9 May 2022

Team 5

Hella New Zealand

Rear Lamp Communication Project

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Abstract

Our design group has been commissioned by Hella NZ to develop a proof of concept for an analogue system that can communicate the speed of a leading vehicle to the following vehicle behind it via a light signal. This product is being designed with the intention of it being a part of the future for improvements to car safety on our roads. Hella stated that our proof of concept must meet certain requirements such as price, accuracy, reliability, robustness and response speed.

This report contains our proposal for the transmitter and the receiver where the transmitter will be embedded into the brake light and the receiver will be embedded into the front headlights. An LED transmits a PWM signal via light that contains the speed of the car in the duty cycle. The system was simulated and tested with the findings presented in this report. Furthermore included in the report was the various reasoning behind what was done to achieve the client's requirements. This included ensuring compliance with ISO16750-2 and cost reduction measures.

Due to circumstantial conditions, building the product and testing it was not possible. In order to reach a final decision on this proof of concept, it would be recommended to build a physical copy and test it further.

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1.0 INTRODUCTION

1.1 Design Brief

This system was designed for the engineering company Hella NZ. It was designed with the purpose in mind of being a low-cost anti-collision technology to prevent road crashes while having an edge over the competitors in terms of price. Hella has requested Junior Engineers to develop a proof of concept.

The design is split into two products, an auxiliary headlamp receiver (Rx), and an LED auxiliary tail lamp transmitter (Tx). The LED tail lamp transmits a signal, via the brake lights, where the speed of the car is contained within the duty cycle of a pulse width modulated signal. The receiver located in the headlights receives the signal and decodes the light signal.

1.2 Client Requirements

The client has set requirements on how they want the system to be designed. These requirements were stated during the client presentation:

- Design must be purely analogue
- Cheap in order to be mass-produced and be profitable
- Circuit response must be fast enough to meet safety requirements
- Accurate reading of the front vehicle speed
- Must connect to a variable 9-16V DC car power supply and be installed with easy to existing light system
- Able to operate reliably in non-ideal weather conditions

1.3 Tools Used

LTspice was used frequently throughout the design process and was used to validate and test individual components and the system as a whole. LTspice was extremely useful when simulating waveforms and looking into the response of the circuit when subjugated to different conditions.

MATLAB is software that is widely used throughout the world in many engineering and scientific fields giving us confidence in its reliability. MATLAB was used during our design process, even though not as frequently as LTspice. When analysing and designing more complex parts of the circuit, such as a second-order filter, MATLAB was a tool that made the process of calculating optimal values for our components more efficient and less prone to mistakes.

Altium Designer is a tool used to make schematics and PCBs. When all the validation and circuitry were done in LTspice, Altium Designer was used in turning the design from simulations into real-life PCB circuitry that can be used to demonstrate the circuit’s function physically.

1.4 Design Methodology

Our methodology was heavily centred around testing and validating our ideas using LTspice. Making improvements to the circuit in order to be more accurate and faster to comply with the client’s requirements.

2.0 Electronic Design

2.1 Overview of Transmitter

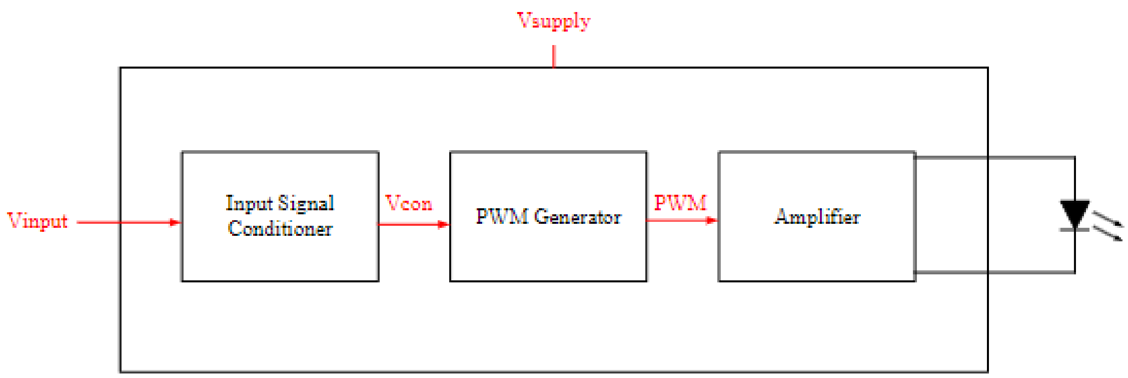


Figure 1: Transmitter Block Diagram

Author: Jackman Lin

The transmitter circuit, which can be divided into three different blocks, takes a voltage signal representing the car speed and converts it into a PWM waveform, with the duty cycle representing the speed of the car.

The first stage is an input signal conditioner designed to take in an input signal between 1-3V with a frequency ranging between 1-2.5kHz, where the frequency represents the vehicle speed, and conditions it into a suitable form for the next stage. The PWM generator takes in the conditioned signal and outputs a PWM signal whose duty cycle directly correlates to the vehicle's speed. At the last stage, the PWM is fed into an amplifier that powers the LED.

2.2 Overview of Receiver

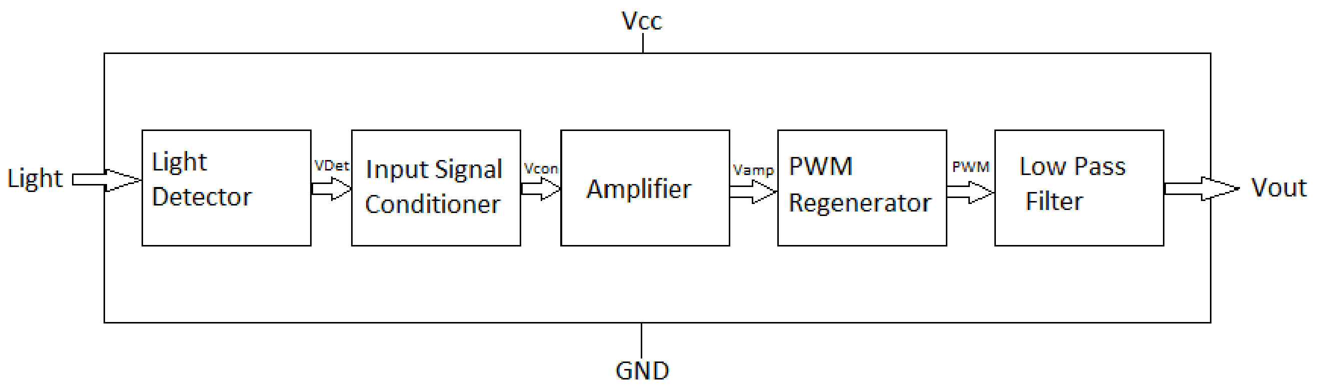


Figure 2: Receiver Circuit Diagram

The receiver circuit consists of five parts. A photodiode converts the strength of the LED light to a current signal which then goes through the ISC, a high pass filter, then is amplified before feeding into the PWM regenerator. In the final stage, the signal is filtered by a second-order low pass filter.

The photo-diode detects the LED light and will create a signal that resembles a PWM signal however this signal is very small with a lot of noise. The signal is then fed into a high pass filter removing any DC offset and then applying a DC offset of Vref(2.5V). Since the signal is small it is fed into a series of 2 amplification stages resulting in a much larger signal. After amplification, the signal enters the PWM Regenerator which produces a clean PWM signal. The final stage of the receiver process is the low pass filter which is off the second order. This filters out the high frequency of the PWM turning it back into a sinusoidal wave that resembles the original at the transmitter.

3.0 Performance

3.1 Total Harmonic Distortion

When the input signal has an offset voltage of 2V with an amplitude of 1V. To improve accuracy the number of significant figures is set to 7, compression is disabled by setting plotwinsize to 0, the simulation maximum timestep is set to 100n, and the total harmonic distortion calculation uses 100 harmonics and the last 50 periods of the waveform.

Table 1: 400mm Distance between Tx and Rx

Input Frequency	Total Harmonic Distortion
1kHz	0.141089%
1.5kHz	0.083575%
2kHz	0.051045%
2.5kHz	0.040693%

Table 2: 100mm Distance between Tx and Rx

Input Frequency	Total Harmonic Distortion
1kHz	0.094473%
1.5kHz	0.100481%
2kHz	0.104532%
2.5kHz	0.109786%

3.2 Maximum Range

The circuit was designed with a 400mm range in mind which corresponds to a photo-diode current of 0.55uA*LED Current. Gradually decreasing current shows that the circuit is able to sufficiently produce the expected output signal until a current of 0.42uA*LED Current. It is difficult to calculate the exact range this represents however it proves the circuit works very confidently at a 400mm range.

3.3 Resistance to Ambient Noise

By adding a constant current to the photo-diode current the effect of ambient lighting can be simulated. The circuit simulation works as intended until a maximum of 8uA.

3.4 Accuracy

Transmitter

Measured using the cursor tool and finding the distance between minimum duty cycles. The decrease in error from 2.5kHz to 1kHz is likely due to the increased resolution in the PWM. Where resolution is defined as the input frequency divided by the PWM frequency.

Table 2: Transmitter Accuracy

Input signal Frequency	LED PWM frequency representation	Error %
2.5kHz	2.6kHz	3.8%
2kHz	1.95kHz	2.5%
1.5kHz	1.46kHz	2.7%
1kHz	1.01kHz	1%

Receiver

Table 3: Receiver Accuracy measured at 400mm

Light detector circuit frequency representation	Output Frequency	Error%
2.6kHz	2.52	3%
1.96kHz	1.99kHz	1.5%
1.46kHz	1.49kHz	2%
1.02kHz	1.01kHz	1%

3.5 Circuit Cost

The proof of concept using through-hole and using the bulk cost of 1000 units the total cost is \$9.30. Using a higher bulk cost for capacitors would significantly reduce the total cost. The circuit was designed with performance in mind therefore few decisions were made to reduce the cost.

4.0 Addressing Client Requirements

4.1 Time Response

The time response is the time it takes for the circuit to reach a steady-state after a change in the frequency. The worst-case simulation shows that the maximum time response of the circuit is 2mS. This response time is acceptable since at most a car will be driving at 100km/h (= 27.7778m/s) in this case the circuit will respond to a change in frequency within 0.06m which is insignificant.

4.2 Optimising Manufacturing Costs

The circuit uses the LM358 op-amp which is a cheaper alternative to an op-amp such as the TLC081 with the downside of a lower slew rate. The PWM frequency is designed with this lower slew rate in mind and performs identically with a tenth of the cost.

Both LM358 and LM393A contain 2 op-amps that the circuit utilises. This halves the cost with the downside of much more clustered traces. However, as a result of this, the circuit requires fewer decoupling capacitors further decreasing the cost.

For the resistor and capacitor values, the e12 series was used since it was deemed that 10% tolerance is acceptable for the circuit and the e-series that is mass-produced will cost lower than using any value.

4.3 Power Supply Robustness

One of the client's main requirements was that the system must meet ISO 16750-2 where a car battery's voltage is between 9-16V. By taking that into consideration, the circuit design includes a regulator L7805CV which will generate a stable 5V for the circuit.

4.4 Failure Risk Evaluation

Transmitter / LED Amplifier

Failure: LED broken

Effect of failure - product impact: Photodiode can’t receive data from LED

Effect of failure - customer impact: System can’t provide the speed of the car

How failure can be communicated or mitigated: A warning indicator could be installed

Transmitter / Input Signal Conditioner

Failure: External noise

Effect of failure - product impact: Components will be damaged if noise is large enough

Effect of failure - customer impact: System will provide inaccurate information

How failure can be communicated or mitigated: Proper shielding for the components.

5.0 PCB Design

5.1 PCB Design - Transmitter

Stitching is removed for visual clarity.

Figure 3: Transmitter PCB Top Layer

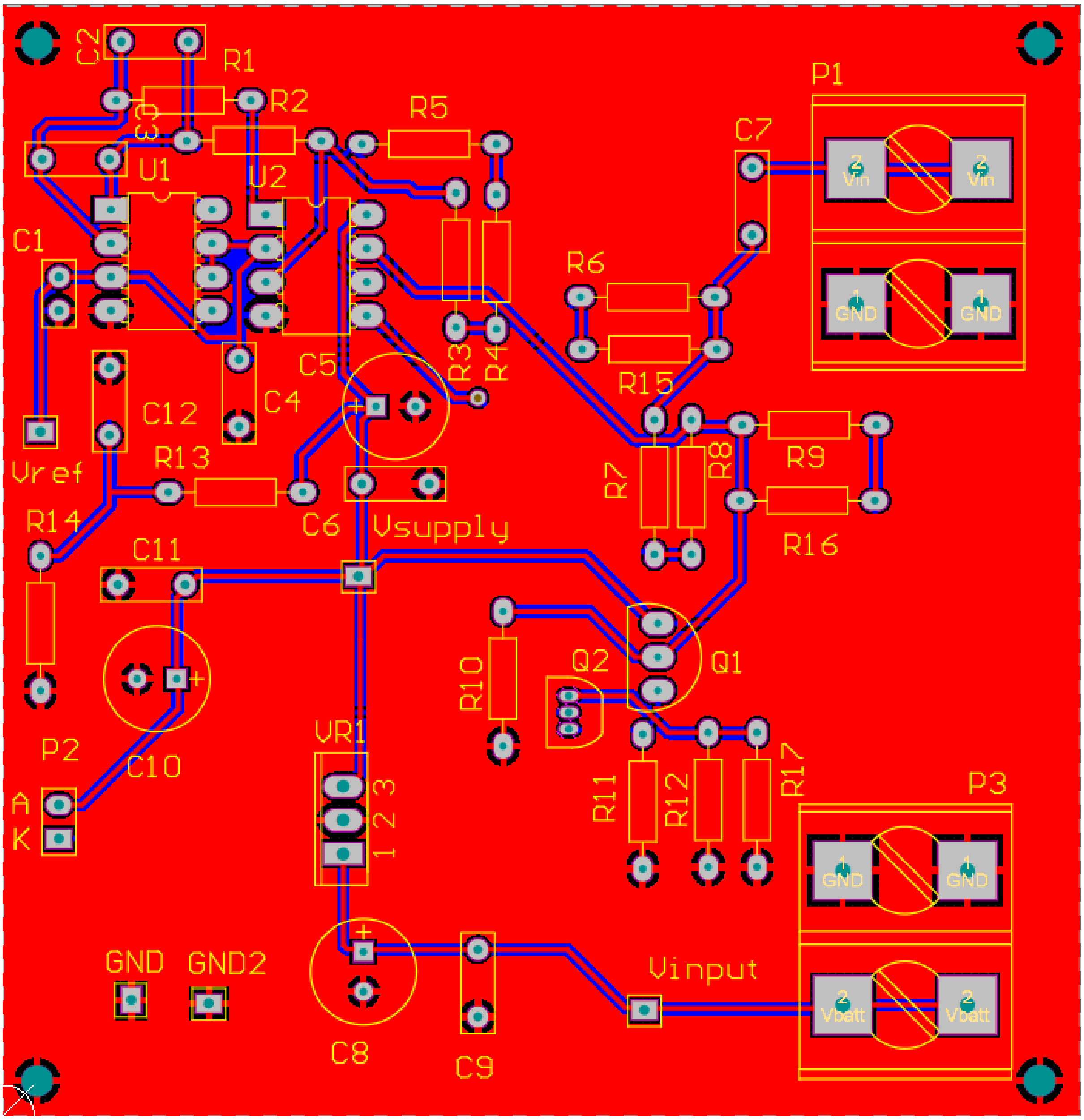
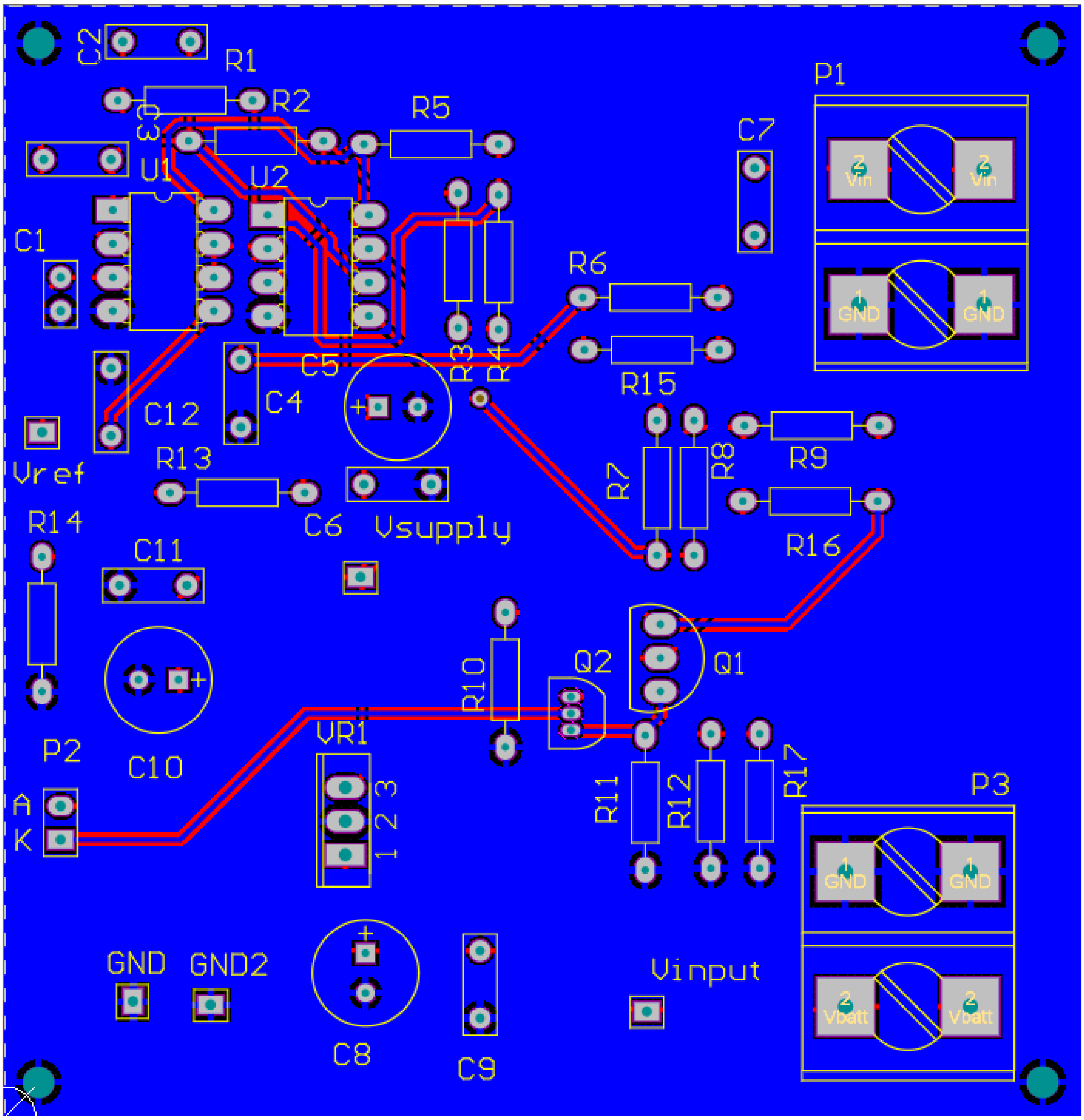


Figure 4: Transmitter PCB Bottom Layer



5.2 PCB Design - Receiver

Stitching is removed for visual clarity.

Figure 5: Receiver PCB Top Layer

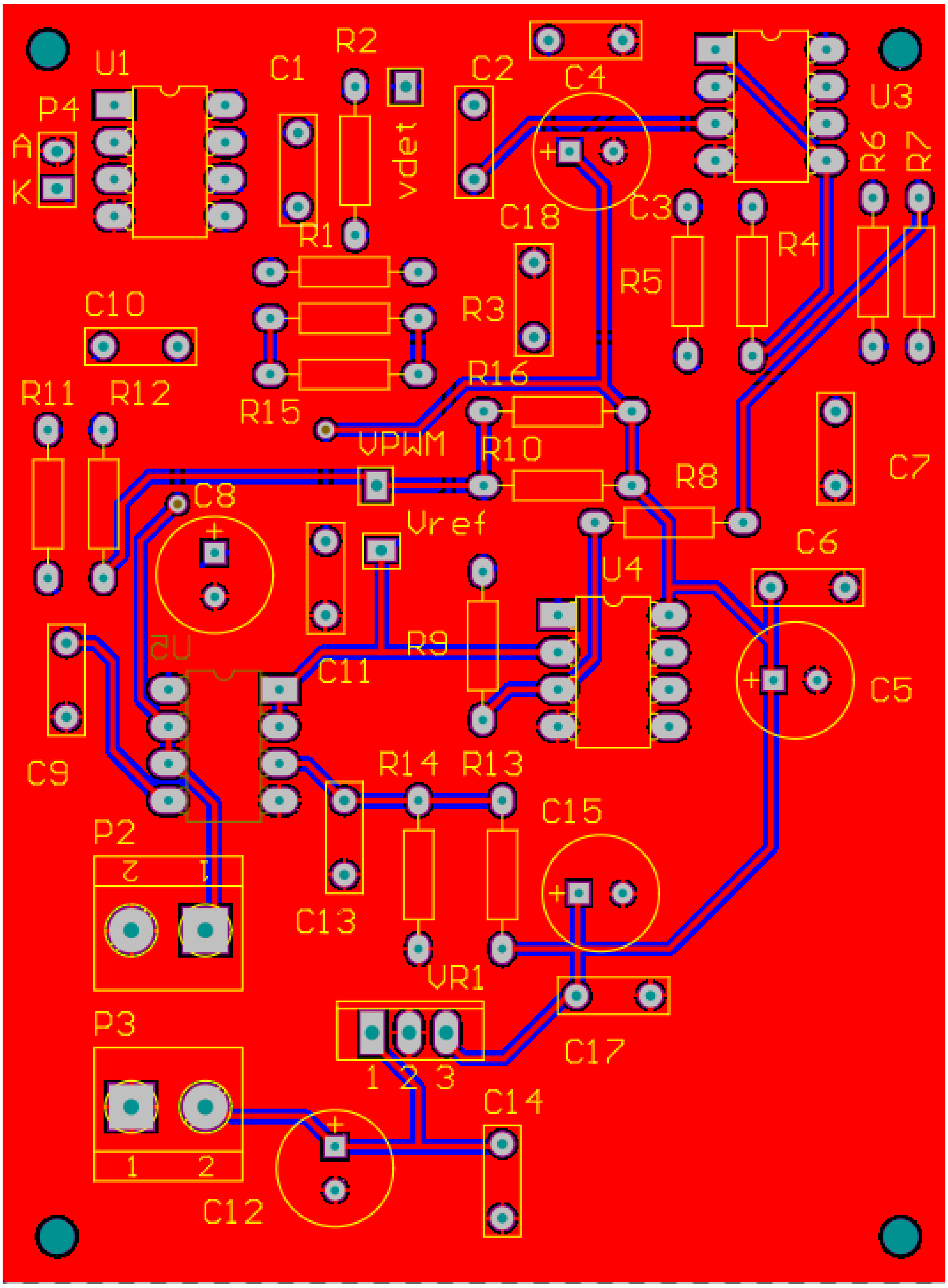
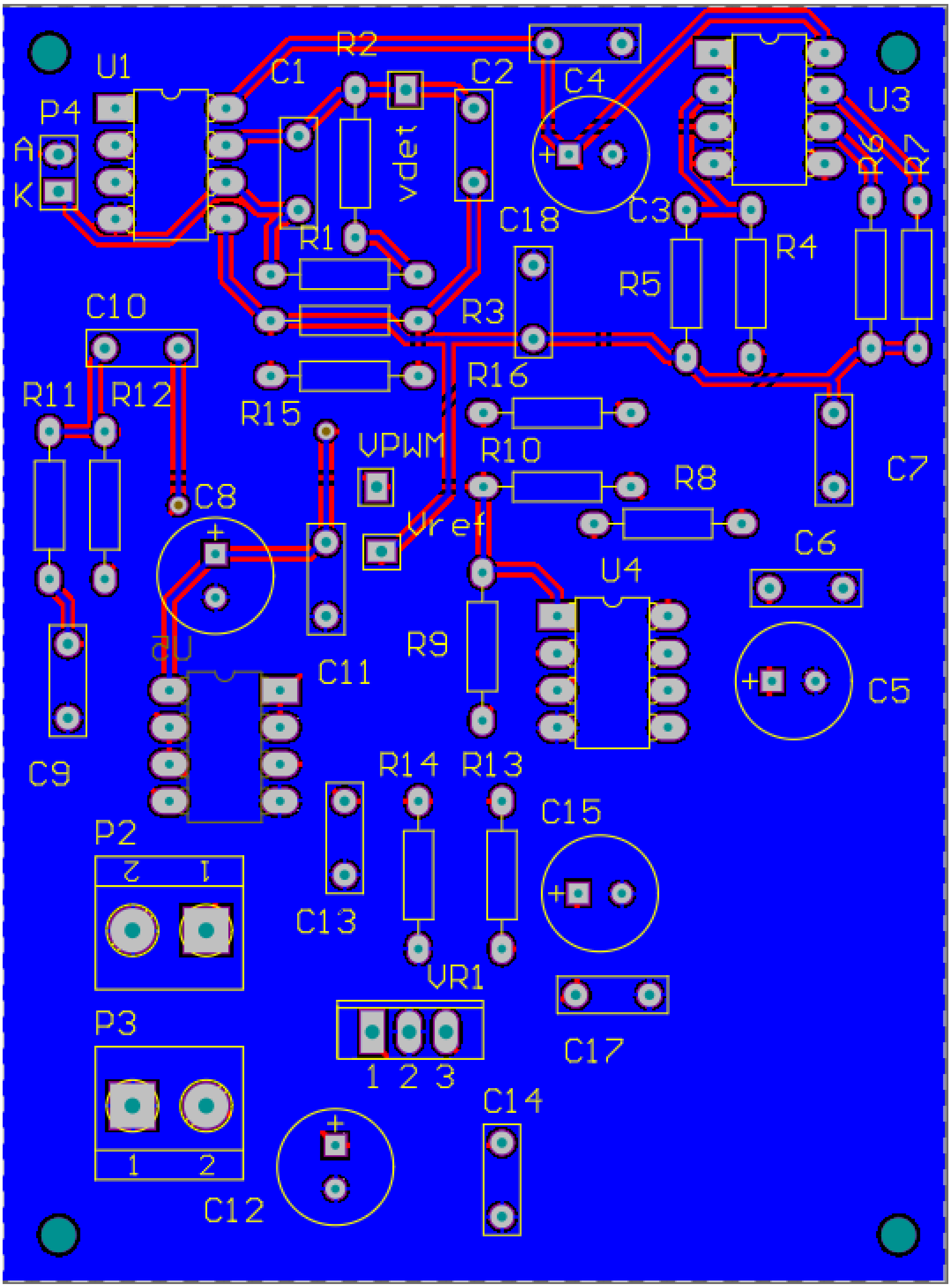


Figure 6: Receiver PCB Bottom Layer



Conclusion

To conclude this report outlines our proof of concept for our anti-collision system commissioned by Hellas NZ.

An LED auxiliary tail lamp transmitter is designed to flash corresponding to a PWM current signal representing the car speed. The auxiliary headlamp receiver amplifies and filters noise to recreate a PWM signal that matches the signal sent by the LED. The accuracy of the PWM signal is 3% while the input frequency is 2.5khz, and it decreases to 1% as the input frequency decreases. After simulating and testing the system, information collected suggests that the worst-case simulation shows that the maximum time response of the circuit is 2mS, this is an acceptable response time. The design total cost is $9.30.

In conclusion, our design meets the client's requirements and achieves its purpose. Further testing could be undertaken after building a physical prototype and testing in real-world conditions.

References

Figure 1 - Lin.J. (2022). *EE310 - Project 1 L1[PDF].* *https://canvas.auckland.ac.nz/courses/72789/files/folder/Project%201%20-%20Speed%20detector/Transmitter/Lectures?preview=8304179*

Appendices

Appendix A: Transmitter

Appendix A aims to display the transmitter circuit in a more detailed and comprehensive manner and will show component values and configurations.

Voltage Regulator

Since the car battery fluctuates around 9-16V, it is not practical to use this to power the system. Instead, it is more reliable to use a voltage regulator to get a stable voltage of 5V to power our circuit. The regulator provides an output current of 1A which is enough to power our circuit safely removing the concern of the circuit failure due to power constraints.

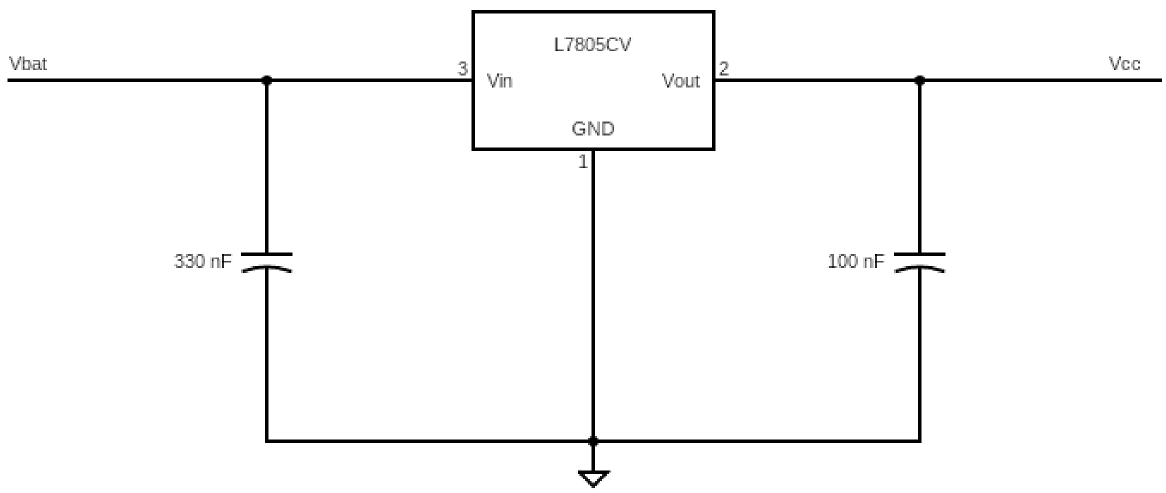


Figure A.1: Voltage regulator circuit

Vref Generation

Vref which is equal to Vcc/2 is used as the reference voltage throughout the circuit. It is generated using a voltage divider and a buffer is placed to prevent loading on the circuit which would cause inaccuracies.

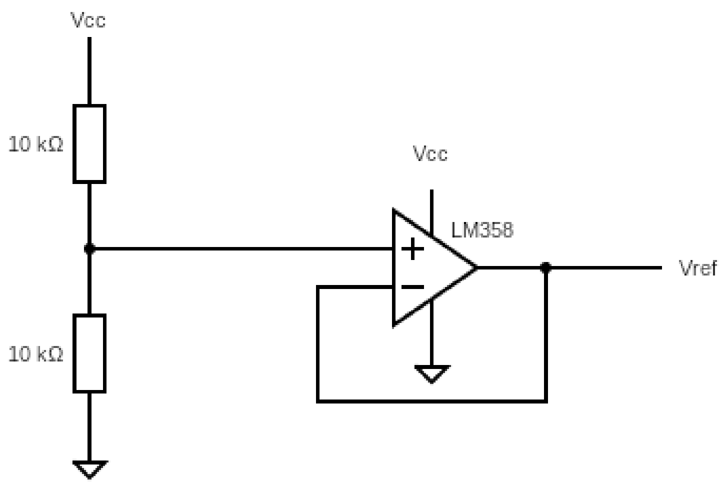


Figure A.2: Voltage reference generator

Stage 1: Input Signal Conditioner

The Input Signal Conditioner is designed using a high pass filter whose purpose is to remove any DC offset from the input signal. When choosing our cutoff frequency our main concerns and considerations were the accuracy and time response of the circuit which were part of the client requirements. Higher cutoff frequencies resulted in faster circuit response times but increased attenuation with loss of data. After testing and simulation, the best choice was a cutoff frequency of 219Hz which gave a balance of both. To determine the values of the capacitor and resistors for the cutoff frequency, the resistor value was chosen as $22k\Omega$ and the capacitor is chosen as 33nF.

$$f = \frac{1}{2\pi RC}$$

$$f = \frac{1}{2\pi \cdot 22k \cdot 33n}$$

$$f = 219\ Hz$$

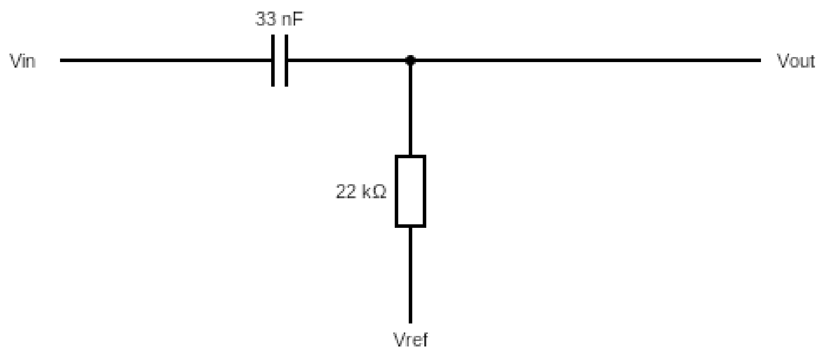


Figure A.3: Input Signal Conditioner

Stage 2: Triangle Wave Generator and PWM

The Triangle Wave Generator is made of an integrator op-amp configuration to generate the triangle wave and a comparator to generate a square wave. The system is designed to output a 2.5V peak to peak triangle wave with a frequency of 25kHz.

Using the equation $f \ = \ \frac{R3}{4R1R2C1}$ resistor and capacitor values were chosen to generate a frequency of 25Khz.

Due to the frequency not being that high the slew rate required from the op-amp was also not that high. It was decided that the best choice was the LM358 which provides the required slew rate and minimizes cost.

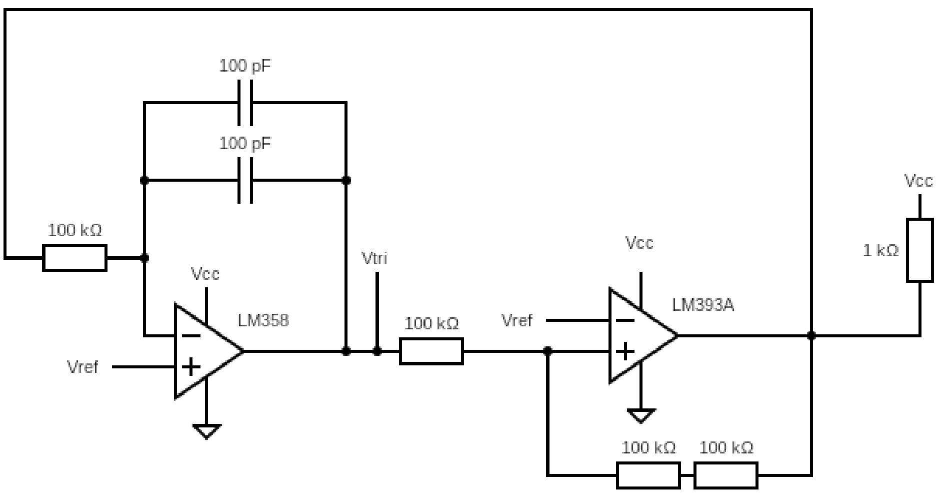


Figure A.4: Triangle Wave Generator

The PWM generator includes an LM393A comparator as it is relatively cheap and has a response time of 500ns. A pull-up resistor is included in the design as the LM393A is an open collector comparator. To determine the resistor values, the hysteresis band is set to 100mV.

Using the equation $V_{high} = V_{tri}\frac{(R_1+R_2)}{R_2}$ and $V_{low} = \frac{(R_1+R_2)}{R_2}(V_{tri} - 5(\frac{R_1}{R_1+R_2}))$

R2 and R3 are determined. The pull-up resistor was chosen after considering that the output sink current needed to be between 6-16mA.

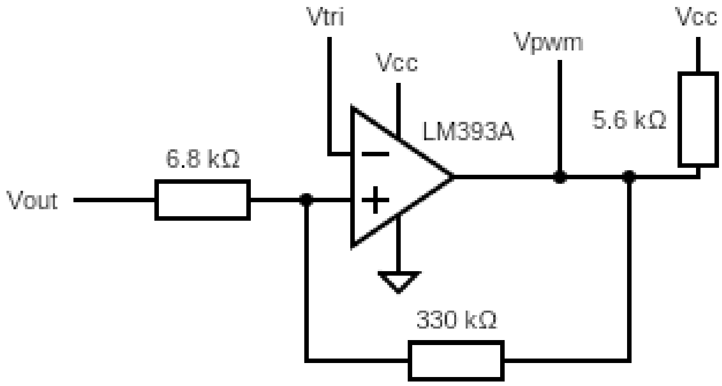


Figure A.5: PWM generator circuit

Stage 3: LED Amplifier

The LED amplifier is designed using a Darlington pair configuration which consists of BC547B and BC639 to provide the required current for the LED to operate and also has a gain of 20000. KA3529 was chosen as the LED of choice due to the light being red and also it has a forward current of 150mA.

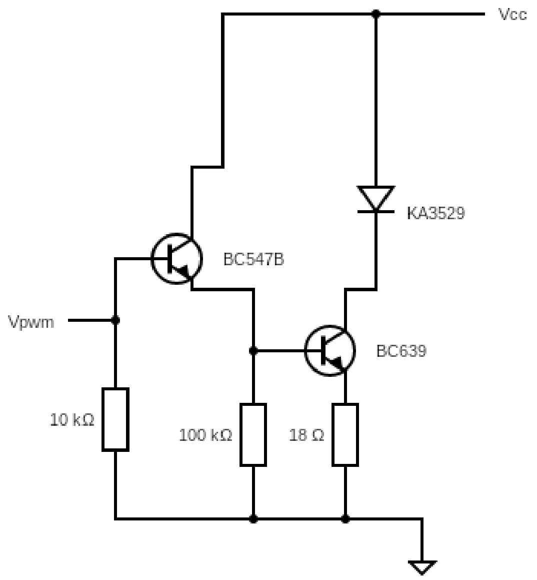


Figure A.6: LED Amplifier circuit

Appendix B: Receiver

Appendix B aims to display the receiver circuit in a more detailed manner and will show the component values and configurations.

Stage 1: Light Detector Circuit

The Light Detector circuit is a circuit that has a photodiode used to convert light into current. It then has a transimpedance amplifier which is used to convert current into voltage and a capacitor is added in parallel with the resistor to stabilise the entire circuit. The amplifier has a cutoff frequency of 0.36Mhz

Using the equation $f_c = \frac{1}{2\pi RC}$

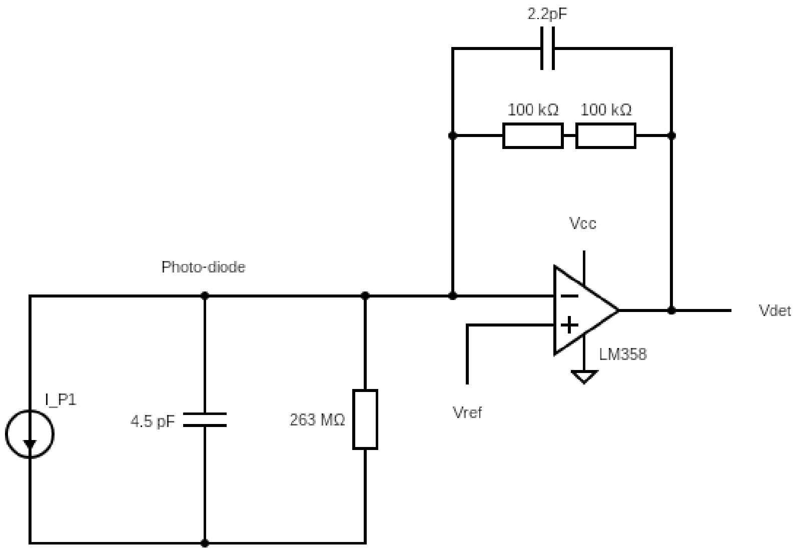


Figure B.1: Light Detector Circuit

Stage 2: High Pass Filter

The high pass filter is used to remove any DC offset caused by photo-diode dark current or noise and sets a new DC bias which is useful for the following stages. The high pass filter was designed with balanced signal stability and time response. Time response is decreased by increasing the cutoff frequency since it is inversely proportional. $\tau = \frac{1}{2\pi f_c}$

Cutoff is at $f_c = \frac{1}{2\pi RC}$ = 318Hz and the time constant is 0.5ms this was the minimum before the signal became distorted.

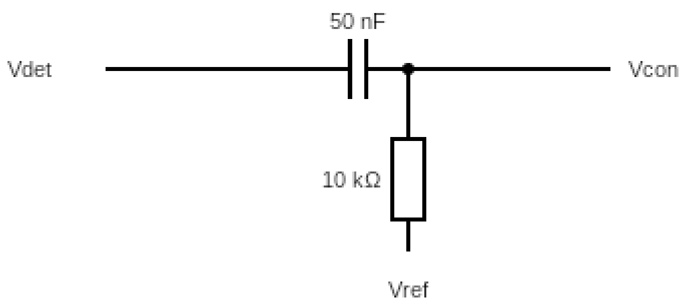


Figure B.2: High Pass Filter Circuit

Stage 3: Amplification

The Amplification stage uses 2 amplifiers and is used to amplify the signal from the high pass filter. The design contains 2 amplification stages which leave open the option for increasing frequency without exceeding the GWB product. The LM358 comes with 2 op-amps and there is no cost difference between using both or one. The same gain was chosen for both amplifiers for the purpose of simplicity. The resistor ratio was chosen so maximum amplification does not cause the signal to clip. The gain is found using the following equation $G = 1 + \frac{R_2}{R_1}$

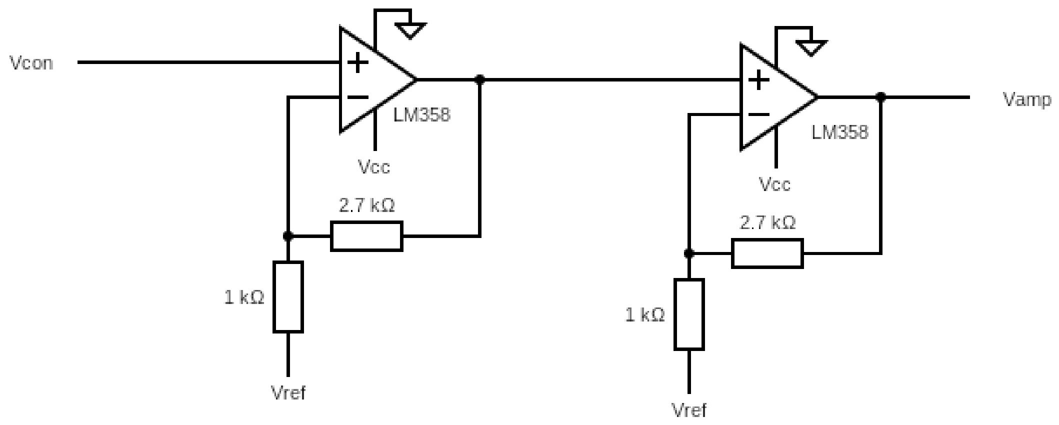


Figure B.3: Signal Amplifier circuit

Stage 4: PWM Regenerator

Using a Schmitt trigger the noisy PWM is recreated as a clean PWM before the final stage. The LM393A comparator returns a high voltage when the input is higher than 2.55V and returns a low if the voltage is lower than 2.45V. The hysteresis band of 100mV was chosen using the 400mm range signal ideally for higher noise resistance the hysteresis band would be higher however due to amplification issues 100mV was the highest possible. The optimal Schmitt trigger resistors were found using a MATLAB code where

$V_{high} = V_{bias}\frac{(R_1+R_2)}{R_2}$ and

$V_{low} = \frac{(R_1+R_2)}{R_2}(V_{bias} - 5(\frac{R_1}{R_1+R_2})$ where

$V_{bias} = 2.5V$

The pull-up resistor value was chosen so the comparator output sink current was roughly 7mA to satisfy the datasheet requirement of 6-21mA

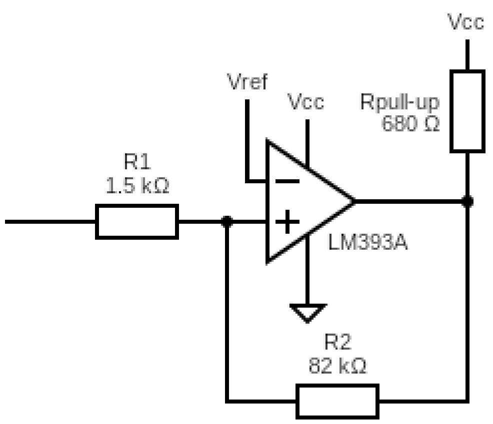


Figure B.4: PWM Regenerator Circuit

Stage 4: Second-Order Low-pass filter

This low-pass filter is the final stage of the circuit and transfers the regenerated PWM into a sinusoid wave with ideally the same frequency as the input. This is done by filtering the high-frequency components that make up the sharp edges of the PWM. The circuit uses a second-order type 1 Chebyshev filter, this allows for a steep transition which is ideal for cutting off all frequencies higher than the cutoff frequency.

The values for the filter were found using a MATLAB code that calculates the value for C6 using the formula $\frac{1}{C_5 R_1 R_2 a_0 \omega}$ with C5, R1 and R2 being matrices containing all e12 values than using this C6 value the corresponding a1ω value was found with the formula $\frac{R_1+R_2}{R_1 R_2 C_6}$. The outputted 3-dimensional matrix was then used to find the values for a1ω that were closest to ideal and the corresponding C6 value. This circuit has a cutoff frequency of 1kHz and an a1ω of 6894 (ideal = 6897) and a quality factor of $\frac{\sqrt{a_0}}{a_1}$ = 0.9539db. Code can be found in Appendix D Figure D:1.

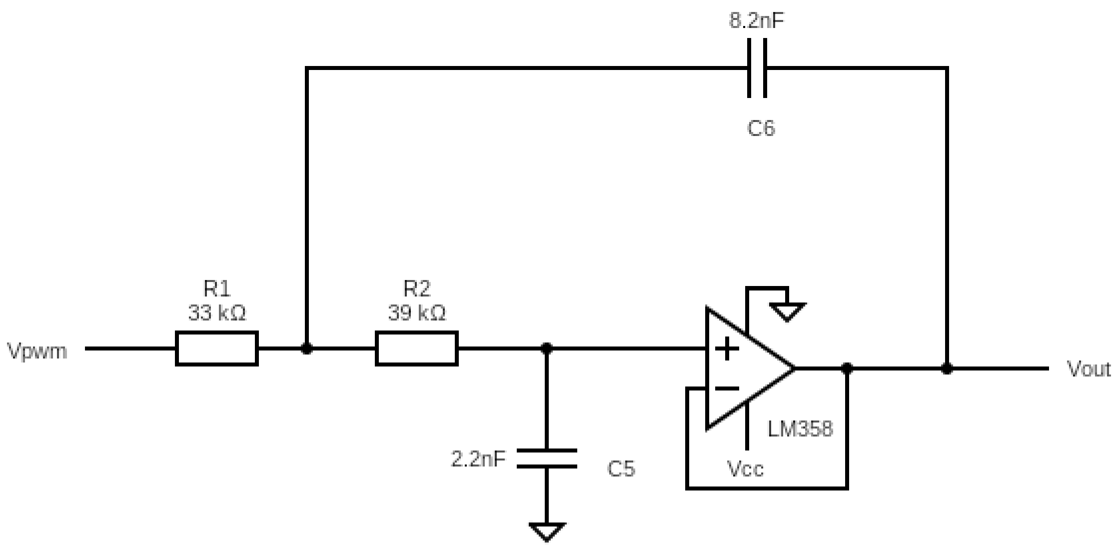


Figure B.5: Second-order Low-pass filter Circuit

Appendix C: Components and Cost

Summary of the components used as well as their cost, quantity, and values and product number.

Table 4: Resistors

Resistance(ohms)	Quantity	Unit price (at 1000)	Product Number
330k	1	$0.05852	RSF1JA330K
100k	7	$0.0478	SFR16S0001003JA100
82k	1	$0.0478	SFR2500008202JA100
39k	1	$0.06438	RSMF2JB39K0
33k	1	$0.02926	RSMF12JB33K0
22k	1	$0.0478	SFR2500002202JA100
10k	6	$0.02926	RSMF12JB10K0
6.8k	1	$0.02926	RSMF12JB6K80
5.6k	1	$0.05852	RSF1JB5K60
2.7k	2	$0.02926	RSMF12JB2K70
1.5k	1	$0.02926	RSMF12JB1K50
1k	3	$0.02926	RSMF12JB1K00
680	1	$0.02926	RSMF12JB680R
18	1	$0.06438	RSMF2JB18R0

Table 5: Capacitors

Capacitance(F)	Quantity	Unit price (at 1000)	Product number
22u	2	$0.06599	ESK226M025AC3AA
10u	6	$0.06514	ESK106M035AC3AA
0.33u	12	$0.07737	C315C104M5U5TA
0.1u	2	$0.12269	C412C334M5U5TA7200
0.05u	1	$0.89018	S503Z69Z5UL63L0R
0.033u	1	$0.09704	K333K15X7RF5TL2
8200p	1	$0.14801	C315C822K5R5TA
2200p	1	$0.07412	D222K25Y5PH63J5R
100p	2	$0.07941	K101K10X7RH5UH5
2.2p	1	$0.11341	FA18C0G1H2R2CNU06

Table 6: Other Components

Transistors:	
BC547B	$0.17069
BC639 (BC639G)	$0.17
LED:	
KA3529	$0.62
Photo-diode:	
SFH203P	$0.54232
Opamp:	
LM358 (LM358P)	$0.24567 x4

LM393A (LM393N)	$0.75204 x2
Regulator:	
L7805CV	$0.4884 x2

Appendix D: MATLAB Code

Appendix D aims to display the MATLAB code used to calculate the values for the sallen-key second-order low pass filter and the hysteresis band for the PWM generator.

Figure D:1 Chebyshev.m

```
clear
clc
freq = 1000;
a0_t = 1.1025*((2*pi*freq)^2);
a1_t = 1.0977*(2*pi*freq);
R1 = [10000, 12000, 15000, 18000, 22000, 27000, 33000, 39000, 47000, 56000,
68000, 82000];
R2 = [10000, 12000, 15000, 18000, 22000, 27000, 33000, 39000, 47000, 56000,
68000, 82000];
C5 = [1e-9, 1.2e-9, 1.5e-9, 1.8e-9, 2.2e-9, 2.7e-9, 3.3e-9, 3.9e-9, 4.7e-9,
5.6e-9, 6.8e-9, 8.2e-9];
n = length(C5);
m = length (R1);
p = length (R2);
%a0 perfect
for c = 1:n
    for k = 1:m
        for q = 1:p
           C6(c, k, q) = 1 / (C5(c)*R1(k)*R2(q)*a0_t);
           a1(c, k, q) = (R1(k)+R2(q)) / (R1(k)*R2(q)*C6(c, k, q));
         end
    end
end
%a1 perfect
% for c = 1:n
%     for k = 1:m
%         for q = 1:p
%             C6(c, k , q) = (R1(k)+R2(q))/(R1(k)*R2(q)*a1_t);
%              a0(c, k, q) = 1/(C6(c, k, q)*R1(k)*R2(q)*C5(c));
%         end
%         end
%     end
Practical_R1 = 33000;
Practical_R2 = 39000;
Practical_C6 = 0.082e-7;
```

```
Practical_a1 =
(Practical_R1+Practical_R2)/(Practical_R1*Practical_R2*Practical_C6);
```

Figure D:2 Hysterisis Band

```
clear
clc
Vbias = 2.5;
Theory_Vlow = 2.45; % or higher
Theory_Vhigh = 2.55; % or lower
R1 = [1000, 1200, 1500, 1800, 2200, 2700, 3300, 3900, 4700, 5600, 6800,
8200];
R2 = [10000, 12000, 15000, 18000, 22000, 27000, 33000, 39000, 47000, 56000,
68000, 82000];
n = length(R1);
m = length(R2);
for c = 1:n
   for j = 1:m
       Vhigh(c,j) = Vbias * ((R1(c)+R2(j))/R2(j));
       Vlow(c,j) = ((R1(c)+R2(j))/R2(j)) * (Vbias - 5*(R1(c)/(R1(c)+R2(j))));
   end
end
```

Appendix E: Selected Component Datasheets

Appendix E aims to display selected component datasheets that was used in the design.

Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
V_O	Output voltage	T_J = 25 °C	4.8	5	5.2	V
V_O	Output voltage	I_O = 5 mA to 1 A, V_I = 7 to 18 V	4.75	5	5.25	V
V_O	Output voltage	I_O = 1 A, V_I = 18 to 20V, T_J = 25 °C	4.75	5	5.25	V
ΔV_O (1)	Line regulation	V_I = 7 to 25 V, T_J = 25 °C		3	100	mV
		V_I = 8 to 12 V, T_J = 25 °C		1	50	
ΔV_O (1)	Load regulation	I_O = 5 mA to 1.5 A, T_J = 25 °C			100	mV
		I_O = 250 to 750 mA, T_J = 25 °C			50	
I_d	Quiescent current	T_J = 25° C			8	mA
ΔI_d	Quiescent current change	I_O = 5 mA to 1 A			0.5	mA
		V_I = 7 to 23 V			0.8	
$\Delta V_O/\Delta T$	Output voltage drift	I_O = 5 mA		-1.1		mV/°C
eN	Output noise voltage	B = 10 Hz to 100 kHz, T_J = 25 °C		40		µV/V_O
SVR	Supply voltage rejection	V_I = 8 to 18 V, f = 120 Hz	62			dB
V_d	Dropout voltage	I_O = 1 A, T_J = 25 °C		2		V
R_O	Output resistance	f = 1 kHz		17		mΩ
I_{sc}	Short circuit current	V_I = 35 V, T_J = 25 °C		0.75		A
I_{scp}	Short circuit peak current	T_J = 25 °C		2.2		A

1. *Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty cycle is used.*

Figure E:1 L7805CV Voltage Regulator