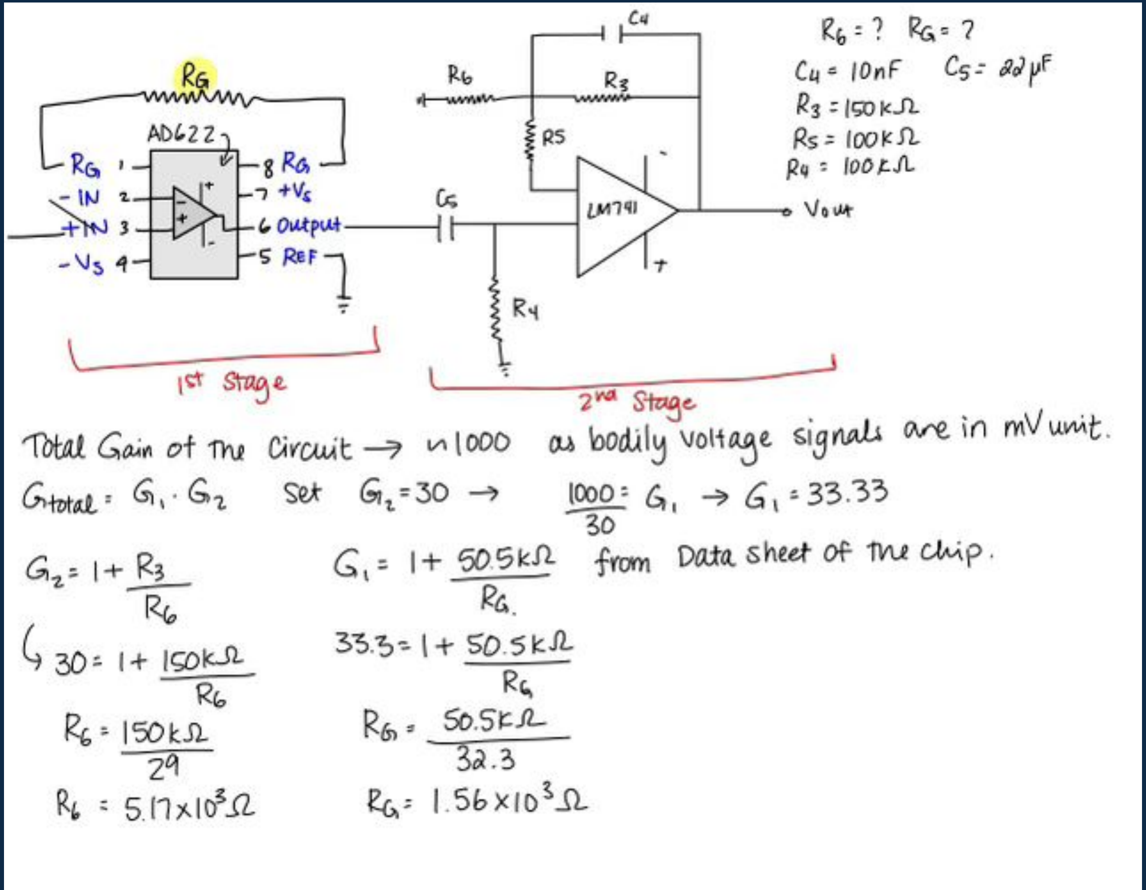
ECG General Circuit Diagram as it is essential for BP estimation, sourced from BENG 152





- Using AD622 and LM741 Op Amps for this ECG circuit
- By using AD622, we can reduce the complexity of the circuit and only worry about building everything to the right of the diodes, gain of the AD622 amp is determined by Rg which is not shown in the circuit
- R1-C1 and R2-C2 are combinations of low pass filters
- R4-C5 make a high pass filter, with time constant of 2.2s and cut off frequency of 0.07 Hz
- R3-C4 are low pass filters; for low frequencies the capacitor is open, and for high it is short, tau= 1.5 ms, cut-off frequency of 100 Hz.
- Hence, the right stage of the circuit (right of AD622) has a bandpass filter from 0.07-100Hz, good for rejecting common mode 60Hz noise.
- Powering the two chips using 2- 9V batteries, and the input signals would be from the leads placed on the chest and the abdomen

Determination of Circuit Component Values Depending On The Constraints



- 3 leads were placed on the body
  - Lower abdomen (GND)
  - Right chest (-)
  - Left chest (+)
- The left chest lead inputs into pin 3, right chest lead inputs to pin 2, and the abdomen lead inputs to pin 5 of the AD622 chip
- Vout is where the analog signal goes into the daq on a PC so that MATLAB can output the ECG chart depending on the voltage signals and do appropriate analysis and calculations

Blood Pressure Estimation

- BP estimation function

$$BP_n = a \cdot lnPTT + b \cdot HR + c \cdot BP_{n-1} + d \qquad (4)$$

- Where PTT can be obtained from the time difference between ECG and PPG signals,.
- HR can be easily measured from the ECG, and BP_{n-1} is the previous BP estimate.
- The four coefficients (a,b,c and d) can be calculated by applying the least square method.

Various equations have been proposed:

- BP = a*ln(PTT) + b
- BP=a/PTT + b
- $BP=a/(PTT+c)^2 + b$

M Goutham, M Thanusha, A Shrikanth, CP Rupesh Project Presentation (2016)

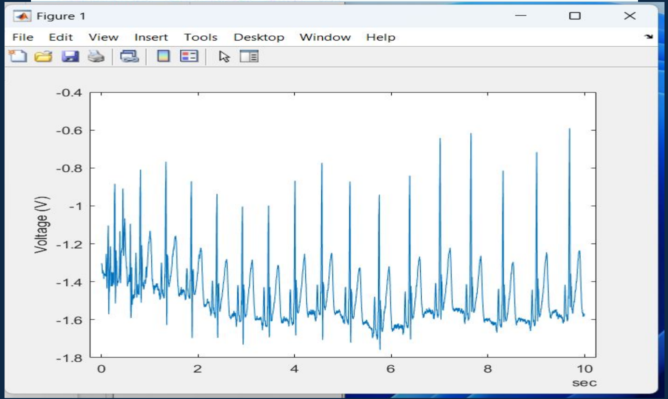
- t = 60000/HRbpm - PAT
- SystolicBP = 184.3 - 1.329*HRbpm + 0.0848*t
- DiastolicBP = 55.96 - 0.02912*HRbpm + 0.02302*t

ECG with PPG using Arduino by Peter Balch - https://www.instructables.com/ECG-With-PPG-Using-Arduino/

- Several different sources were studied to determine the estimation relationship between PPG signals and BP
- Determined that one needs both ECG and PPG signals for this
  - Need PAT which is Pulse Arrival Time i.e. the time elapsed between the R-wave of ECG and the systolic peak in PPG
- For this project, we have decided to use the formulas seen in the very bottom picture as it clearly outputs both systolic and diastolic blood pressure

ECG Circuit Validation And MATLAB Algorithm for ECG Chart

```
d = daqlist;
d(1, :)
d{1, "DeviceInfo"}
dq = daq("ni")
ch = addinput(dq,"Dev1", "ai0","Voltage")
data = read(dq, seconds(10));
plot(data.Time, data.Dev1_ai0);
ylabel("Voltage (V)");
dq.Rate = 400;
[data, startTime] = read(dq, seconds(10));
plot(data.Time, data.cDev1_ai0);
ylabel("Voltage (V)");
```



This is an example of an ECG waveform outputted using 3 lead configuration and the ECG circuit shown earlier.

We attempted to write a MATLAB algorithm for peak detection over a threshold voltage, but we were unable to get it to work. The period of time, the circuit and algorithm records the data coming from the leads placed on the body can be changed by setting the seconds value of choice where the zero in 10 is selected. This also validates the circuit constructed for ECG signal collection.

The code on the top left:

- Retrieves a list of available data acquisition devices and displays information about the first device.
- Creates a Data Acquisition Toolbox object (‘dq’) for National Instruments hardware.
- Adds an analog input channel ("ai0") from the device "Dev1" to ‘dq’ to measure voltage.
- Reads voltage data from the analog input channel for 1 second and plots it against time.
- Sets the acquisition rate of ‘dq’ to 5000 samples per second, reads data for 2 seconds, and plots the newly acquired voltage data against time.
- When the code is compiled after execution, the time and voltage readings for the ECG graph can be found in the workspace section of the MATLAB window with their respective matrix
- A similar code can also be used for PPG signals, as the end result output from the analog circuit will also be voltage readings, which can be plotted using MATLAB

ECG and PPG Peak Detection

Code is referenced from an open source through MathWorks (Abhijith Bailur)

```
%% peak detection of ECG
j=1;
n=length(y);
for i=2:n-1
    if y(i)> y(i-1) && y(i)>= y(i+1) && y(i)> 0.45*max(y)
       val(j)= y(i);
       pos(j)=i;
       j=j+1;
     end
end
ecg_peaks=j-1;
ecg_pos=pos./1000;
plot(pos,val,'*r');
title('ECG peak');
```

```
%% peak detection of PPG
m=1;
n=length(z);
for i=2:n-1
    if z(i)> z(i-1) && z(i)>= z(i+1) && z(i)> 0.45*max(z)
       val(m)= z(i);
       pos1(m)=i;
       m=m+1;
     end
end
ppg_peaks=m-1;
ppg_pos=pos1./1000;
ppg_val=val;
plot(pos1,val,'*g');
title('ECG & PPG signal');
legend('ECG signal','PPG signal');
```

Peak Detection for ECG signals

- First of we have a loop iteration that processes each data point of ECG signal
- Then, using if and conditional statements we can set peak criteria that will iterate through the dataset matrix, and check if a point is greater than the one prior and after it, and makes sure it is above the threshold
- If it is, then the voltage amplitude and the time position are stored in an array with “val” and “pos”
- And then again, in the plot you can see a peak identified with red asterisks

Peak Detection for PPG signals

- Similar loop iteration as the ECG peak detection section
- Follows the same peak counting criteria as the ECG
- Similar to the ECG, the voltage value and the time position is stored in an array of “val” and “pos1”
- Then just like the ECG code, the peaks in the PPG code is plotted with the peaks marked with green asterisks

HR, HRV, and PRV Determination

- Calculating Heart Rate from ECG signal using the time intervals between successive R peaks that were detected by the code presented in the previous slide (RR Interval) as seen in the for loop. It is saved in a new array with j elements called ‘e’
- HR is calculated using the formula that takes 60 seconds and divides it by the mean RR interval (seconds)
- Furthermore, HRV can be estimated using the formula 60/e; which takes into account each RR interval data point

Pulse Rate Variability is the variation in heart rate similar to HRV but from PPG

- This code is very similar to the ECG HRV code, where time intervals between each PPG signal peak is determined by calculating the difference between successive PPG peaks from the ‘pos1’ array.
- The calculation of pulse rate and pulse rate variability is analogous to the heart rate and heart rate variability calculations as seen in the picture on the top right
- Bth the HRV and PRV metrics are also displayed as can be seen in the algorithm in the top right and bottom right images

Pulse Transit Time calculation using the time interval array of both the ECG and PPG for each successive peak in both waveform

- Simply done by subtracting ECG peak time position from PPG peak time position as determined by the code in the previous slide
- And then a graph with each PTT can be plotted

```
j=1;
for i=1:ecg_peaks-1
    e(j)= ecg_pos(i+1)-ecg_pos(i);% gives RR interval
    j=j+1;

end
hr=60./mean(e); % 60/ mean of RR interval

hrv= (60./e); % 60/ each RR interval
figure,stairs(hrv);
title('HRV');
xlabel('samples');
ylabel('hrv');
```

```
%% PRV
k=1;
for i=1:ppg_peaks-1
    f(k)= ppg_pos(i+1)-ppg_pos(i);
    k=k+1;
end
pr=60./mean(f);
prv= 60./f;
figure,stairs(prv);
title('PRV');
xlabel('samples');
ylabel('prv');
%% PTT
ptt=(ppg_pos-ecg_pos);
figure,stairs(ptt);
title('PTT');
xlabel('ptt');
ylabel('time');
```

Code is referenced from an open source through MathWorks (Abhijith Bailur)

Using The Calculated HR and PAT to Estimate BP

Code is written by Mohak using values from previous code

Calculating Pulse Arrival Time (PAT)

- Initializes an array called ‘pat’ of zeros with a length equal to the minimum number of detected peaks in both ECG and PPG signal -1
- Iterates over the indices of the minimum number of detected peaks between the two signals as seen in the for loop
- In the loop, it calculates the PAT for each pair of corresponding peaks by subtracting ECG peak position from PPG peak position, representing the time difference between the arrival of the pulse wave at the PPG sensor and the corresponding R peak in the ECG signal
- Then we can calculate the mean PAT for each peak in ECG and PPG

Using HR calculated earlier, and PAT to estimate Systolic and Diastolic Blood Pressure

- Here, we are using the relationship that we had found while doing literature review for estimating the systolic (SBP) and diastolic (DBP) blood pressure
- The code then prints the estimated SBP and DBP value

```
% Calculate Pulse Arrival Time (PAT)
pat = zeros(1, min(ecg_peaks, ppg_peaks) - 1);
for i = 1:min(ecg_peaks, ppg_peaks) - 1
    pat(i) = ppg_pos(i) - ecg_pos(i);
end

% Calculate mean PAT
mean_pat = mean(pat);
```

```
% Estimate Systolic Blood Pressure (SBP)
sbp = 184.3 - 1.329 * hr + 0.0848 * ((6000 / hr) - mean_pat);

% Estimate Diastolic Blood Pressure (DBP)
dbp = 55.96 - 0.02912 * hr + 0.02302 * ((6000 / hr) - mean_pat);

% Display the estimated SBP and DBP
fprintf('Estimated Systolic Blood Pressure (SBP): %.2f mmHg\n', sbp);
fprintf('Estimated Diastolic Blood Pressure (DBP): %.2f mmHg\n', dbp);
```

- t = 60000/HRbpm - PAT
- SystolicBP = 184.3 - 1.329*HRbpm + 0.0848*t
- DiastolicBP = 55.96 - 0.02912*HRbpm + 0.02302*t

Formula from: ECG with PPG using Arduino by Peter Balch - https://www.instructables.com/ECG-With-PPG-Using-Arduino/

Algorithm Validation

- We were unable to perform validation of the algorithm because for that, we will need biological signals generated from a PPG circuit, as well as a daq device which we do not have access to.
- ECG signal recording and plotting algorithm was validated because we had collected signal data, and validated the algorithm in BENG 152 which some students were enrolled in the current quarter.
- However, it can easily be done if the described apparatus is constructed physically for both PPG and ECG signal acquisition

Other similar devices

- Apple Watch Series 4,5,6 have PPG sensors built into them
  - Use green LED lights & light sensitive photodiodes to detect blood flow in the wrist
- Fitbit trackers also have PPG sensors built in to measure heart rate
  - Detects changes in blood volume in the blood vessels
  - Analyzes & uses to detect irregularities and potential signs of Afib
- Samsung Watches also have built in PPG sensor
  - Measures blood pressure, heart rate, and heart rhythm
- Garmin Elevate
  - Heart rate technology sensor that uses PPG
- Oura Ring
  - Infrared PPG sensors are used inside the ring to detect heart rate and respiration

Limitations

- Accuracy of PPG can be influenced by many factors
  - Skin tone (melanin absorption creates decreased signal intensity)
  - Age (skin thickness/vessel/capillary change signal intensity and modify PPG waveform)
  - Sweat (decreases signal intensity and modifies PPG waveform)
  - Level of activity (increases respiratory rate, causing low frequency noise which modifies PPG waveform)
  - Need both for blood pressure estimation, makes device less mobile and less user friendly
- Sensitive to motion
- Signal can be noisy
- Sensitive to ambient light
- Can't directly measure blood pressure, only estimate
- Requires two 9V batteries and a 5V battery, as well as a PC. We could probably do better with power cost, and this also prevents any portability. As this design stands, it would probably be easier for a patient to have their blood pressure measured with a cuff, and heart rate and SPO_2 measured separately with a PPG sensor.

Possible Future Improvements

- Since the peak interval accuracy of PPG’s is limited due to the large amount of power required by the LED’s, compact fluorescent lumen can be used. With their lower energy cost, the sampling rate could be increased, aiding with the peak interval accuracy. We can also try to refactor to reduce power consumption
- This could also help with measuring heart rate variability, which takes around 5 minutes. The problem with compact fluorescent lumens would be the increased heat output.
- Since PPG’s are sensitive to ambient light, a shroud could be added around the device to reduce the ambient light interference and clear up noise.
- Incorporate the system to a wearable device like a watch/wristband/glove.
- Incorporating machine learning to estimate blood pressure without ecg would make our device much more portable

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