Project : Digital Pulse Oximeter.

Principle:

1). Beer's Law: $I = I_0 \cdot 10^{-\varepsilon C L}$

I_0: light intensity entering sample.

I: ~ leaving sample.

ε: extinction coefficient

C: sample concentration

L: sample length (depth)

2) Absorbance of Hemoglobin (Hb) and Oxygenated Hemoglobin (Hb_{O_2}) at various wavelength.

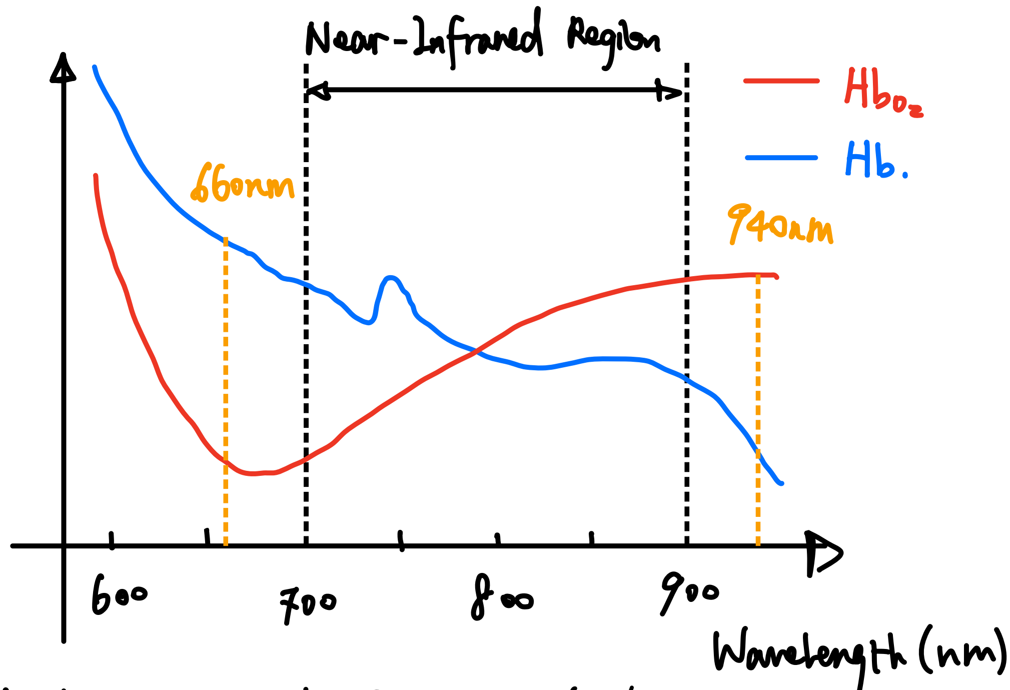
Absorbance:

$A = \varepsilon C L$.

* assume C and L constant.

$C = 1\,mmol$

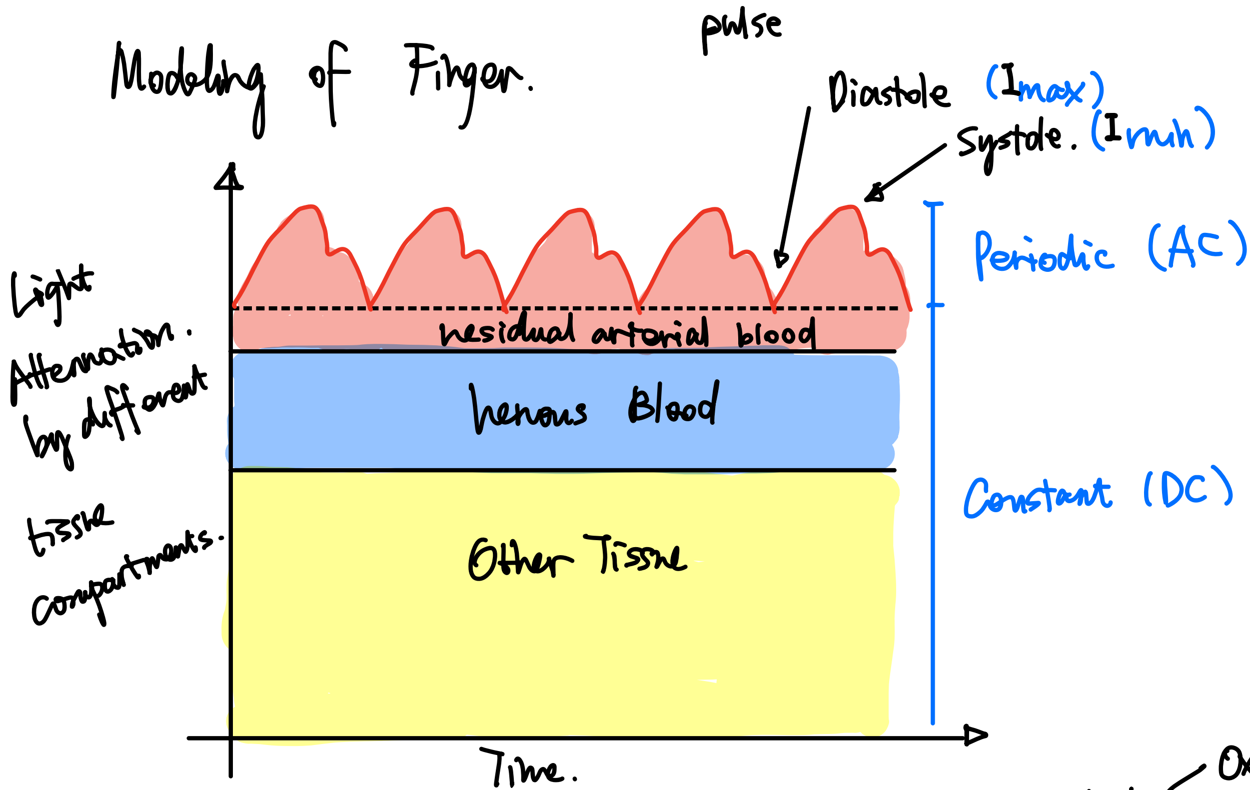
$L: 1\,cm$



	wavelength	ε_{Hb}	$\varepsilon_{Hb_{O_2}}$
λ_1	660	0.81	0.08
λ_2	940	0.18	0.29

(L/(mmol·cm))

Modeling of Finger.



Periodic arterial blood < Oxg / non-oxg.

at systole:

$$I_{min} = I_0 10^{-\varepsilon_{DC} C_{DC} \cdot L_{DC} - (\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) L_{max}}$$

at diastole:

$$I_{max} = I_0 10^{-\varepsilon_{DC} C_{DC} \cdot L_{DC} - (\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) L_{min}}$$

ratio:

$$\frac{I_{min}}{I_{max}} = \frac{I_0 10^{-\varepsilon_{DC} C_{DC} \cdot L_{DC} - (\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) L_{max}}}{I_0 10^{-\varepsilon_{DC} C_{DC} \cdot L_{DC} - (\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) L_{min}}}$$

$$= 10^{-\cancel{\varepsilon_{DC} C_{DC} L_{DC}} - (\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2})(L_{max} - L_{min}) + \cancel{\varepsilon_{DC} C_{DC} L_{DC}}}$$

$$= 10^{-(\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) \Delta L}$$

$$\Rightarrow \log \frac{I_{min}}{I_{max}} = -(\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) \Delta L$$

$$\boxed{A = (\varepsilon_{Hb} C_{Hb} + \varepsilon_{HbO_2} C_{HbO_2}) \Delta L = \log \frac{I_{max}}{I_{min}}}$$

where $I_{max} = I_{max,AC} + I_{DC} = I_{max} + I_{offset}$

$I_{min} = I_{min,AC} + I_{DC} = I_{min} + I_{offset}$

$$\Rightarrow \quad C_{Hb} = \frac{A}{\Delta L} - \frac{\varepsilon_{HbO_2} C_{HbO_2}}{\varepsilon_{Hb}}, \quad C_{HbO_2} = \frac{A}{\Delta L} - \frac{\varepsilon_{Hb} C_{Hb}}{\varepsilon_{HbO_2}}$$

at λ_1 and λ_2 (660 nm and 940 nm to maximize diffs)

$$A_{\lambda_1} = (\varepsilon_{Hb,\lambda_1} C_{Hb} + \varepsilon_{HbO_2,\lambda_1} C_{HbO_2})\Delta L$$

$$A_{\lambda_2} = (\varepsilon_{Hb,\lambda_2} C_{Hb} + \varepsilon_{HbO_2,\lambda_2} C_{HbO_2})\Delta L$$

$$\frac{A_{\lambda_1}}{A_{\lambda_2}} = \frac{\varepsilon_{Hb,\lambda_1} C_{Hb} + \varepsilon_{HbO_2,\lambda_1} C_{HbO_2}}{\varepsilon_{Hb,\lambda_2} C_{Hb} + \varepsilon_{HbO_2,\lambda_2} C_{HbO_2}}$$

$$(\varepsilon_{Hb,\lambda_2} C_{Hb} + \varepsilon_{HbO_2,\lambda_2} C_{HbO_2}) A_{\lambda_1} = (\varepsilon_{Hb,\lambda_1} C_{Hb} + \varepsilon_{HbO_2,\lambda_1} C_{HbO_2}) A_{\lambda_2}$$

$$C_{Hb}(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2}) = C_{HbO_2}(\varepsilon_{HbO_2,\lambda_1} A_{\lambda_2} - \varepsilon_{HbO_2,\lambda_2} A_{\lambda_1})$$

$$\Rightarrow \quad C_{Hb} = C_{HbO_2} \frac{(\varepsilon_{HbO_2,\lambda_1} A_{\lambda_2} - \varepsilon_{HbO_2,\lambda_2} A_{\lambda_1})}{(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2})}$$

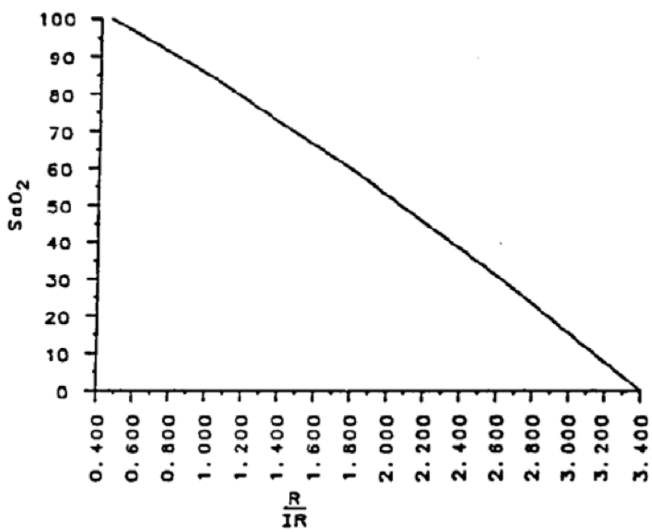
$$SpO_2 = \frac{C_{HbO_2}}{C_{HbO_2} + C_{Hb}} = \frac{\cancel{C_{HbO_2}}}{\cancel{C_{HbO_2}}\left(1 + \frac{(\varepsilon_{HbO_2,\lambda_1} A_{\lambda_2} - \varepsilon_{HbO_2,\lambda_2} A_{\lambda_1})}{(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2})}\right)}$$

$$\boxed{= \frac{(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2})}{(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2}) + (\varepsilon_{HbO_2,\lambda_1} A_{\lambda_2} - \varepsilon_{HbO_2,\lambda_2} A_{\lambda_1})}}$$

or uses Empirically determined relationship between

SpO_2 and normalised $(I_{max,R} - I_{min,R})/(I_{max\,IR} - I_{min,IR})$

$$SpO_2\,(\%) = A - B \cdot \frac{(I_{max,R} - I_{min,R})/\,I_{offset,R}}{(I_{max\,IR} - I_{min,IR})/\,I_{offset,IR}}$$

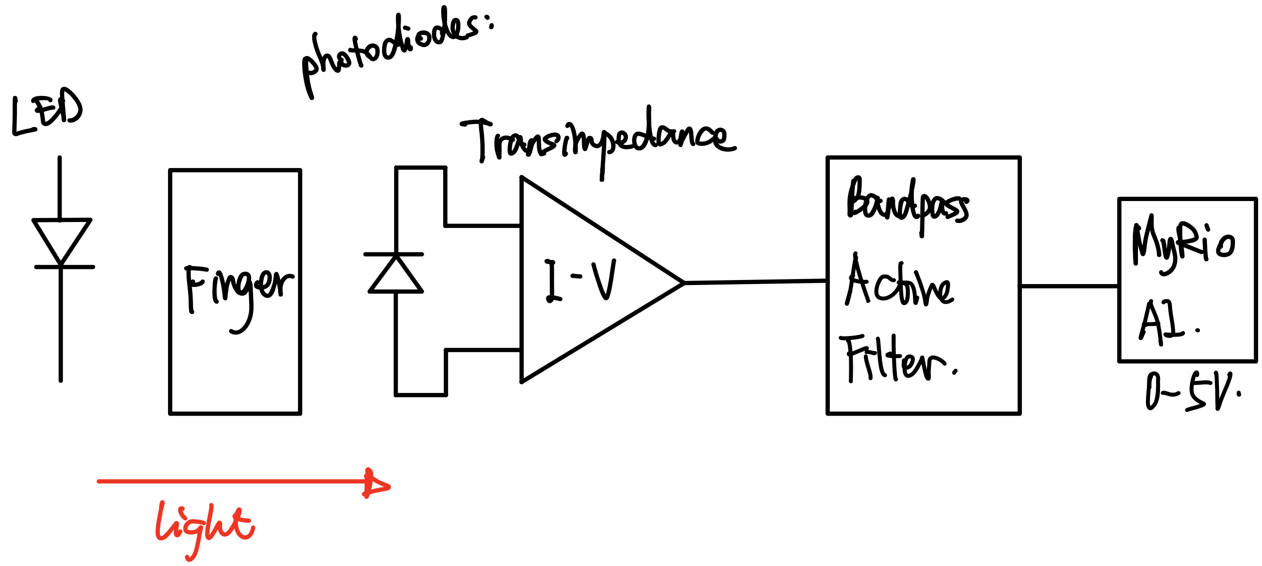


$A = 110$

$B = 25$

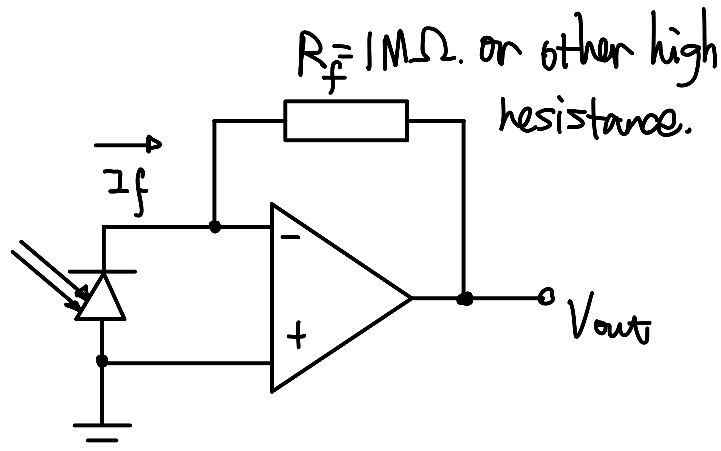
* final choice of formula depends on how easily the DC component of the channel readings can be calibrated.

Theoretical Schematic



- Power.

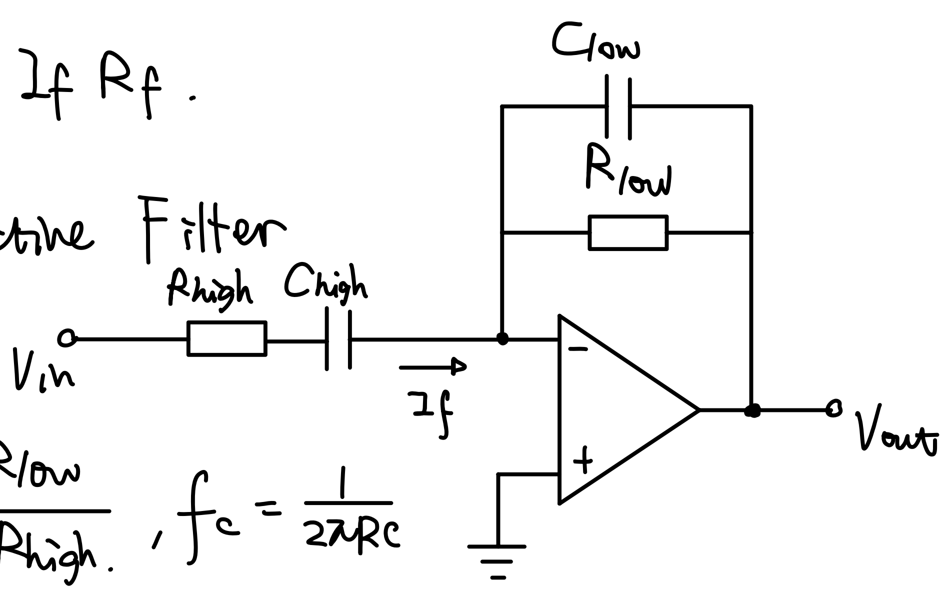
- Transimpedance Amplifier.



– Measure idle voltage / finger-inserted voltage.
compare to myRio AI. port.

$$V_{out} = -I_f R_f.$$

- Bandpass Active Filter

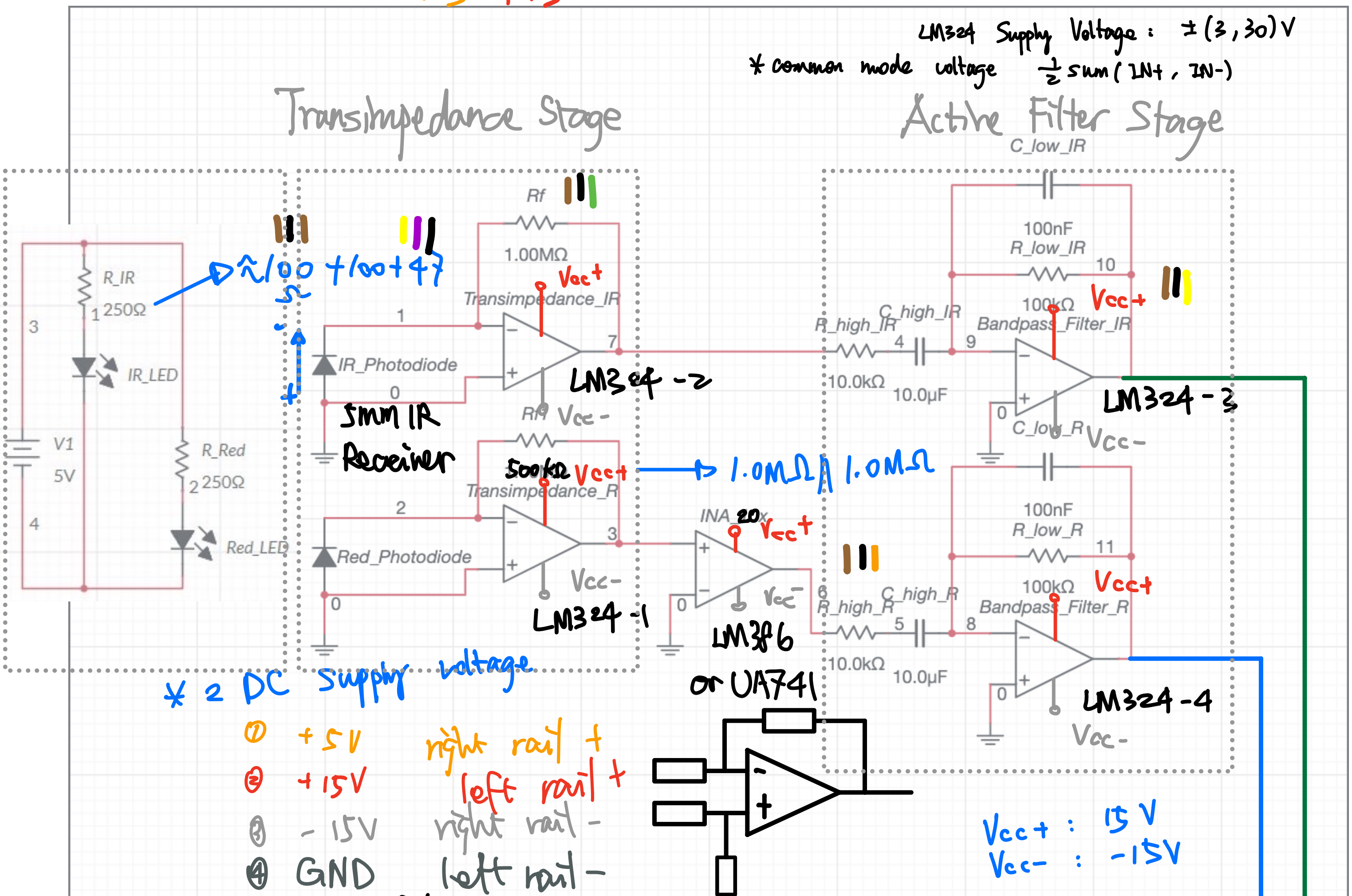


$$\frac{V_{out}}{V_{in}} = \frac{R_{low}}{R_{high}}, \quad f_c = \frac{1}{2\pi RC}$$

Wiring:

* color code: Vcc+ Vcc- GND Signal (Red) Signal (IR)

+5 +15



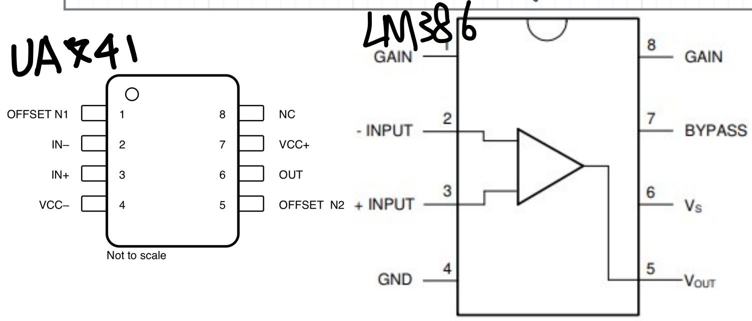
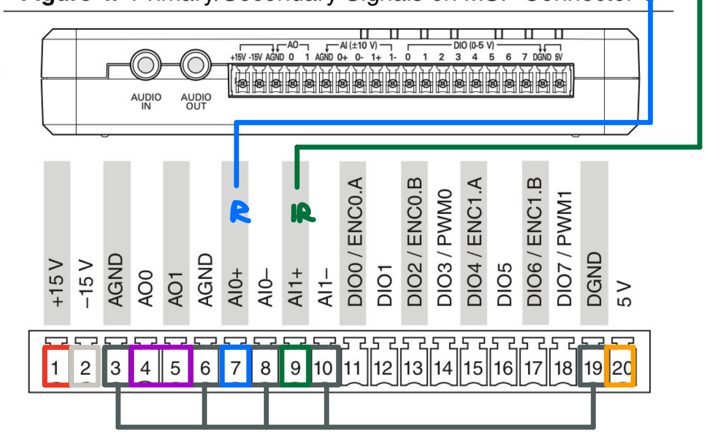
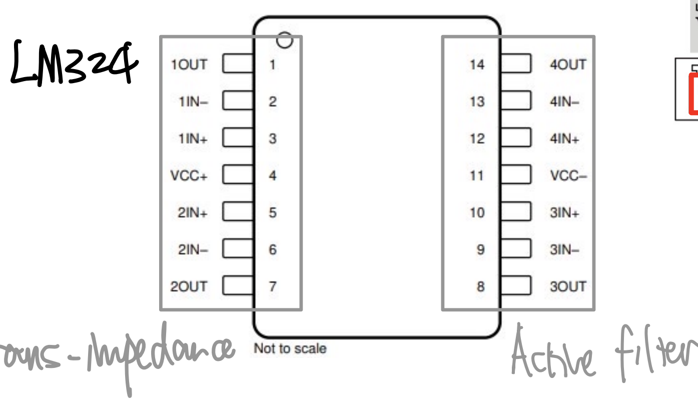


Figure 4. Primary/Secondary Signals on MSP Connector C

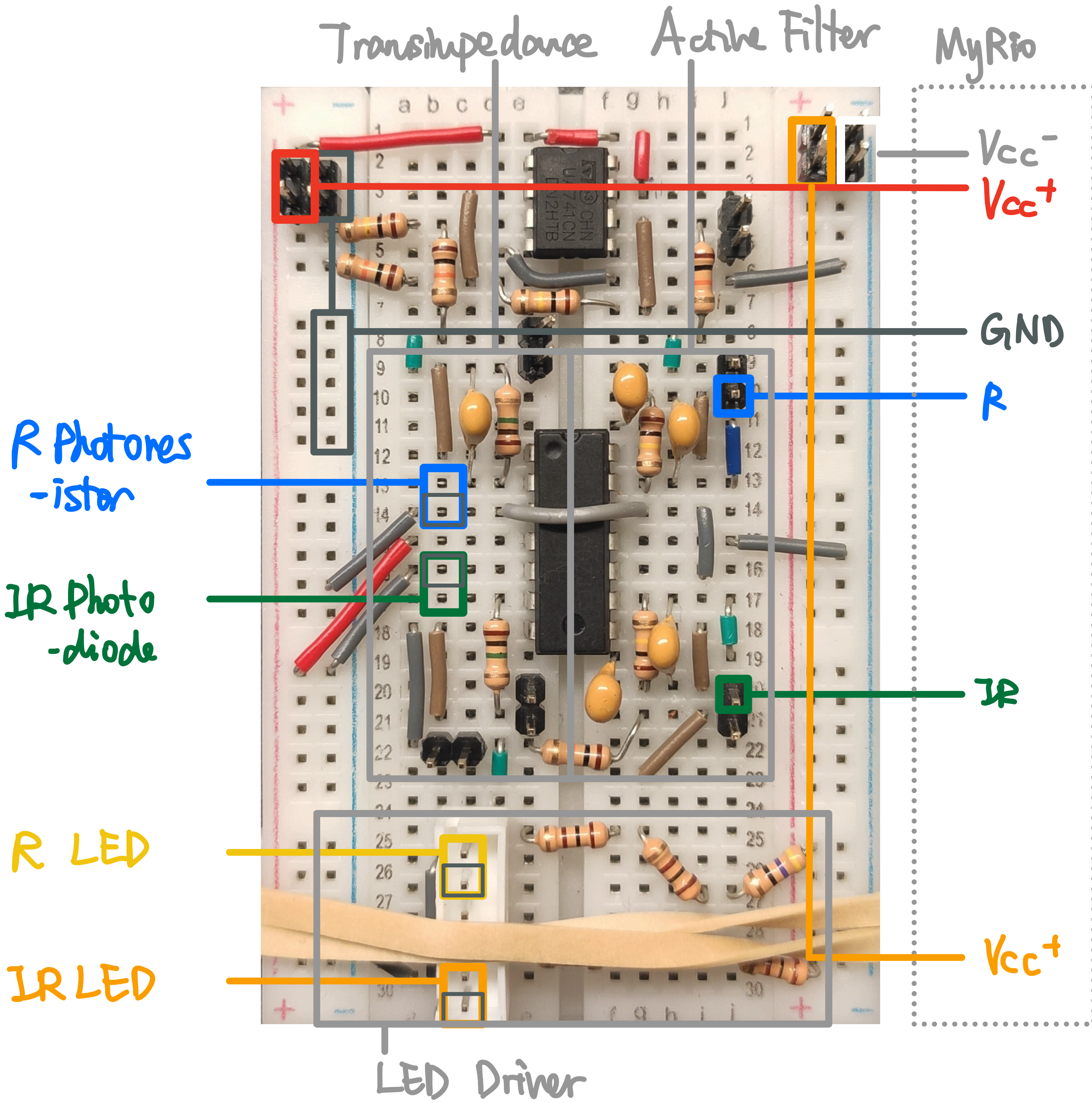




$$V_R = V_{AI0+} - V_{AI0-}$$

$$V_{IR} = V_{AI1+} - V_{AI1-}$$

Bread Board Circuit Layout Diagram.



* added an additional capacitor at R Transimpedance Stage.

* left room for change Gain of IR Active Filter Stage.

Resistor choice: (based on LM324; LM386 has preset gains)

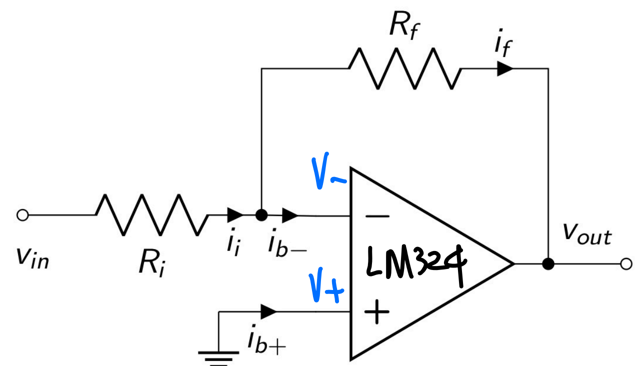
LM324:

- bias current (i_b)

  $\leq \pm 35 \, nA$

- input impedance (R_{in})

  $= 1 \, G\Omega$



To avoid signal clipping at A10, let ideal output

$V_{out,i} = 5V \cdot 90\% = -4.5V$

and the error tolerance 1%

in worse case $V_{out} = (1 - 1\%) \times V_{out,i} = -4.4550V$

assume ideal non-inverting input & virtual short.

$$V_- = V_+ = 0V$$

$$i_f = \frac{V_- - V_{out}}{R_f} = \frac{4.4550V}{R_f}$$

$$V_{in} = -V_{out,i} \cdot \frac{R_i}{R_f} = 4.5V \cdot \frac{R_i}{R_f}$$

$$i_i = \frac{V_{in} - V_-}{R_i} = \frac{V_{in}}{R_i} = \frac{4.5V}{R_f}$$

According to KCL (at - input node): $i_i = i_{b-} + i_f$

$i_{b-} = i_i - i_f$ and $i_{b-} = 35 \, nA = \dfrac{4.5V - 4.4550V}{R_f}$

so $R_{f,upper} = \dfrac{(4.5 - 4.4550)V}{35 \times 10^{-9} A} = 1.3 \times 10^{6} \Omega = 1.3 M\Omega$

- however, the input impedance $R_{in} = 1 G\Omega$

  we want $R_f \lll R_{in}$

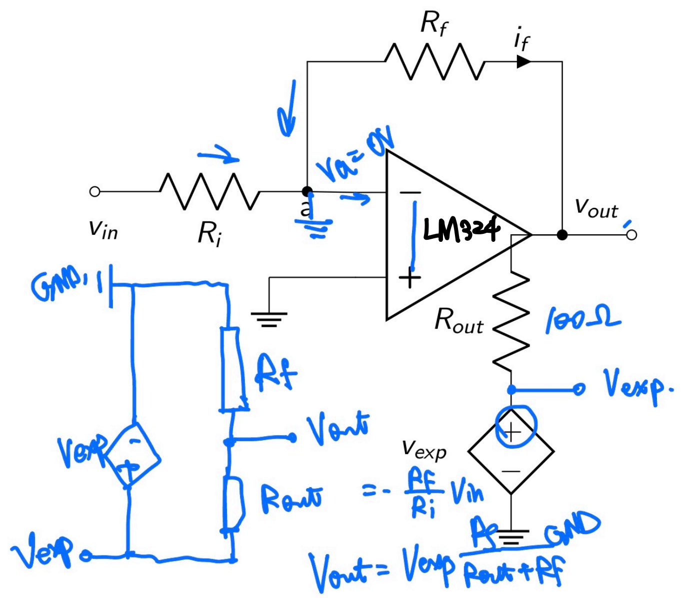
* the desired upper bound of R_f is around $130 k\Omega$

- output impedance (R_{out})

  $= 300\Omega$

- output current (I_{out})

  $\leq -60 mA$



* assume input side fully ideal, $V_a = 0V$

the output impedance R_{out} forms a voltage divider with R_f

if we would like 99% preserved $\dfrac{V_{out}}{V_{exp}}$

$$V_{out} = V_{exp} \cdot \frac{R_f}{R_f + R_{out}} \Rightarrow \frac{R_{f,lower}}{R_{f,lower} + 300\Omega} = 0.99$$

$\Rightarrow R_{f,lower} = 29.7 k\Omega$

Thus for LM324: $30 k\Omega \leq R_f \leq 130 k\Omega$

Circuit Characterization.

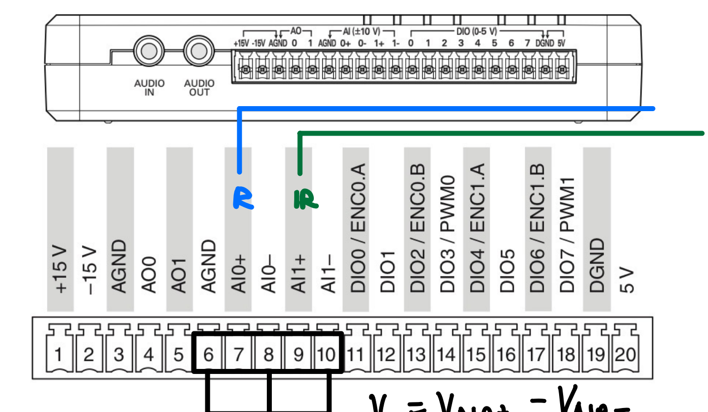
pin layout:

Fgen : offset sine signal. $\begin{cases} R: C/AO1, 4 \rightarrow +INPUT, 3 \\ IR: C/AO0, 2 \rightarrow 3IN^-, 9 \end{cases}$

Circuit Output:

amplified & filtered signal $\begin{cases} R: 4OUT, 14 \rightarrow C/AI0^+, 3 \\ IR: 3OUT, 8 \rightarrow C/AI1^+, 5 \end{cases}$

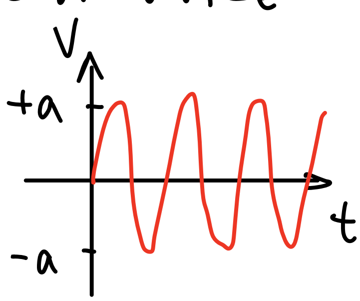
Figure 4. Primary/Secondary Signals on MSP Connector C

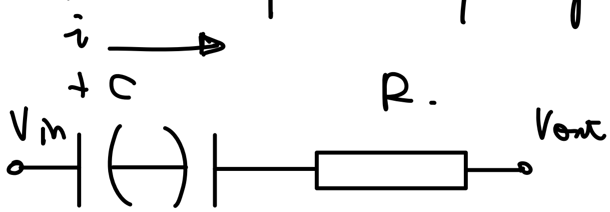


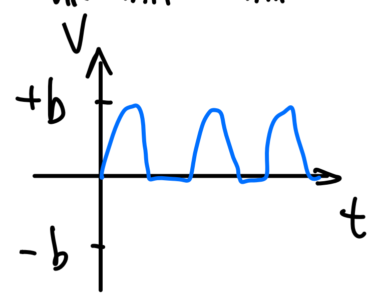
$V_R = V_{AI0+} - V_{AI0-}$

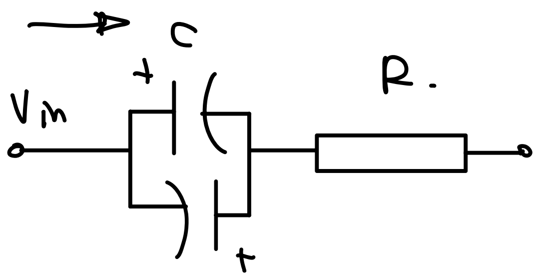
- Characterize : Gain vs. Input Frequency

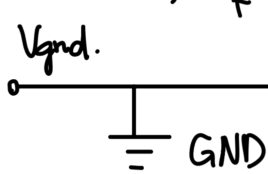
$V_{IR} = V_{AI1+} - V_{AI1-}$









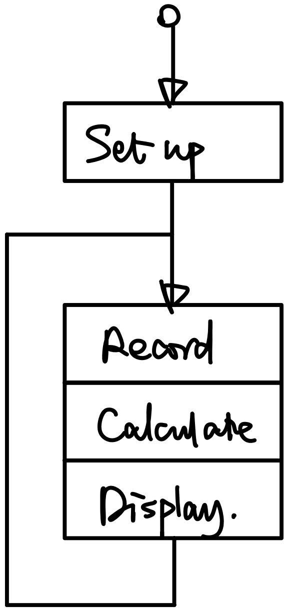


LabVIEW Program Design:

① Super Loop & Producer consumer loop.

Super Loop: (for proof of concept)

Entry point.



AIOs , calibration data.

2 Voltage readings

convert → Intensity , Imax/Imin, A , O_2 saturation

FFT → heart rate

Producer - Consumer Loop: (for future improvements)

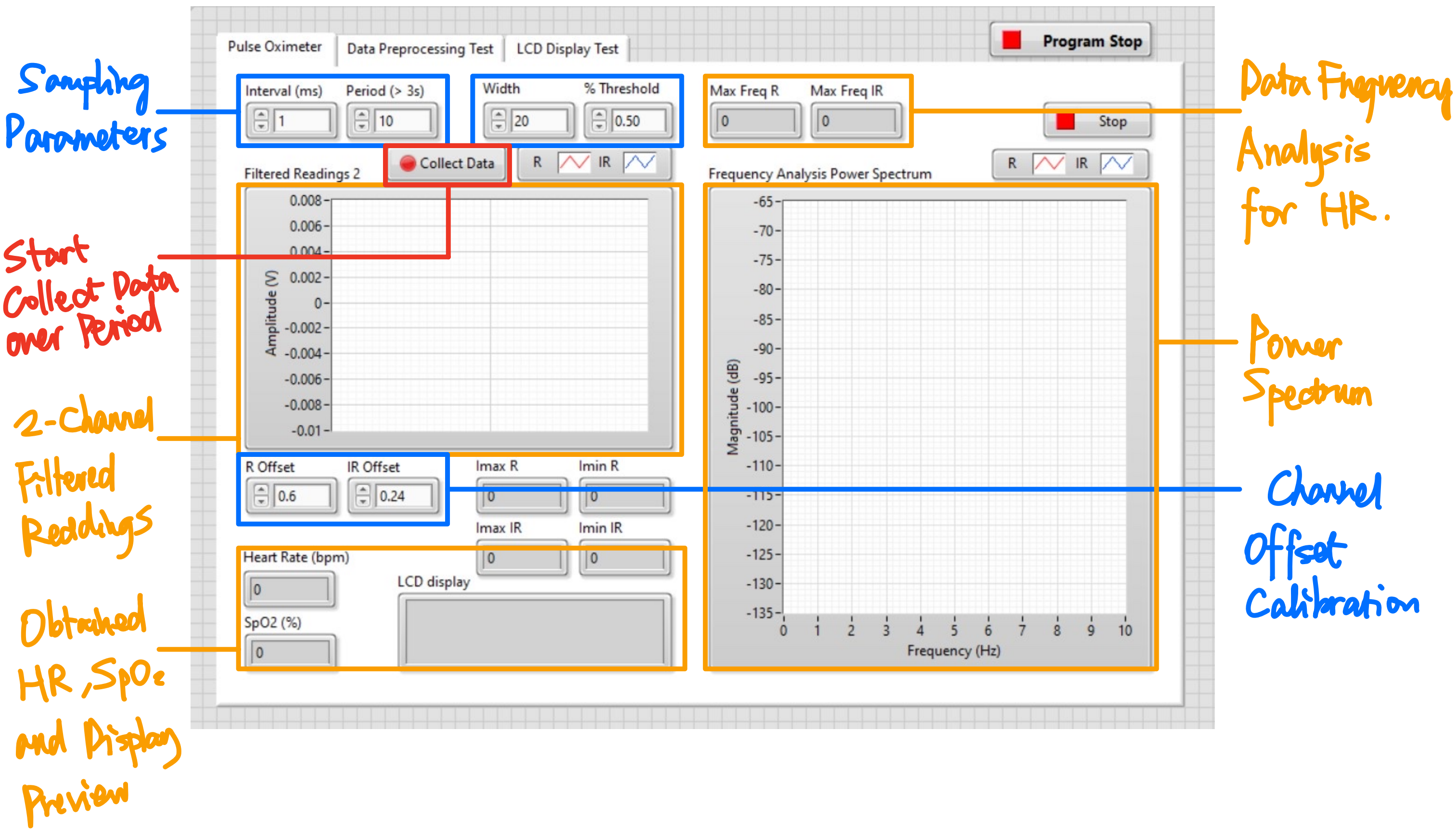
2 Voltage readings

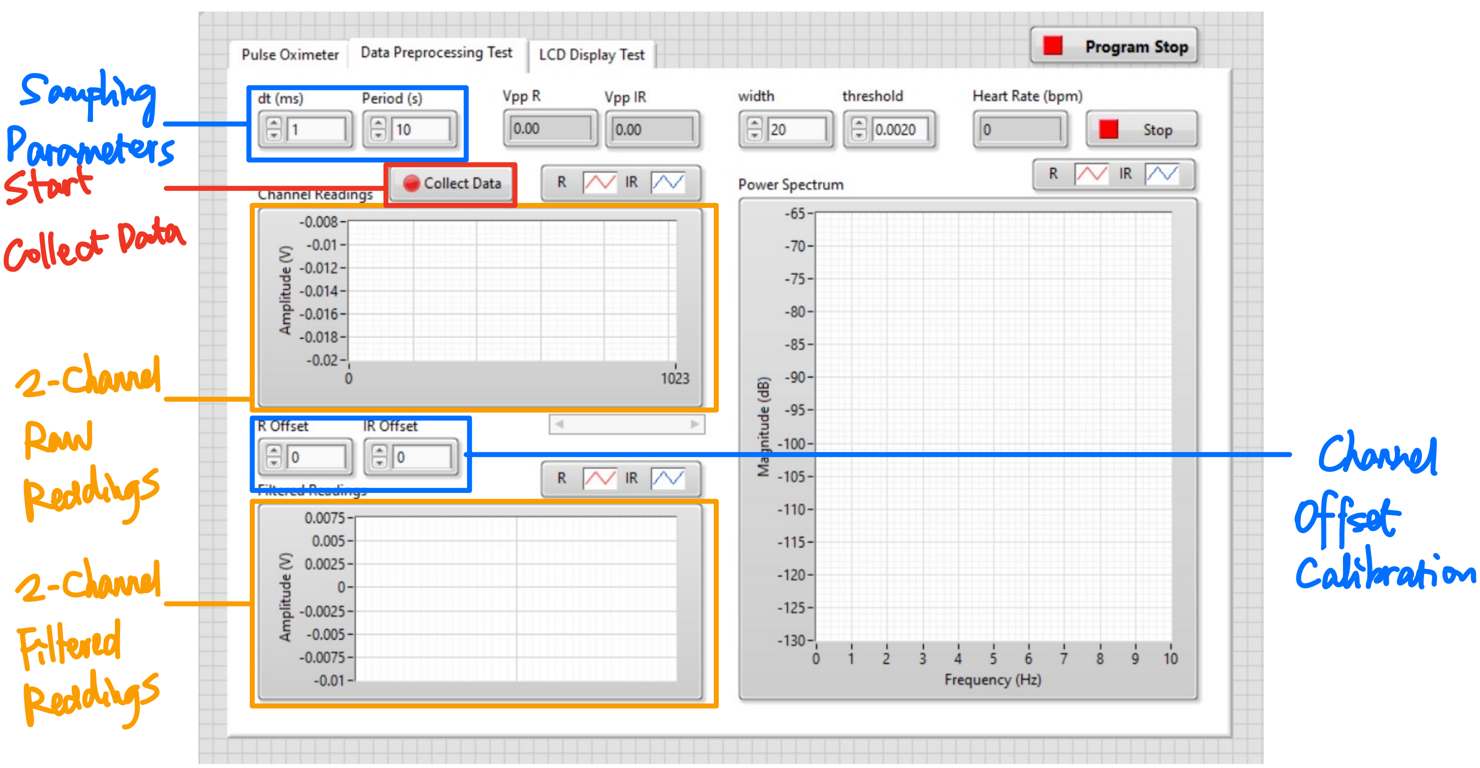
convert → Intensity , Imax/Imin, A , O_2 saturation

FFT → heart rate

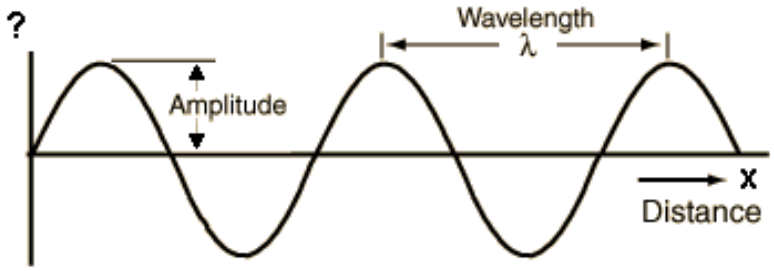
LabVIEW Front Panel Preview

① Pulse Oximeter. Tab.





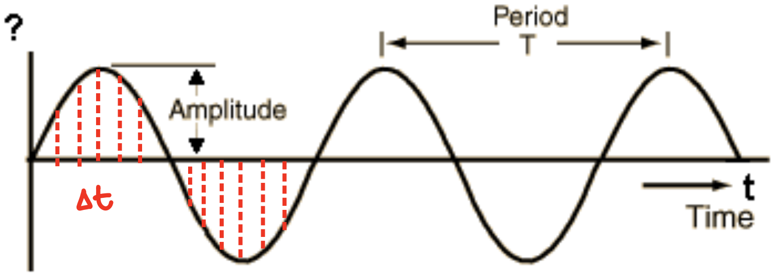
② Test Program:



Sine Pattern

Inputs
- # sample
- amplitude
- cycles

output
- sine wave Y array



Period T, Freq $f = \frac{1}{T}$

Equations:

$$\text{Waveform duration} = \text{Period} \cdot \#\text{ of period}.$$

$$\Delta t \cdot \#\text{sample} = T \cdot \#\text{ cycle}.$$

$$\Delta t \cdot \#\text{sample/cycle} \cdot \cancel{\#\text{cycle}} = \frac{1}{f} \cdot \cancel{\#\text{ cycle}}.$$

$$\Delta t = \frac{1}{f \cdot \#\text{sample/cycle}}$$

if $f = 10\,Hz = 10\,s^{-1}$, $\#\text{sample/cycle} = 128/\text{cycle}$.

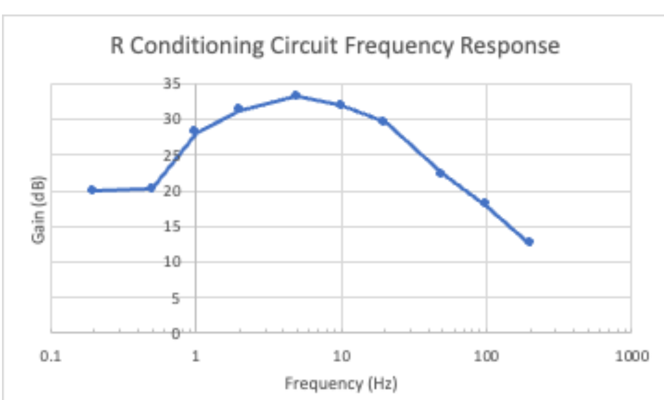
$$\Delta t = \frac{1}{10\,s^{-1} \cdot 128} = \frac{1}{1280\,s^{-1}} = \frac{1}{1280}\,s.$$

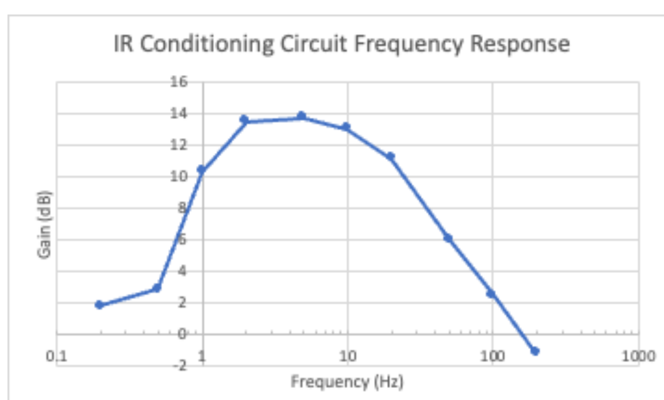
Use Scope & Fgen for NI myRio.

Freq response data:

R				
Frequency (Hz)	Input (Vpp)	Output (Vpp)	Gain	Gain (dB)
0.2	0.034	0.336	9.882352941	19.89720721
0.5	0.043	0.439	10.20930233	20.17992129
1	0.039	0.996	25.53846154	28.14389463
2	0.039	1.436	36.82051282	31.32179666
5	0.039	1.799	46.12820513	33.27933113
10	0.039	1.548	39.69230769	31.97412699
20	0.039	1.167	29.92307692	29.52012498
50	0.044	0.571	12.97727273	22.26366864
100	0.039	0.312	8	18.06179974
200	0.039	0.166	4.256410256	12.58086962

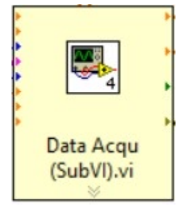
IR				
Frequency (Hz)	Input (Vpp)	Output (Vpp)	Gain	Gain (dB)
0.2	0.039	0.048	1.230769231	1.803532607
0.5	0.039	0.054	1.384615385	2.826583056
1	0.034	0.112	3.294117647	10.35478211
2	0.034	0.161	4.735294118	13.50693918
5	0.039	0.19	4.871794872	13.75377988
10	0.039	0.175	4.487179487	13.03946883
20	0.039	0.141	3.615384615	11.16309011
50	0.039	0.078	2	6.020599913
100	0.039	0.052	1.333333333	2.498774732
200	0.039	0.034	0.871794872	-1.1917138





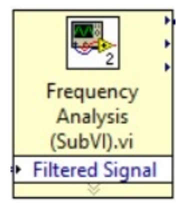
③ Functional SubVIs :

1. Data Accquiring :



Input : C side AI0,1 channels

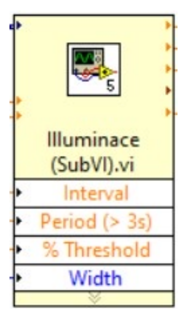
Output : 2 1D arrays containing R, IR channel readings.



2. FFT- Frequency Analysis.

Input : 2-channel filtered signal waveform

Output : 2-channel Power-spectrum



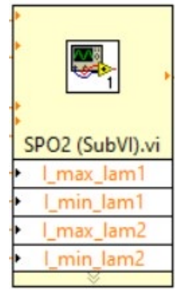
3. Illuminance Calculator

Input : 2-channel filtered signal waveform

Output : $I_{max, R}$ $I_{min, R}$

$I_{max, IR}$ $I_{min, IR}$.

4. SpO_2 Calculator.



Inputs: (I_{max}, I_{min}) at $\lambda_{1,2}$

$$A_{\lambda_i} = \log \frac{I_{max,\lambda i}}{I_{min,\lambda i}} \quad , \quad \lambda_i \ , \ i \in 1,2$$

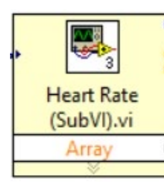
	wavelength	ε_{Hb}	ε_{HbO_2} (L/(mmol·cm))
λ_1	660	0.81	0.08
λ_2	940	0.18	0.29

$$SpO_2 = \frac{(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2})}{(\varepsilon_{Hb,\lambda_2} A_{\lambda_1} - \varepsilon_{Hb,\lambda_1} A_{\lambda_2}) + (\varepsilon_{HbO_2,\lambda_1} A_{\lambda_2} - \varepsilon_{HbO_2,\lambda_2} A_{\lambda_1})}$$

$$SpO_2\ (\%) = A - B \cdot \frac{(I_{max,\lambda_1} - I_{min,\lambda_1}) / I_{offset,\lambda_1}}{(I_{max,\lambda_2} - I_{min,\lambda_2}) / I_{offset,\lambda_2}}$$

Output: SpO_2

5. Heart Rate Calculator.

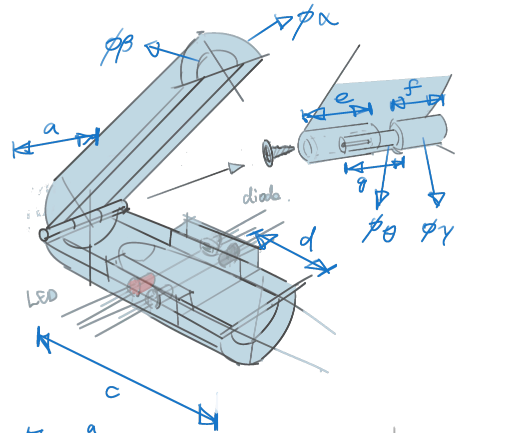


Input: 2-channel Power-spectrum

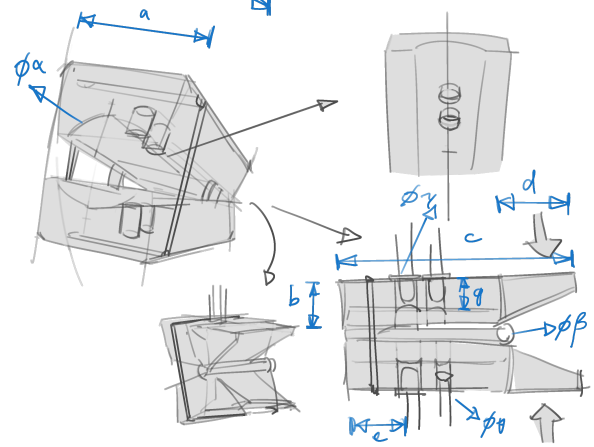
Output: Average Heart Rate (bpm)

Finger Clip Design.

design 1.



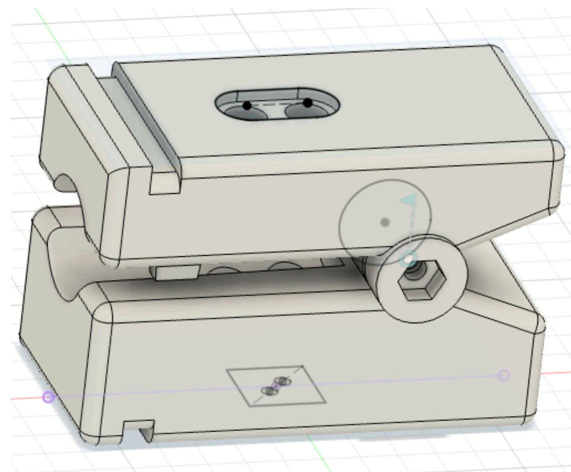
design 2.



Finger Clip Modeling

V1.

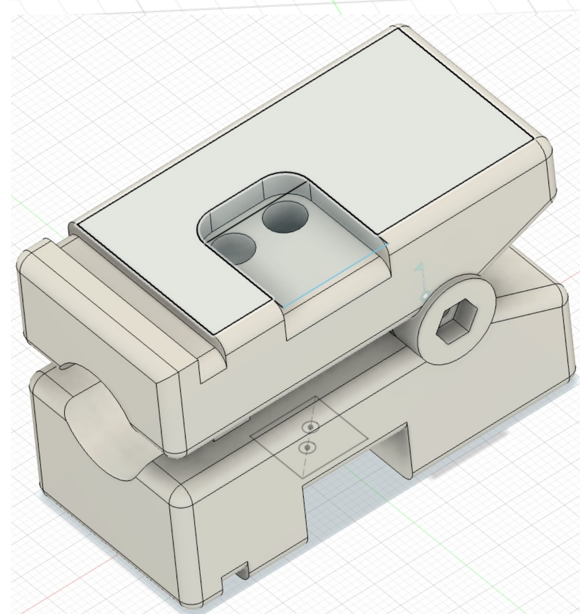
① designed to fit with a M3 bolt & nuts.



V2.

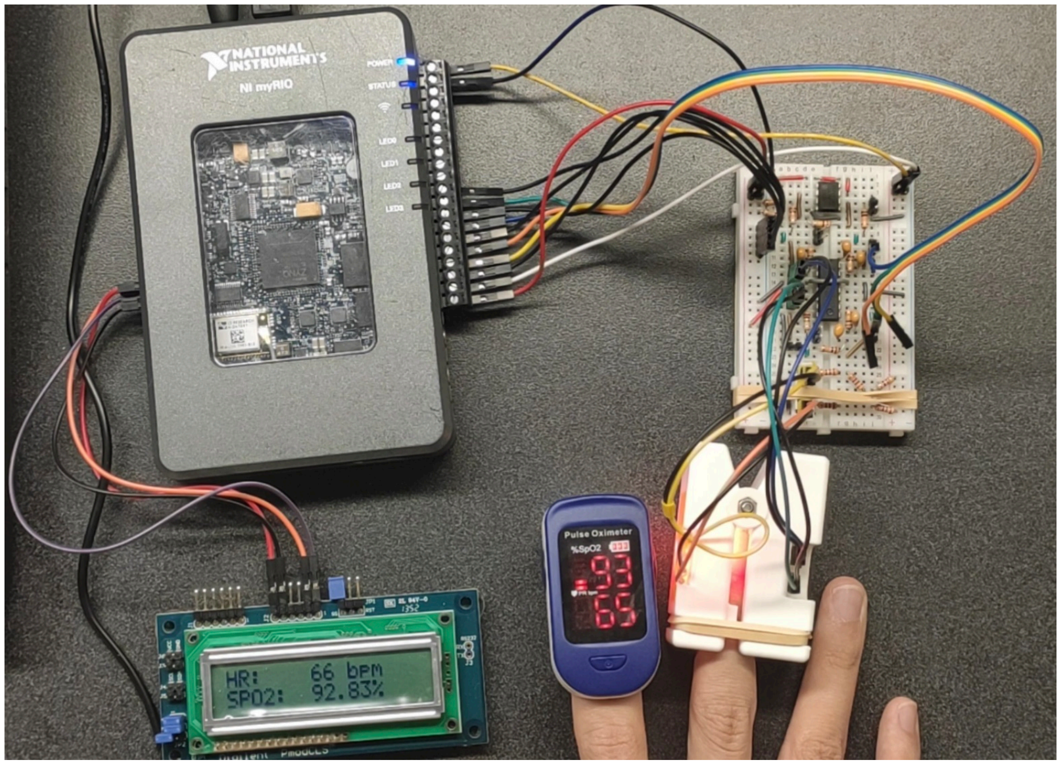
② added cable management slots

③ adjusted dimensions for 3d printing



System Preview.

1. readings compared to commercial product after holding breath. 30s



2. readings compared to commercial product