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E344 Assignment 1

Cameron Oosthuysen

23782684

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September 25, 2022

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Contents

List of Figures

List of Tables

Nomenclature

Variables and functions

A_v	Gain
V_0	Output Voltage
R_x	Resistor of arbitrary name
f_c	Corner frequency
F	Farads
Ω	Ohms

Acronyms and abbreviations

Op-Amp	operational amplifier
CMRR	Common Mode Rejection Ratio
PWM	Pulse Width Modulation
LPF	Low-Pass Filter
MCU	Micro-controller (unit)
RC	Resistor and Capacitor
DAC	Digital to Analog
BJT	Bipolar Junction Transistor
MOSFET	Metal-Oxide Semiconductor Field Effect Transistor

Chapter 1

Literature survey

The basic Op-amp construction is of a 3-terminal device, with 2-inputs and 1- output, (excluding power connections). Op-amps operate from either dual positive and an corresponding negative supply but can also operate from a single DC voltage.
The main features of an Op-amp include:

- High input impedance
- Low output impedance
- Voltage gain determined by the resistor network within its feedback loop

There are many applications for op-amps. We are especially interested in their filter capabilities, since we have a noise component added to our circuit which is undesired and must be removed. What is also desirable is a gain, since we need our voltage to be proportional to current, which is small in general, but the pins on a typical micro controller require $\approx 3V$ to recognise a high input. More of this will be discussed in the design component of this report.

1.1. Operational amplifiers

Operational amplifiers: limitations and considerations

The first limitation of an Op-amp will be the voltage supply limitations. An op-amp cannot generate a voltage greater than its supply voltage Vcc. This means that we are restricted with our gain design. Input Bias currents are also present in practical op-amps and are often assumed to be zero in calculations but in reality they are not. They are caused by the internal construction of the op-amp. For practical op-amps there is a limited common mode voltage range CMMR and calculated as CMMR $= 20log|\frac{A_{DM}}{A_{CM}}|$. Table 1.1 shows our Op-amp characteristics and the limits we are bounded by. For the specifications of assignment A1, we fit these limitations quite easily. The choice of op-amp for this application is good. [3]

Table 1.1: Limitations for the MCP6242 Op-amp

Op-amp characteristic	**Limitation**
Differential input voltage	$V_{DD} - V_{SS} < 7V$
Current at output and supply pins	$30mA$
Analog inputs	$V_{SS} - 0.3V to V_{DD} + 0.3V$
All other inputs	$V_{SS} - 1V to V_{DD} + 1V$

Operational amplifier configurations

Inverting Op-Amp:

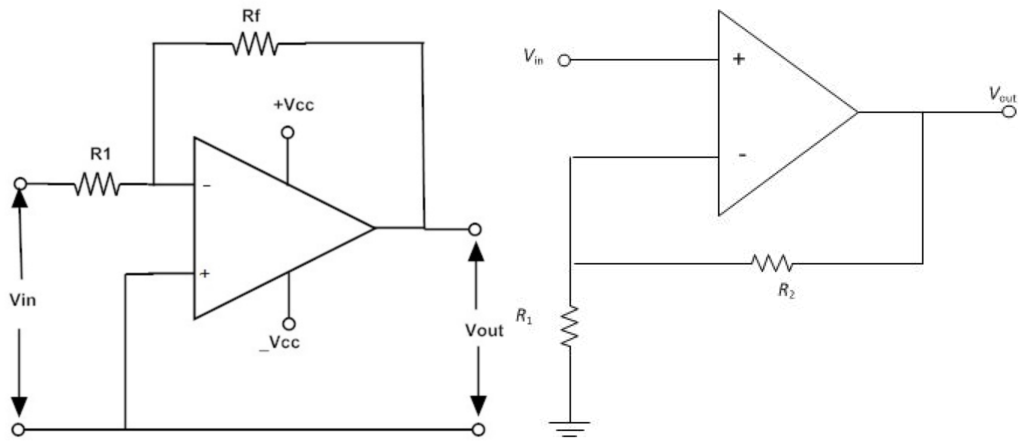
This op-amp will produce an output which is out of phase with respect to its input by 180° and its gain can be calculated as $A_v = \frac{-R_f}{R_i}$

Non-inverting Op-amp:

In contrast to the inverting op-amp, as the name suggests, will produce an output with respect to its input with no phase shift. Its gain can be calculated as $A_v = \frac{R_f}{R_i}$

Differential amplifier:

This op-amp amplifies the difference between two input voltages but suppresses any voltage common to the two inputs. Its output voltage can be calculated as $V_O = A_d(V_1 - V_2)$ [4]



(a) Inverting Op-amp

(b) Non-inverting Op-amp

Figure 1.1: Inverting and non-inverting op-amp schematics

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1.2. Current sensing

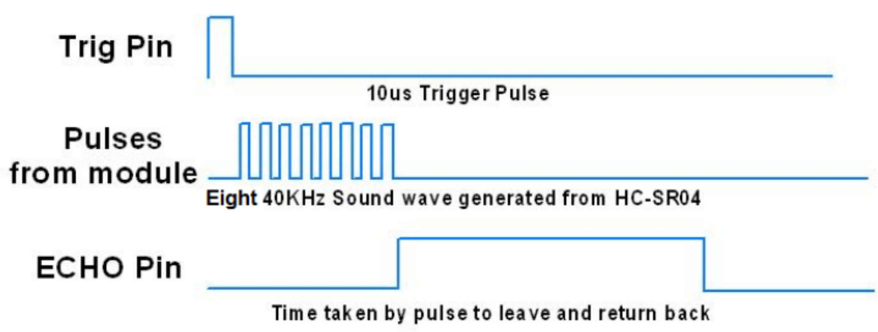
A few examples where current sensing circuits are current control, current limiting, and remaining battery level detection circuits. We will make use of a low-side current sensing circuit since our load is connected to a voltage rail. A high-side current sensing circuit will have its load connected to ground. One way to achieve a low side current sensing resistor is achieved with a shunt resistor, an op-amp and some resistors and capacitors. A load current will pass through a shunt resistor an there will be a shunt voltage drop across that resistor. For our application on the other hand, it can easily be done with a low-pass filter.

1.3. Ultrasonic Sensor

Our RC car that we are designing needs to be able to drive autonomously. In order to achieve this we would have to implement something that can sense objects in front of the RC car so that it move out of harms way. For this project, we have decided to choose the HC-SR04 ultrasonic range module. Important electrical characteristics of the sensor:

- 5V voltage supply
- 15mA current pull during operation
- Resulting in 75mW of power being consumed by this component.

The sensor has 4 pins namely V_{cc}, Trig, Echo and Ground. the V_{cc} pin is where the voltage supply will be connected to the sensor. The Trig pin is used to identify when the sensor should physically start sensing. In order to start detecting objects we send a TTL single of 10μs to the sensor. It receives it and response by sending a 8-cycle sonic burst signal at 40KHz and raise its echo pin. The echo pin is the pin which will provide us with useful information to calculate distance between the sensor and an object it is measuring. It is now sending sending a wave outwards and this wave will reflect off an object. The receiving sensor on the ultrasonic sensor will receive the wave and will pull the echo pin low. The period of that echo wave is used to then calculate the distance that the object is away from the sensor. The formula used to calculate the distance is $\frac{microseconds}{58}$=answer in centimeters [5].



(a) Timing diagram of the ultrasonic sensor

Figure 1.2: Figure shows the timing diagram of how distance is calibrated from the sent wave of the

.

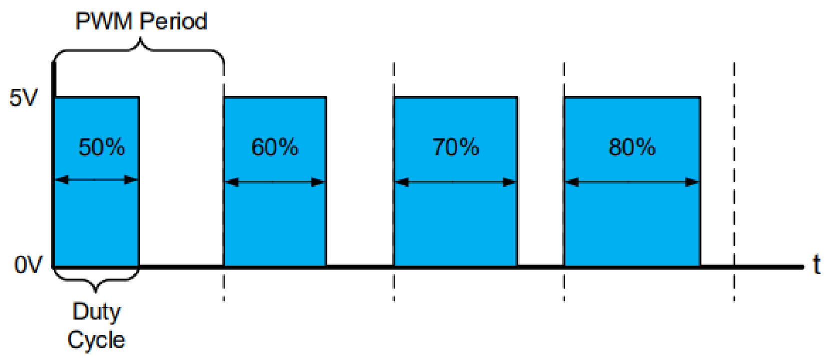
The output voltage of a PWM signal can be calculated as:

$$V_{out} = Amplitude \cdot Dutycycle \tag{1.1}$$

To verify this, a voltage measurement was taken at the output of the first LTSpice pulse output which was 6000μs and our max period is 60000μs so it is 10% duty cycle. With a gain of zero, the output voltage was ≈500mV, which is what is expected.

1.4. PWM to Analog Conversion

PWM modules generate pulse-width modulated digital signals. In a PWM signal, the base frequency is fixed, while the actual pulse-width is variable.



(a) PWM Signal visualised at different duty cycles

Figure 1.3: The figure clearly shows how a PWM signal is transmitted at different duty cycles

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As stated previously, we can convert this PWM signal to a analog signal using $V_{out} = Amplitude \cdot Dutycycle$. The duty cycle is related to the analog voltage output and is what determines the magnitude of the that analog output. The only downside to this conversion is noise. We will have to pass the signal through some form of filter to smooth out the output. We will also have to have to add some form of gain, since we need 1m distance to be above 3V but no more than 3.6V because we do not want to blow the pin on MCU. For the lowest measurement of distance (5cm) we need our voltage to be below 0.3V (almost unreadable by the MCU pin) [6].

The noise requirement is extremely low for our analog output, $< 70mV$ to be exact. In order to achieve this, a second order filter is almost guaranteed. A active filter will be used since they generally work better as filters and they can have a resistor. feedback network to provide gain. We also have access to MCP6242 op-amps which are ideal for the application.

The frequency of our received PWM signals are ≈16Hz, since the base frequency of a PWM is fixed as stated.. When we design our filter we need to filter out and attenuate any signals that are $> 16Hz$. More of this will be discussed in design section of the report.

1.5. Fundamental Operation of the Range Sensor

"Ultrasonic waves travel faster than the speed of audible sound (i.e. the sound that humans can hear). Ultrasonic sensors have two main components: the transmitter (which emits the sound using piezoelectric crystals) and the receiver (which encounters the sound after it has travelled to and from the target)" [7].

Now a question that will interest you, how does a piezoelectric disc generate ultrasonic waves. Materials are made of crystals. These crystals are made of atoms and are arranged in a specific way. The atoms have varying polarity. Certain materials have crystal structures very sensitive to electric field and certain materials vibrate under time-dependant voltages. These crystals demonstrate a phenomenon known as the piezoelectric effect. In these crystals, such as quartz, tourmaline and Rochelle's salt, a hexagonal shape at both ends is evident. The 3 axes in which these crystals operate are:

- Optical
- Electrical
- Mechanical

When pressure or mechanical force is applied along the polarization axis of the piezoelectric crystals it produces electricity (signals). For the HC-SR04 sensor, the optimal crystal was selected to perform the function that the engineers wanted. If you would create one of these at home, other crystals can be used. One should ensure that it its signals that it generates are viable for the particular application.

We have discussed the Trig and Echo pin of the HC-SR04 but how does it actually work? The Trig pin is set High for 10μs and during this time, it sends a ultrasonic burst of 40KHz signals. This 8-pulse pattern is specially designed so that the receiver can distinguish the transmitted pulses from ambient ultrasonic noise. The echo pin goes high when one of these bursts are transmitted and remains high until the receiving end senses that echo again, in which it also goes low. The time the echo pin stays is what is used to calculated the distance measured by the sensor [**?**].

1.6. Digital to Analog Converter

If there is a digital output and we need analog output, we need to convert that digital signal into the analog signal. DAC (Digital to analog converter) takes digital inputs and generates the output which is equivalent to the analog signal [?].

The easiest and most common way to approach designing a DAC is to use a ladder resistor summing amplifier. It consists of a ladder of resistors in parallel that have the binary inputs connected to them. However many bits you want to send will determine how many resistors you will have in your ladder. If the summing point of the resistors is connecting to the inverting input, it will produce the negative sum of the resistors. Vice versa for the non-inverting op-amp. There is a feedback resistor connected which determines determines a gain as will be discussed in the detail section. Another way to approach this is using a R-2R amplifier. Its similar but there are some complexities in implementing it [?].

First of all, large resistors will be chosen for the ladder resistors to limit current since the there is a maximum driving current on the IO pins, which is the pins we will use for our binary inputs into the summing amplifier. Furthermore we will have extremely large input impedance into the op-amp to which has all ready been discussed.

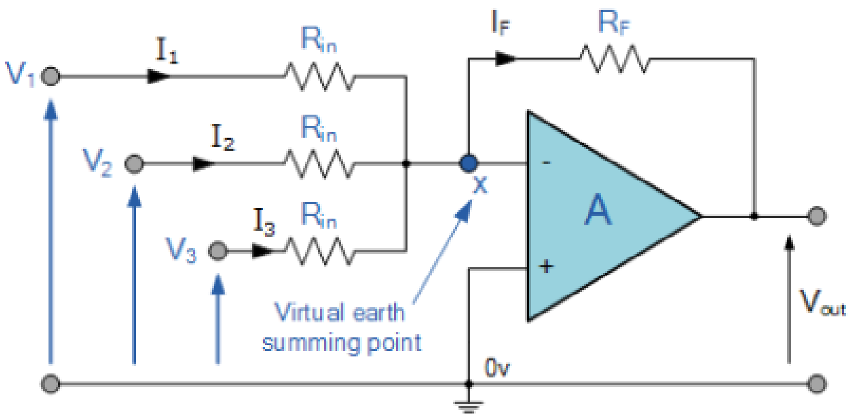

Figure 1.4: Basic example of DAC summing amplifier

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1.7. Lead Acid Battery

Lead acid batteries are most commonly used in applications where the battery needs to be rechargeable, which is ideal for our project. They do unfortunately have low energy density, moderate efficiency and high maintenance requirements. This does not stop them from dominating the rechargeable battery market. A lead-acid battery consists of a negative electrode made of spongy or porous lead. The lead is porous to facilitate lead formation and dissolution. The positive electrode is made of lead oxide. Both electrodes are immersed in an electrolytic solution of sulfuric acid and water.

The lead acid battery uses the constant current constant voltage (CCCV) charge method. A regulated current raises the terminal voltage until the upper charge voltage limit is reached, at which point the current drops due to saturation. The charge time is 12–16 hours and up to 36–48 hours for large stationary batteries. With higher charge currents and multi-stage charge methods, the charge time can be reduced to 8–10 hours; however, without full topping charge. Lead acid is sluggish and cannot be charged as quickly as other battery systems. [8]

With the CCCV method, lead acid batteries are charged in three stages, which are (1) constant-current charge, (2) topping charge and (3) float charge. The constant-current charge applies the bulk of the charge and takes up roughly half of the required charge time; the topping charge continues at a lower charge current and provides saturation, and the float charge compensates for the loss caused by self-discharge. [8]

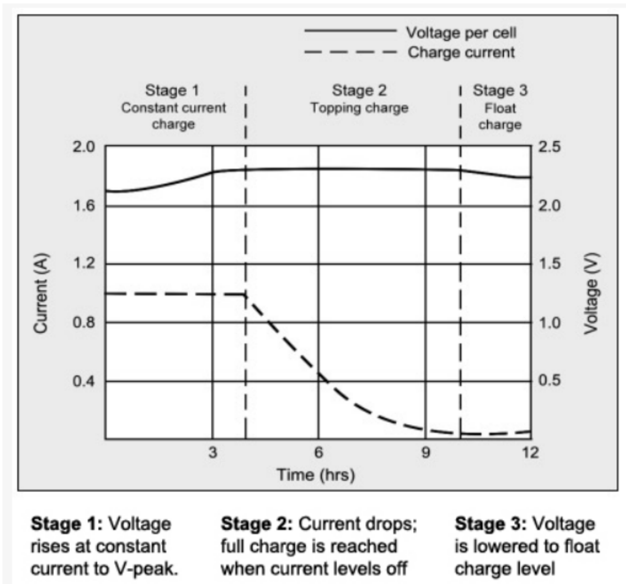

Figure 1.5: Voltage and current curve of

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Chapter 2

Detail design

For our application, a low side current sensing circuit, we will have to make the first decision and that will be what op-amp will we use in order for us to produce a gain and filter out some noise. One can design the current sensor with a single-ended implementation or a differential input implementation. Both can achieve the requirements of the task but there will be drawbacks for picking one or the other and trade-offs will have to be taken into account. The single-ended implementation is the easiest and cheapest of the 2 designs which is why I have chosen to implement it. If this design is chosen, you will trade-off accuracy. With this method, parasitic resistances and the temperature coefficients of the resistor gain network will significantly affect accuracy. We are essentially adding gain to noise. If the filters are designed correctly though this should not be an issue. For the differential input implementation, accuracy will be limited by the CMRR and drift of the solution, which are a function of the op-amp and the matching of the gain resistors. The better the CMRR, the more costly the circuit will be [9].

2.1. Current sensor

For the single-ended circuit, either a inverting or a non-inverting op-amp will be required. I have chosen to work with a non-inverting because we do not require a phase shift for our application. For the filter section of the op-amp, a low-pass filter will be chosen since we can design for a cutoff frequency much lower than required and it will attenuate signals much higher than that designed cutoff frequency. We have artificial noise implemented in the circuit. The noise is 10mV and has a frequency of 1KHz. I will choose a cutoff frequency of 100Hz and design the low-pass filter to be second order to attenuate quicker to 1KHz. You do not want to choose a cutoff frequency to low, it will give us undesired transient behaviour. To fit in our current requirements of 150μA I will choose my capacitor values first. I will choose them to be small as possible (100nF) so that my resistor values can be larger to limit current. The calculations for a second order RC filter are as follows:

$$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$$

$$100 = \frac{1}{2\pi\sqrt{2R \cdot 2(100 \cdot 10^{-9})}}$$

$$R = 16k\Omega$$

Now we have designed our RC filter. Now we need to amplify our voltage so that it follows the current and will also be acceptable by our micro-controller. The acceptable range of voltage that can enter a pin's on the ESP32 MCU is $3.0V < Pin < 3.6V$ [5]The original voltage through the sense resistor with no noise attached to it was 12mV. We need it to be $\approx 3.3V$ so our op-amp will most definitely have a feedback network for gain. The calculations are as follows:

$$A_v = \frac{3.3}{0.012}$$

$$A_v = 275V/V$$

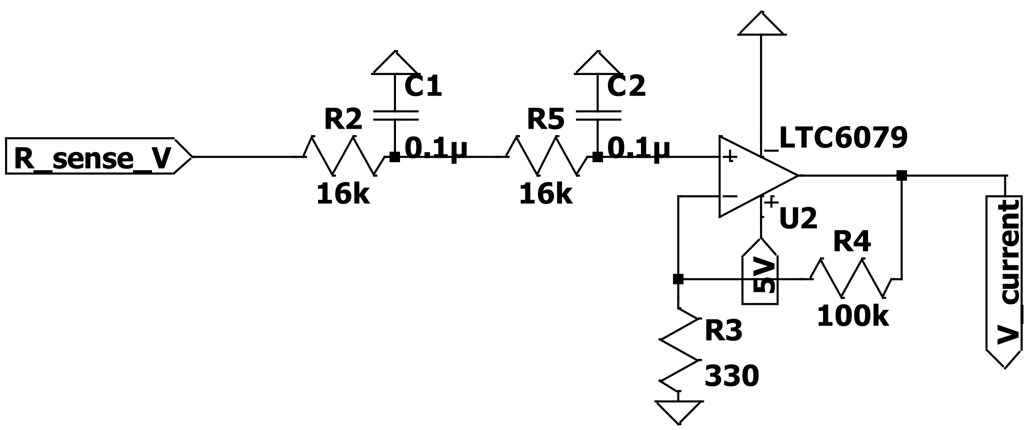
Now we know that our resistor feedback network must be in a ratio that produces a gain of 275V/V. I will choose the first resistor. The larger the better since we want to sink as much current as possible. I will choose $R_f = 100k\Omega$. Now all we need is the resistor to ground R_g.

$$A_v = \frac{R_f}{R_g}$$

$$275 = \frac{100k\Omega}{R_g}$$

$$R_g \approx 330\Omega$$

Through testing the DC motor, it was found that supplying a 6V DC supply to it resulted in about 200mA-250mA current being drawn by the motor. When stalled it was 1A. A safe design range would be about 1.2A, which was edited in the PWL file to begin with. That is how 12mV over the sense resistor was obtained.



(a) Inverting Op-amp

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Figure 2.1: This figure shows the circuit built in spice

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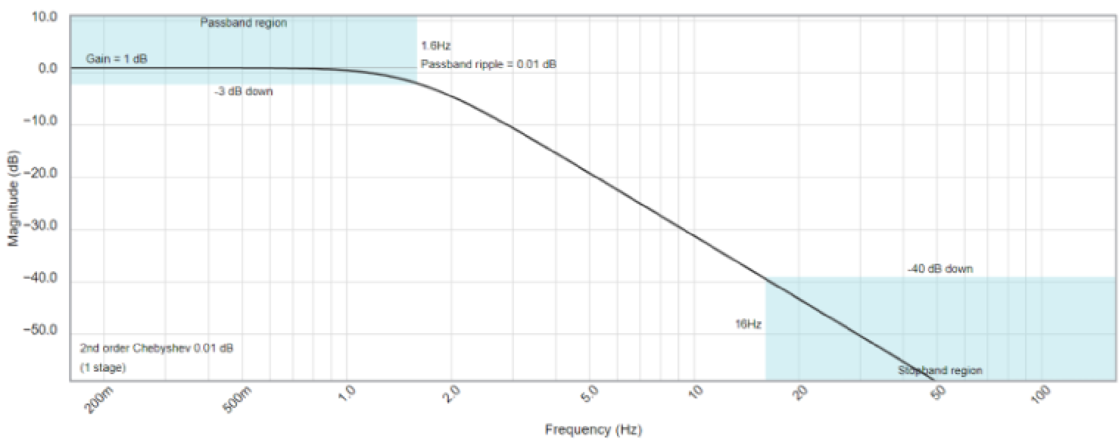
2.2. Analogue Range Sensor

We have chosen to work with the HC-SR04 ultrasonic sensor. It requires a 5V supply which we can draw from a voltage regulator, but we were given leniency in regards to the regulator, since it was scrapped from the project as a whole. The sensor will just draw 5V from a DC supply. It also has an operating current of 15mA, which results in about 75mW of power being drawn. This is all within spec.

The signals that the ultrasonic sensor outputs on the echo pin are ≈16Hz. The duty cycle range of the PWM signals on the echo pin will be $116\mu s(2cm) \leq t \leq 23200\mu s(4m)$ which can be calculated calculated using the $\frac{microseconds}{58}$=answer in centimeters formula. For our specifications, we need to measure $\geq$ 1m and output a voltage $\geq$3V ,but no more than 3.6V (otherwise we pop a pin), and for a $\leq$5cm measurement, we need to output a voltage of $\leq$ 0.3V. The 0.3V is easy to combat, it will just be part of our actual filter design. For the 3V specification required for measurements above 1m, we can abuse op-amp properties. You can just make the V_{DD} 3.3V so it will clip any voltage above 3.3V which is ideal. It is also a good excuse to make use of the 5V-3.3V regulator and now we have a common node to pull any 3.3V from.
A second-order active low pass was chosen for this. Refer to Section 1.4 as motivation for this was discussed. To design a 2^{nd}-order active LPF you will make use of one of two equations. If you are willing to keep both resistors and capacitors the same size in the filter section you can use the simplified version of the equation. The $f_c = \frac{1}{2\pi RC}$ calculation will be used. In order to choose f_c we need to keep in mind that these PWM signals are being received at 16Hz, so 16Hz signals need to be attenuated completely. Choosing a f_c 10x lower is a good rule of thumb. We can design at $f_c = 1.6Hz$ or even lower if we wish. A capacitor will be chosen first (low capacitance $\approx 1\mu F$), so we can purposely design for high resistance so we can sink more current.



(a) Bode plot for f_c choice clarity

Figure 2.2: This bode plot shows the passband of 1.6Hz and stopband of 16Hz

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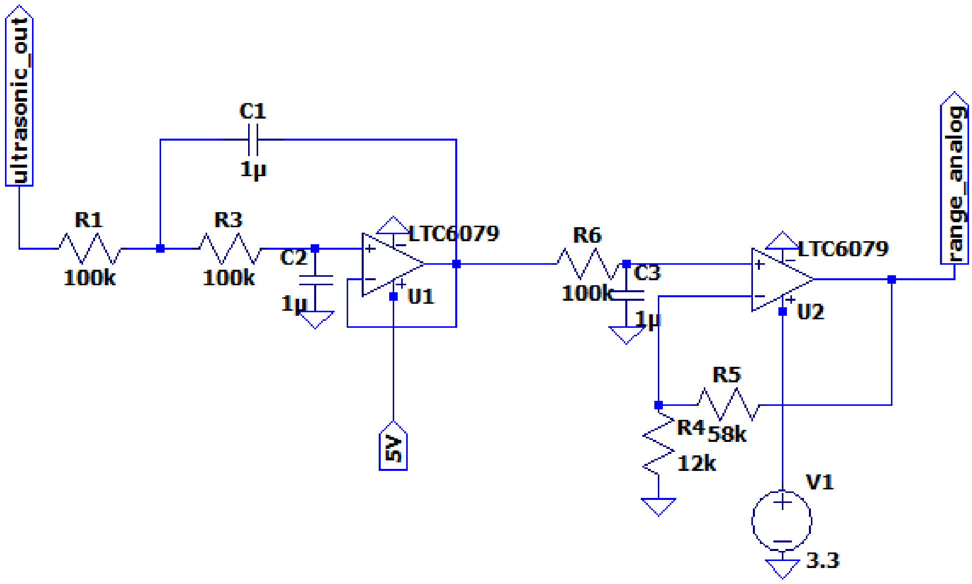
With only the filter connected with no gain, there was about $\approx 500mV$ being received for $6000\mu s$ PWM signals. This is equivalent to 103cm being measured. Our specification says that this should be above 3V. So we need a gain of $\approx 6V/V$ to achieve this. Making use of two op-amps might be a good idea since we can put a RC filter in between them to help filter out even more noise without really affecting the time constant since the active filter is dominant and will filter first. The second op-amp will have the resistor gain network. resistor R_g will be chosen as a standard $10k\Omega$. This results in R_f being $\approx 58k\Omega$ using the standard gain equation previously used in this report. These resistors are high which is always good in current limitations. To combat the fact that the op-amp must output a low voltage ($\leq 0.3V$) for low measurements ($\leq 5cm$) we must just design an extremely good filter so that the time response is quick enough. To ensure we do not pop our pins for high measurements ($\geq 1m$) we can just abuse op-amp properties and connect 3.3V to the V_{DD} port of the op-amp so no voltage can ever exceed that.



(a) Ultrasonic sensor LTSpice schematic

Figure 2.3: Figure shows the LTSpice schematic for the ultrasonic sensor

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Furthermore variable resistors can be used at the gain resistor feedback network. This can assist in deciding what resistor combination is best for the real world application. Since we will hold items at specific distances from the sensor and measure voltage output and there is a high possibility that nonidealities will play a role and our output voltage will not be exactly what we would like. The main nonidealities are the common mode input range which is $V_{ss} - 0.3V$ and $V_{DD} + 0.3V$ and a differential input voltage of $|V_{DD} - V_{SS}|$. In fact, these were so evident in the real life design that almost immediate resistor variation was necessary since the outputs were not what they were suppose to be.

2.3. Digital to Analog converter

The DAC summing amplifier we are designing will have a 4-bit resolution. The first step (0001 as input) will have a size described by the following equation.

$$step(V) = \frac{V_{out}}{2^n}$$

where n is the number of bits being transmitted. This results in the first step having a size of 0.20625V. This means in order to preserve the data being transmitted we have to ensure that our voltage step is less than 0.20625V. This will increase in magnitude per step in multiples of what you decided to make your resistors ratio. The circuit was designed for max output of 3.25V which is above 3V but below 3.3V to protect the DAC pin.

Table 2.1: Resistor weighting chosen and the respective step voltage expected.

Resistor value chosen [kΩ]	**Step voltage [V]**	Digital Input	**Expected V_{out}**
20	0.2065	0001	> 2.9895
40	0.4125	0011	> 2.577
80	0.825	0111	> 1.752
160	1.65	1111	> 0.102

Its worth taken into note that we had to design for inverting input. I.e. for a 0000 digital input we wanted to highest output and for a 1111 digital input we wanted the lowest output. In other words, we will have to have some form of DC level shift attached to our non-inverting terminal of the op-amp which will make $V_- = V_+$. This was done using a simple voltage division circuit with 2 resistors. The one being a potentiometer do adjust for non idealities. The KCL of my circuit was derived and simplified below. [**?**].

$$V_{out} = V_-(1 + R_f(\frac{1}{R_0} + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3})) - R_f(\frac{B_0}{R_0} + \frac{B_1}{R_1} + \frac{B_2}{R_2} + \frac{B_3}{R_3})$$

Where $B_0 - B_3$ represents the digital inputs where B_0 is the least significant bit and B_3 is the most significant bit. Note, the R_f was made as a potentiometer so that the gain can be varied so we can ensure out step sizes meet the requirements of the assignment.A voltage buffer can be added to the output of the DAC to reduce the DAC sensitivity to the input impedance of the circuit that the DAC is connected to.

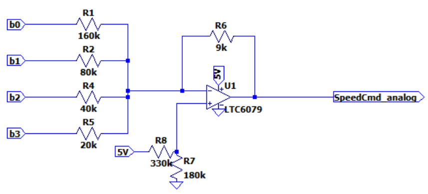


Figure 2.4: LTSpice schematic of the DAC inverting summing amplifier [1]

2.4. Voltage Regulators

2.4.1. 7.2V - 5V Regulator

For the regulator design we have chosen to use the LD1117 Voltage regulator. It is a very general regulator that has multiple ranges for different inputs and output voltages. You can use many configurations to achieve the desired voltage that you want. It is affordable, very easy to get ones hands on it, and is within our specifications, which justifies its choice even further [].

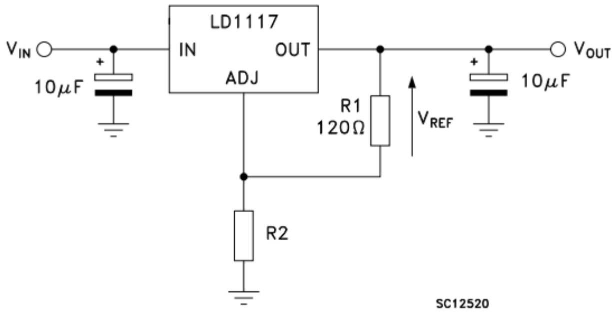


Figure 2.5: 7.2V to 5V regulator circuit schematic [2]

$R_1 = 120\Omega$ given by the datasheet. R_2 can be calculated using a the following equation:

$$V_{out} = V_{Ref}(1 + \frac{R_2}{R_1})$$

Where $V_{out} = 5V$ and $V_{ref} = 1.25V$ which was also provided by the datasheet for this configuration. Using the equation and substituting the required variables you will obtain $R_2 = 360\Omega$. The $10\mu F$ input and output capacitors have been added to improve the transient response and stability of the regulator.

2.4.2. 5V-3.3V Regulator

The 5V-3.3V regulator will be similar to the the 7.2V-5V regulator. It won't require any resistors, but it will require a capacitor at the input and another at the output for the exact same reasons as before.

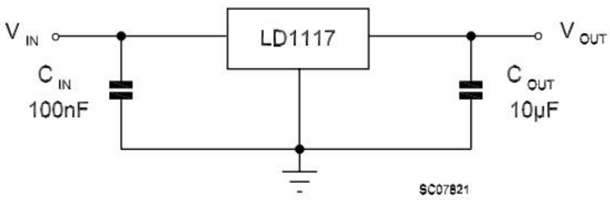


Figure 2.6: 5V to 3.3V regulator circuit schematic [2]

2.5. Motor control signal and driver

2.5.1. Differential Op-amp

Our previously designed DAC is giving a output to motor. Our ultrasonic sensor is a verification of this speed. If a object is far away from the sensor, the sensor will verify that the motor can drive at full speed. If a object is close the ultrasonic sensor needs some way to decrease the voltage from the DAC output. A subtracting(differential) amplifier is required for this to occur.

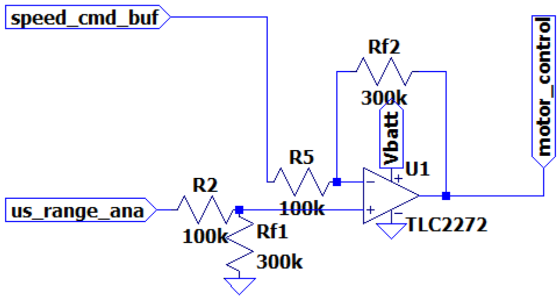


Figure 2.7: Subtracting amplifier schematic

Figure 2.7 shows the general differential amplifier circuit design. Performing a KCL at the input nodes and the output nodes one can derive the following equation:

$$V_{out} = \frac{R_f}{R_1}(V_+ - V_-)$$

Our requirements state that for no object in range for the sensor to detect, we should be outputting maximum voltage. With a load connected that should be $\approx 5.2V$ and for no load it should be $\geq 6.2V$, just like our spice simulation. V_- will be connected to our DAC and V_+ will be connected to our ultrasonic sensor filtered output. Our maximum voltage measured for the ultrasonic sensor is 3.3V. Keeping both R_1 identical and both R_f identical we can calculate R_f to be twice R_1. If we choose $R_1 = 100k\Omega$ then $R_f \approx 200k\Omega$. [10]

2.5.2. Emitter Follower

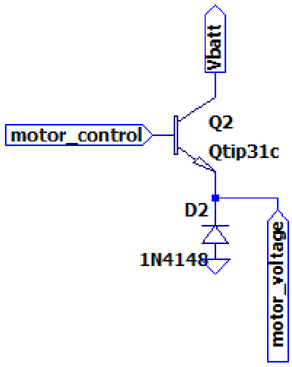


Figure 2.8: Subtracting amplifier schematic

The common collector configuration of a emitter follower is used for impedance matching since it has a very high input impedance and a low output impedance to switch relay coils [11]. This could have also been done using npn or pnp BJT. A advantage of this type of relay circuit to control a motor is the fact that it uses very little power to operate as a switching relay.

We are drawing current from our V_{batt} instead of the ESP32 when there is sufficient current at the base of the transistor. The diode is clamping reverse voltage at the emitter pin of the BJT which protects the transistor by dissipating energy.

2.6. Left Wheel Low-side Switch and current sensor

2.6.1. Low-side Switch

Since a n-channel MOSFET operates using a positive input voltage and has nearly infinite input resistance, it allows for a these MOSFETs to act as switches when they are interfaced with logic gates and drivers capable of producing positive output voltage.

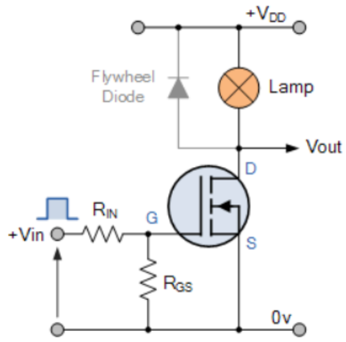


Figure 2.9: MOSFET as a low-side switch schematic []

We are using the MCU to output 3.3V to the V_G of the MOSFET. The GPIO I/O voltage is $\approx 3.3V$. In order for the MOSFET to essentially short and switch on, the V_{GS} threshold voltage electrical characteristic will need to be smaller than 3.3V so there can be a positive voltage over V_{GS} of the MOSFET. If $V_{GS} > 0V$, the MOSFET will switch on. If $V_{GS} \leq 0$ it will essentially open circuit and the circuit will remain off.

Figure 2.9 also shows a pull down resistor connected to V_G of the MOSFET. This is a current limiting resistor and just shunts current to ground. A input series resistor that is connected to V_G is optional.

When the MOSFET is in it's on state, it essentially shorts and current flows through DS of the MOSFET. This I_{DS} current is an important electrical characteristi. of a MOSFET and will also need to be considered when making a decision on a MOSFET, since it needs to be above a certain current rating for our motor specifications,

We were given 4 MOSFETs to choose from. Only one will be a viable optional. The process of choosing and eliminating MOSFETs from the pool is as follows:

- The **IRF9Z24NPbF** is immediately unconsidered since it is p-channel and does not have a positive V_{GS} threshold voltage, thus it cannot switch on for this configuration of a switch.
- The **2N7000** is eliminated since it has $200mA \leq I_{DS} \leq 500mA$ which is not sufficient. Our motor can pull up to 1.2 amps on a stall.

- The **IRF530** is eliminated since it has characteristic of $2.5 \leq V_{GS} \leq 4V$ and V_{GS} is a function of current so we do not want to take the risk of the V_{GS} going beyond 3.3V
- We are left with the **FQD13N06L** which is ideal for our specifications since $1V \leq V_{GS} \leq 2.5V$ and a max $I_D = 11A$ at room temperature.

2.6.2. Current Sensor

For majority of the left hand current sensor, it is basically a copy of the previous current sensor circuit, with improvements. Changes made:

- Gain increased significantly. The 2 resistors responsible for this are in the feedback network of the op-amp. They have been altered.
- Voltage divider at the output of the op-amp has been adjusted to meet the new gain changes.

The switching frequency will have to be less than 100Hz since that was the cutoff frequency chosen in the A1 current sensing circuit. Anything past that will attenuate very quickly since it is second order circuit and will not be observed.

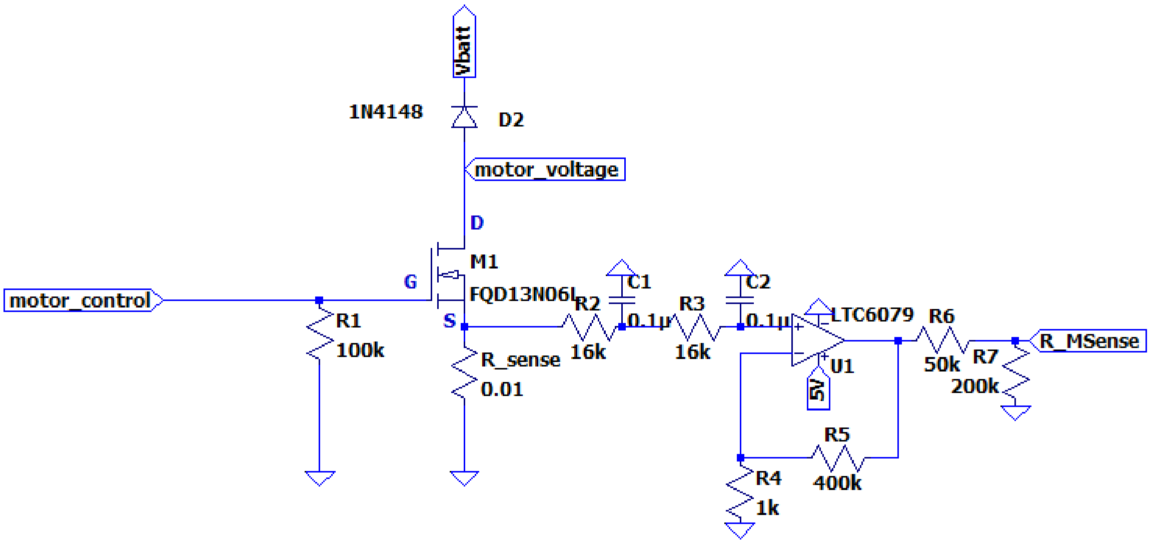


Figure 2.10: MOSFET switching circuit connected to current sensing circuit

2.7. PWM Control and Range Sensing (Firmware)

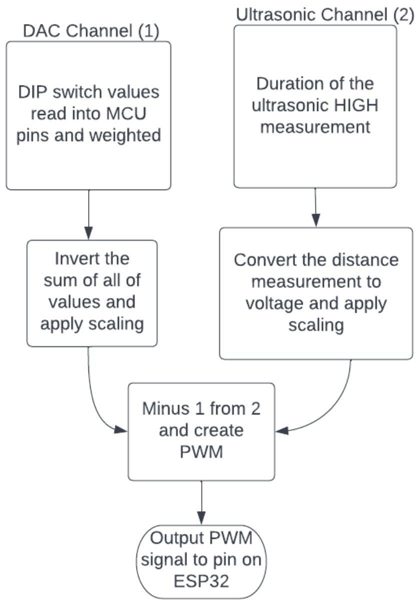


Figure 2.11: flow Diagram representing how the code was implemented

Table 2.2: Pins chosen for DAC input and ESP PWM output

Pin on ESP32	**Pin Description**	Variable Stored
34	GPIO Input only	DAC Bit 3 (MSB)
35	GPIO Input only	DAC Bit 2
32	GPIO I/O	DAC Bit 1
33	GPIO I/0	DAC Bit 0
25	GPIO I/O	Echo from Ultrasonic Range sensor input

Both ultrasonic sensors work on the same trigger pulse as this is the most efficient way of performing the task.

2.8. Battery Charger

Battery chargers are general applications of voltage regulators and they can be seen in the ”Typical Applications” section in the LM317T Datasheet. Figure 2.12 shows a application with adjusted resistors to fit the specifications of the assignment.

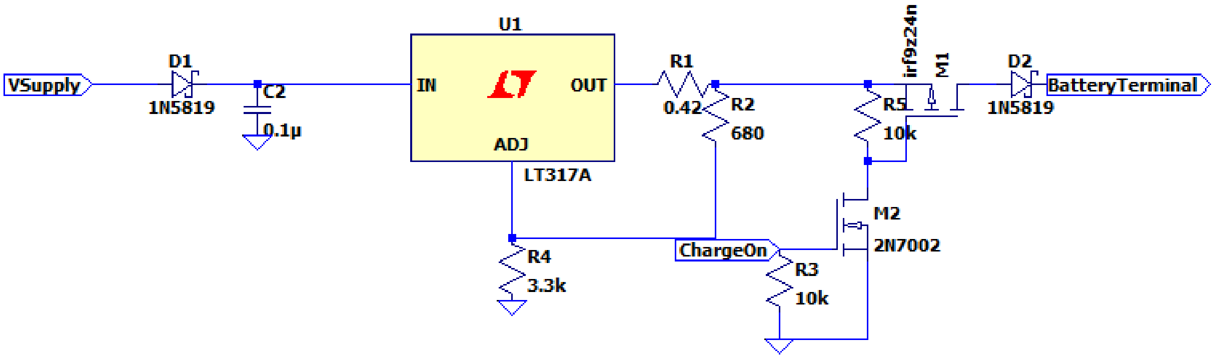


Figure 2.12: 7.2V Lead-acid battery charging circuit with 12V input

The following formula can be used to determine the resistors required to set the output voltage to $V_O \approx 7.2V$.

$$V_O = V_{REF}(1 + \frac{R4}{R2})$$

Where $V_{REF} = 1.25V$, $R4 = 3300\Omega$, $R2 = 680\Omega$. R_1 allows for low charging rates with a fully charged battery, hence its tiny value.

The battery given to us is a 3-cell battery with each cell producing a voltage of about 2.43V-2.47V at room temperature ($25°C$). With this being said, our voltage at steady state charging needs to be in between, $3 \times 2.43V \leq V_{out} \leq 3 \times 2.47V$. This holds and our design is operating as specified.

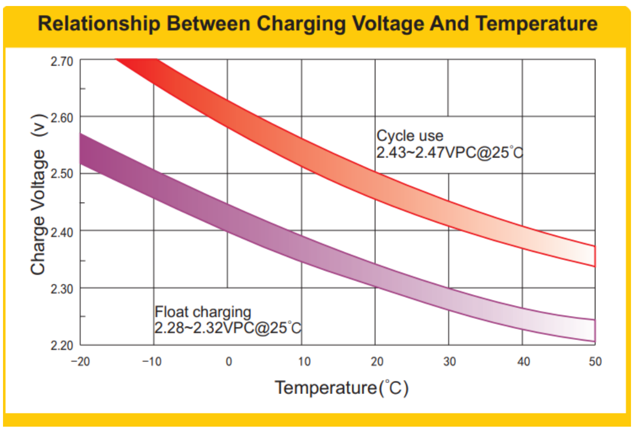


Figure 2.13: Relationship Between Charging Voltage And Temperature (per cell)

R_3 and R_5 are just pull down resistors. Transistor M2 will be acting as a switch. If 3.3V is being supplied at ”Charge On” port then it will allow the battery to be charged by the circuit. The Schottky diode D1 at the input is for reverse polarity protection and the capacitor C2 at the input is for improved transient behaviour.

There is also a current limit requirement in the specifications. We cannot supply more than $\approx 400mA$ since the safe battery charging rate is $0.1C$ according to the datasheet and $4A = 1C$ for our battery given to us. The other battery that was also provided has a safe battery charging rate= $700mA$ since its $1C = 7A$. In practise, these currents can be higher up to $1.2A$ according to the $E - RT - RT640$ datasheet. We can keep it safe and design for 0.1C as this is rule of thumb.

2.9. Under-voltage Protection

If voltage is required to suddenly drop for when voltage supplied to it is below a specific threshold, a Schmitt trigger is the first thing that comes to mind as it does exactly that. It is a circuit designed with an op-amp and with consideration of a upper threshold voltage level and a lower threshold voltage level. A output voltage high (V_{OH}) and a output voltage low (V_{OL}) is chosen and resistors are designed to meet these voltages. When the voltage supplied to the input of the Schmitt trigger is above the upper threshold, or between the upper and lower threshold, it will output its V_{OH}. When the supplied voltage reaches below the lower threshold voltage, it will simply output the V_{OL}. It is a type of comparator circuit and it does all this with the help of hysteresis, which is created by applying postive feedback to the non-inverting input of a comparator or differential amplifier. [12]

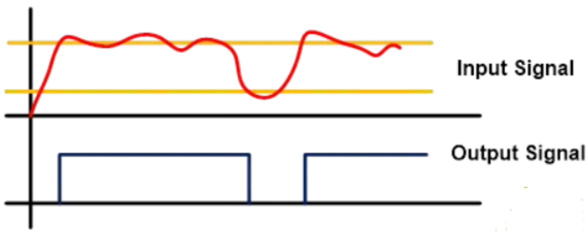


Figure 2.14: Threshold levels of a Schmitt trigger

In Figure 2.14, the orange lines represent the upper and lower threshold voltages. Figure 2.15 below shows a schematic of the designed circuit. There is a couple ways to build this circuit, the simplest version was built in this case. V_1 represents a V_{REF} voltage and will be utilised in calculating resistors values. The $V_{REF} = 2V$ will be obtained from passing a voltage from the 3.3V pin into a voltage divider. The following equations were used to design the resistor values. [12]

$$R_3 = \frac{V_{th} - V_{ref}}{I_{max}}$$

Where I_{MAX} is the maximum input current which was chosen to 1mA for practicality. Choosing a input current higher resulted in very unrealistic resistor values.

$$R_4 = \frac{V_{OH} - V_{OL}}{I_{MAX} - \frac{V_{TL} - V_{REF}}{R_3}}$$

Where V_{TL} is the lower threshold voltage.

$$R_5 = \frac{V_{REF}}{I_{MAX} - (\frac{V_{REF} - V_{OL}}{R_4})}$$

Where the $V_{OH} = 5V$, $V_{OL} = 0V$, $V_{upper} = 3.1V$ (half of 6.2V), $V_{lower} = 2.95V$ (half of 5.9V), $I_{MAX} = 1mA$. V_{upper} and V_{lower} might seem lower than what they are suppose to be which is what brings the report to signal conditioning.

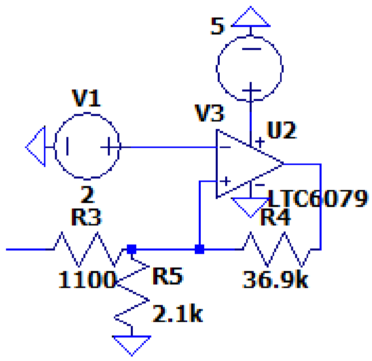


Figure 2.15: Non-inverting Schmitt Trigger SPICE schematic

2.10. Signal conditioning

The 6.2V upper and 5.9V lower threshold voltages need to be scaled so that out ESP MCU can read these values in for later purpose. You can either make a scaling circuit which is the better way, but there a simpler way which also works perfectly. Our max input is 6.2V which is double 3.1V so we can essentially just have a voltage divider which has 2 resistors and keeps the voltages limited between $0.1V \leq V_{V_output} \leq 3.3V$ and for the inverting section we can just connect the output, essentially making it a buffer that has a voltage divider connected to its non-inverting input which limits out voltage into the circuit. It also mitigates input impedance since we do not want the resistor network to affect the input resistance into the under-voltage protection op-amp. [12]

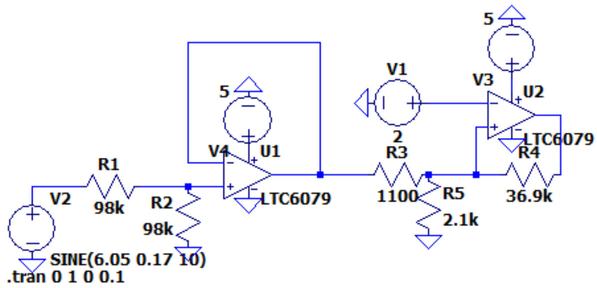


Figure 2.16: Signal conditioning and under-voltage protection full circuit schematic

Chapter 3

Results

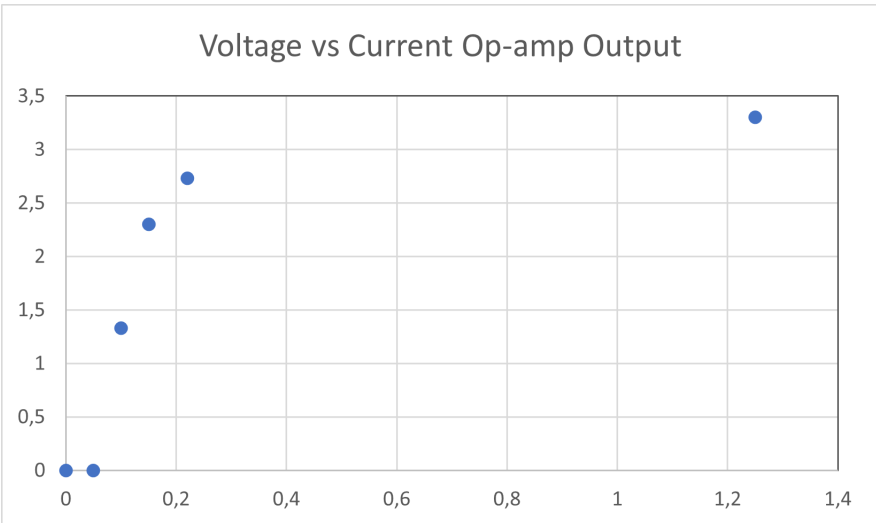
3.1. Motor Measurements

Table 3.1: States of motor and their respective current pull (Simulation)

State	Current
Running	$200 - 250mA$
Small Load	$300 - 400mA$
Stall	$1A$

Table 3.2: States of motor and their respective current pull (Real circuit)

State	Current	Voltage
Zero	$0A$	$0V$
Free Running	$220mA$	$2.7V$
Running Constricted	$340mA$	$3.05V$
Stall	$1.2A$	$3.33V$



(a) Voltage vs current

Figure 3.1: Voltage vs current for the op-amp with motor connected to the circuit

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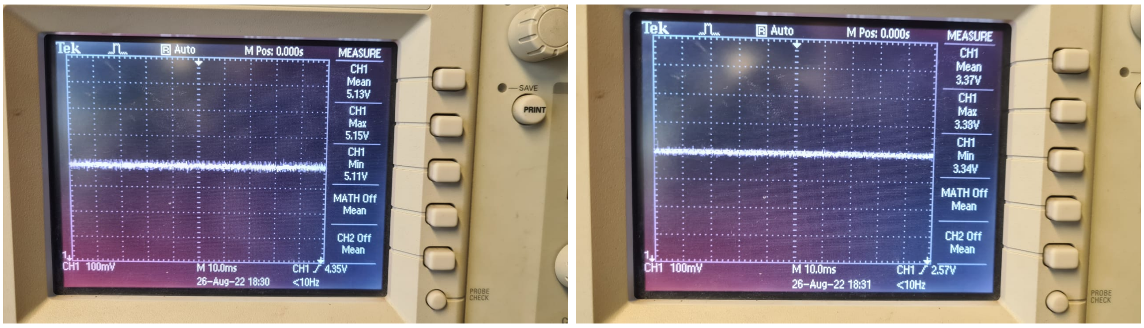
3.2. Voltage Regulator



(a) 7.2V-5V Regulator voltage measured and observed on oscilloscope.

(b) 5V-3.3V regulator voltage measured and observed on oscilloscope

Figure 3.2: Displaying the 2 voltage regulators and there respective voltages measured on an oscilloscope. **Note,** it was scaled and measured with a probe so noise is evident and can be seen

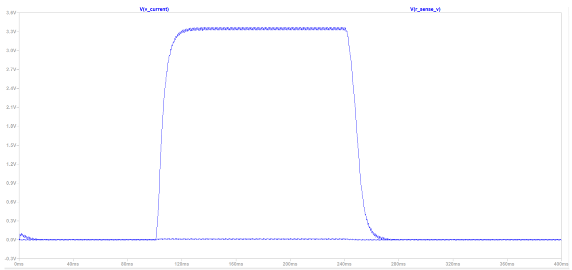
.

Table 3.3: Voltage regulator measurements oscilloscope vs multimeter

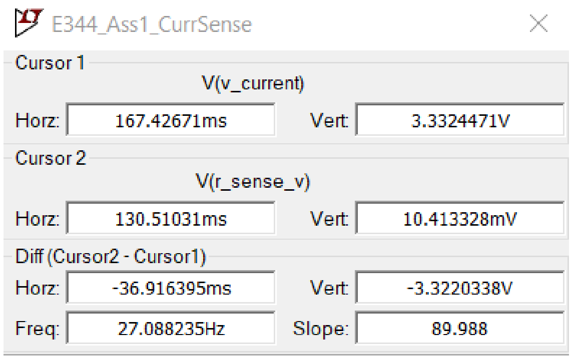
Regulator	Oscilloscope Voltage	Multimeter Voltage
5V	5.13V	5.04V
3.3V	3.37	3.30V

The oscilloscope measurement and multimeter measurements are corresponding and they only have a slight difference between them, with the obvious fact that the oscilloscope probe was detecting noise and this has an effect on the measurement. The results for the regulators are satisfactory and meet specifications. If any op-amps or components require 5V/3.3V, they will pull from these regulators.

3.3. Current sensor



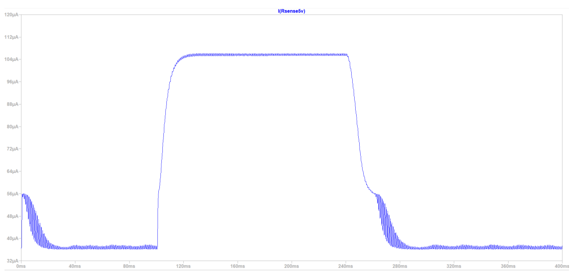
(a) Input of the Op-Amp measured at V_{Rsense} vs Output at V$_{c}urrentnode$



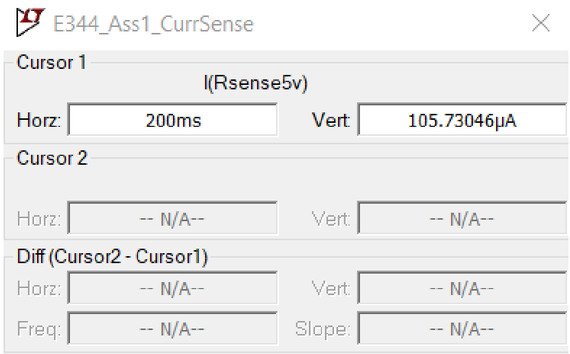
(b) Non-inverting Op-amp

Figure 3.3: Input of the Op-Amp measured at V_{Rsense} vs Output at $V_{currentnode}$

.



(a) Current through the sense resistor. It fits in the requirements



(b) Current through the sense resistor (Text format)

Figure 3.4: Current measured through the sense resistor

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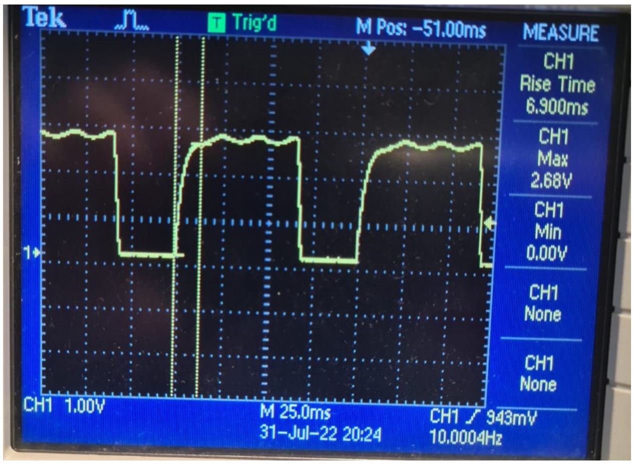
The circuit was practically realised. The motor and the shunt resistor was connected to the circuit. The first aspect that had to be verified was the step response of the op-amp. The following procedure was followed to measure step response of the op-amp:

- Connected 5V supply to the op-amp
- Connected signal generator probes to the circuit. The configuration was square wave, 6mV pk-pk, 10Hz (100ms), and a duty cycle of 70% so the wave is easier to visualise.
- Connected a oscilloscope probe to the the output of the op-amp. The output was measured.

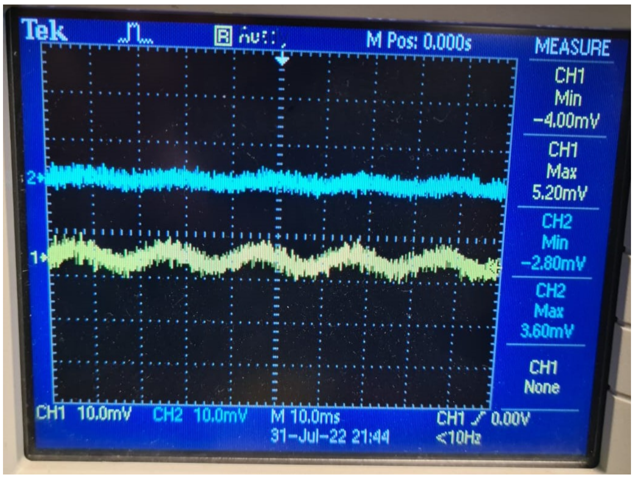


(a) Step response of the op-amp measured

Figure 3.5: The figure shows the step response measured after a square wave was inputted into the op-amp

.

Note, the noise channel was just removed for clarity as one could not really see the graph when the noise was present on the oscilloscope. The time measured to reach 90% of the final value was 7ms. This is fast and was well within the requirements.



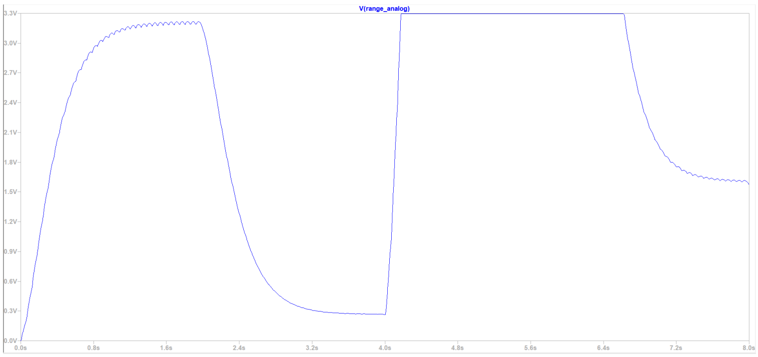
(a) Noise measured on oscilloscope

Figure 3.6: Natural noise being amplified by the circuit

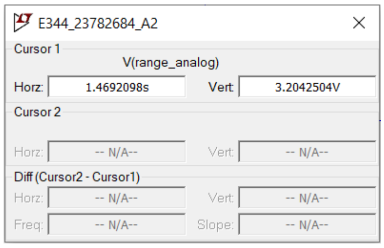
.

There was a slight gain in noise when natural noise as passed through the op-amp. This was a good indication of how well my op-amp deals with noise. Some artificial noise was then added to the circuit by using a signal generator and connecting it to the circuit. 10mV at 1000Hz was supplied to the input of the op amp and the output was measured well under 250mV at the output. The output was not measured above 100mV. The circuit dealt with noise sufficiently.

3.4. Ultrasonic Range Sensor

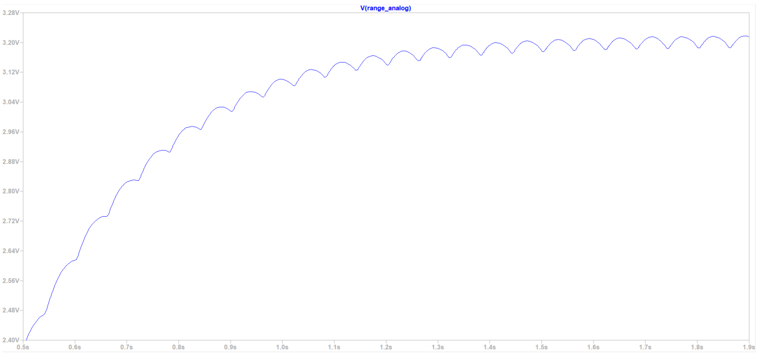


(a) Full range LTSpice graph output of ultrasonic sensor

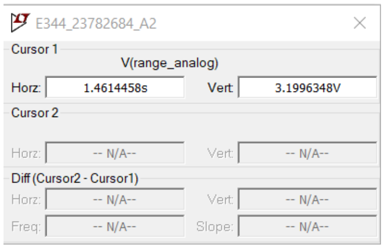


(b) Measurement of the graph at 6000 $\mu s (\approx 103cm)$

Figure 3.7: Full range output of the ultrasonic sensor stepping from 0s - 6000μs(103cm) - 500μs (9cm) - 23200μs (4m max possible measurement) - 3000μs (52cm) in this respective order. **Note,** the 3.3V clipping at 4m measurement

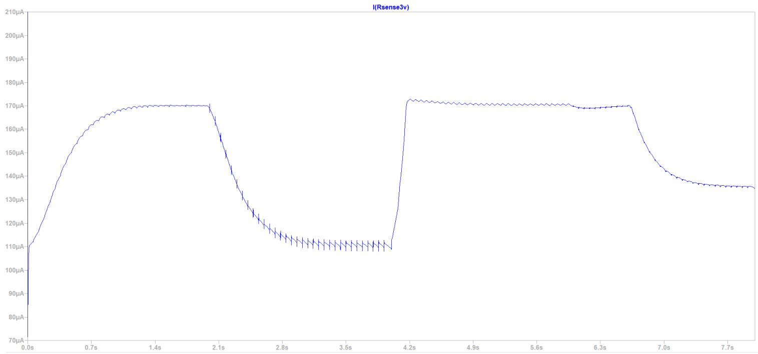


(a) Noise on the analog output of our ultrasonic sensor

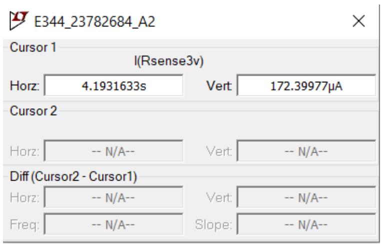


(b) Noise measurement on analog output of 103cm

Figure 3.8: Noise shown and measured on 6000μs (103cm) output. It is below 70mV pk-pk.



(a) Sense resistor's current pull graph output for full range

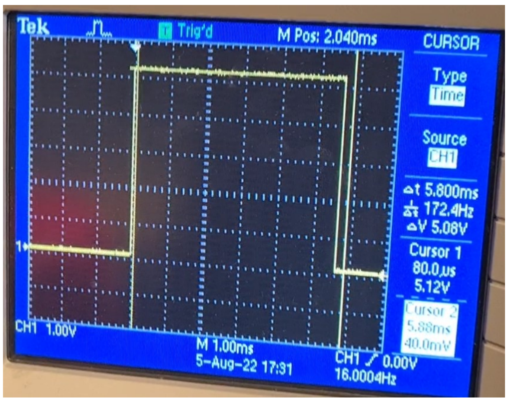


(b) Sense resistor's current pull measurement for 3.2V output

Figure 3.9: Current measured on the sense resistor ensuring that it is indeed below 750μA. $\approx$170μA measured for 3.2V output. It is well within spec. **Note,** this is the same respective order of measurements that Figure 3.8 has used

(a) Step response measurement of actual ultrasonic sensor op-amp

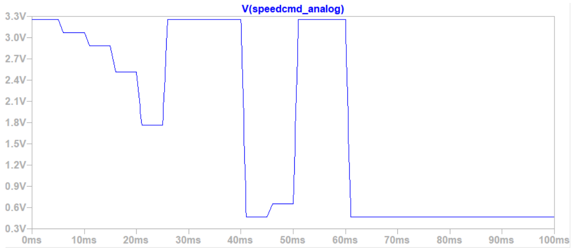
Figure 3.10: Step response measurement of the built ultrasonic sensor op-amp for a measurement of 100cm. **Note,** the measurement is about 0.6s for 0V-3.2V which is almost identical to Spice and is most definitely built correctly.



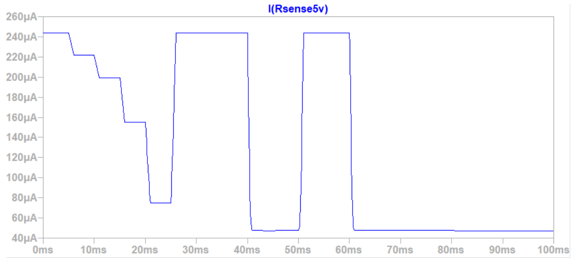
(a) PWM Echo signal measurement for 1m distance

Figure 3.11: PWM Echo signal measured at 1m. **Note,** It is measured $\approx$6000μs which, once again, is almost identical to spice simulation.

3.5. Digital to Analog Converter

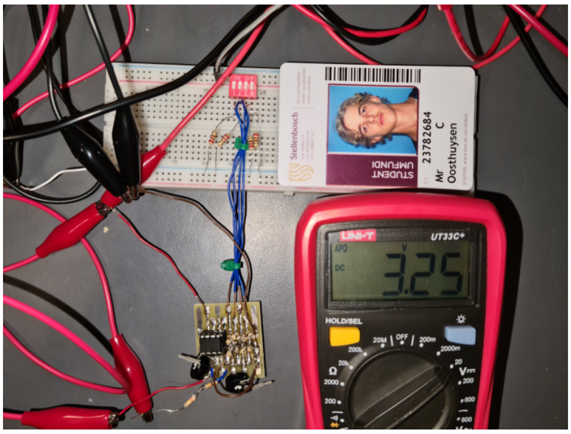


(a) Voltage output range from 0000 (high output) to 1111 (low output). **Note,** high output was $3.25V > 3V$ and low output was $0.44V < 0.5V$ which meets specification.

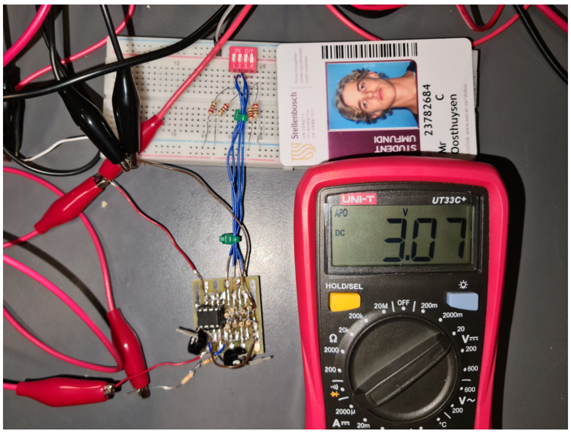


(b) Current pull of the 5V sense resistor. 250μA Pulled for high output

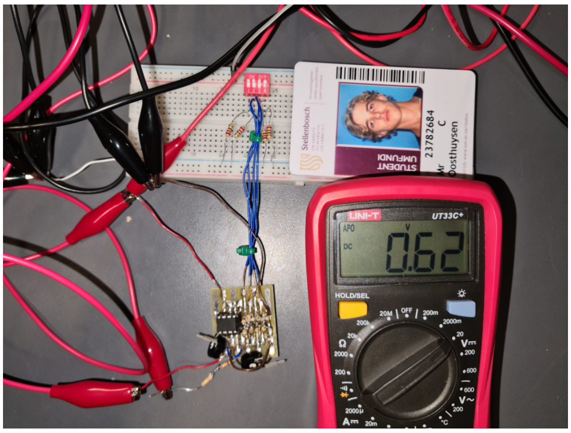
Figure 3.12: Spice simulated results of the digital to analog converter inverting summing amplifier with DC level shift.



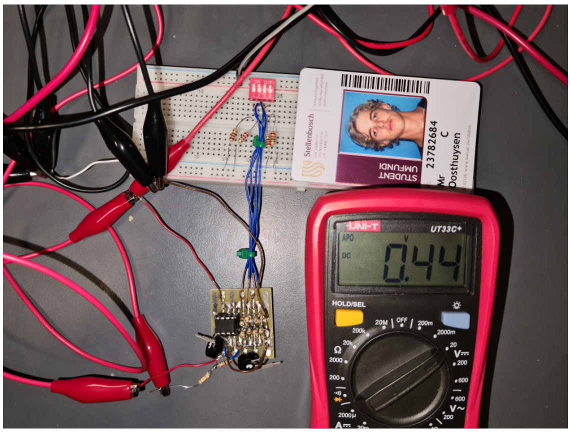
(a) Voltage output for High (0000)



(b) Voltage output for 0001



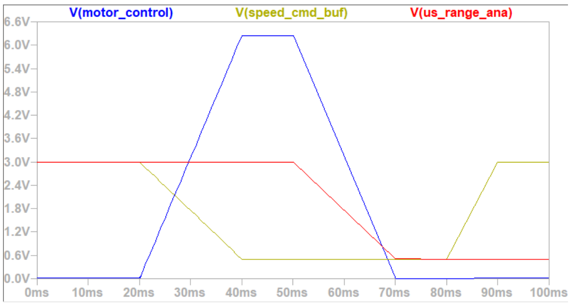
(c) Voltage output for 1110



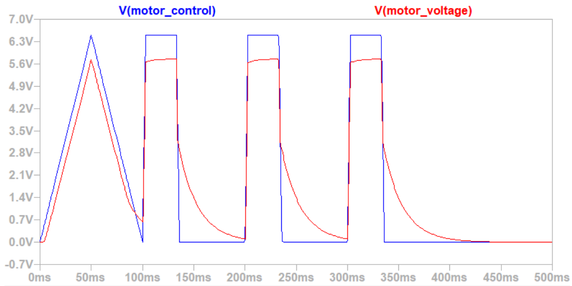
(d) Voltage output for 1111

Figure 3.13: Voltage outputs of the op-amp for different digital inputs where B0 represents the least significant bit and B3 represents the most significant bit

3.6. Motor Control



(a) Differential amplifier output with given inputs



(b) Output of the emitter follower transistor configuration

Figure 3.14: Motor control circuits simulation outputs and their respective inputs

Figure 3.15: Voltage measured over the motor for high DAC input (1111) and the object far away

Table 3.4: Motor states and its respective voltage measurements with entire circuit attached.

Motor State	Measured voltage
Fast (1111) and object close	$0V$
Fast (1111) and object far away	$5.8V$
Slow (1000) and object close	$0V$
Slow (1000) and object far away	$3.71V$

Note, the rubric stated for slow input for the motor which was difficult to interpret so the slowest DAC input of 1000 was chosen with b_3 chosen to be one which is the most significant bit, which means it will be supplying the least amount of voltage since our DAC is inverted. The results measured agree with the simulated results and are satisfactory.

3.7. Left Side Wheel Control

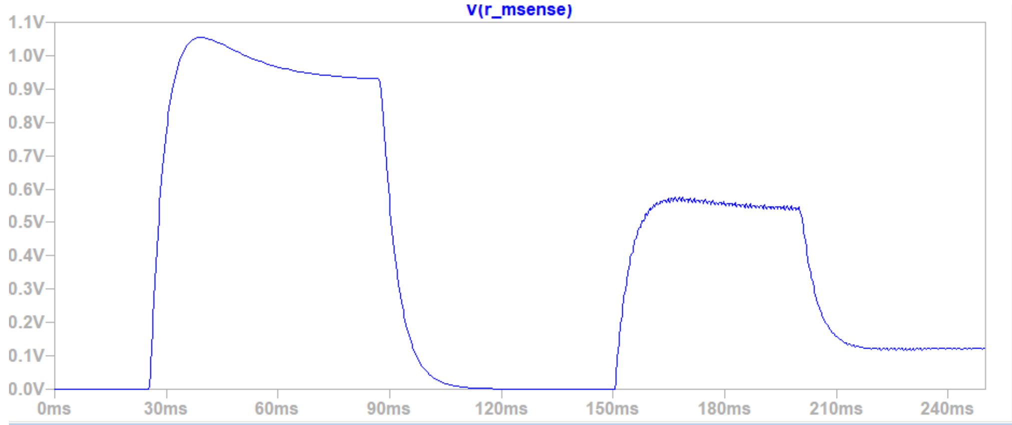
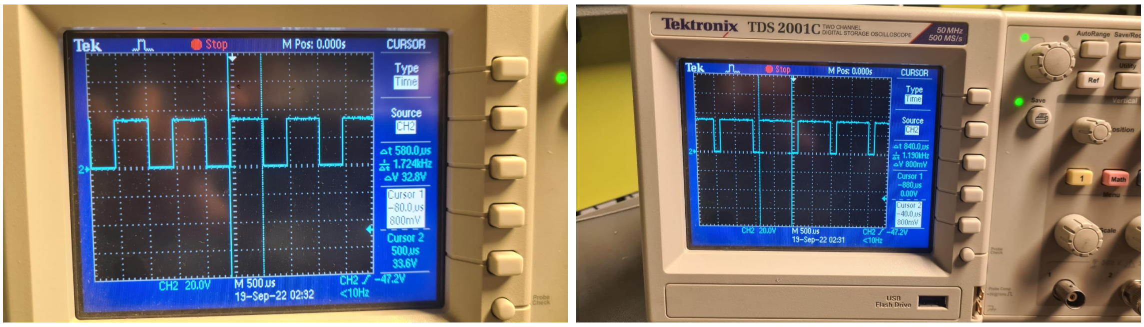


Figure 3.16: SPICE measurements of the output of the current sensor built for circuit A5



(a) 1000 Binary input and object far away **(b)** 1100 Binary input and object far away

Figure 3.17: Oscilloscope measurements of the PWM signals produced by pin 25 as result of the difference between the binary input and the ultrasonic sensor

Table 3.5: Measurements of the PWM signal on oscilloscopes

Distance	DAC Input	Oscilloscope Measurement
Far away (1m)	1000	$580\mu s$
Close (10cm)	1000	0s
Far away (1m)	1100	$840\mu s$
Close (10cm)	1100	0s

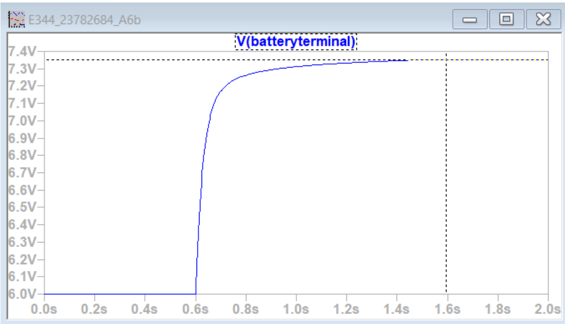
Table 3.6: Measurements the current sensing output (Msense)

Distance	DAC	Spice simulated current	Multimeter Measurement
Far away (1m)	1000	$0.79A$	$0.77A$
Close (10cm)	1000	$0A$	$0A$
Far away (1m)	1100	$0.58A$	$0.56A$
Close (10cm)	1100	$0A$	$0A$

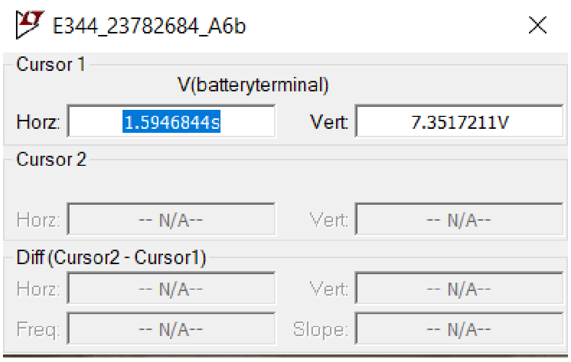
3.8. Battery Charger

Table 3.7: Measurements of the battery charger taken with multimeter with respective loads

Resistor	Voltage Measured
$1k\Omega$	7.13V
$50\Omega + 1k\Omega$(Parallel)	6.68V



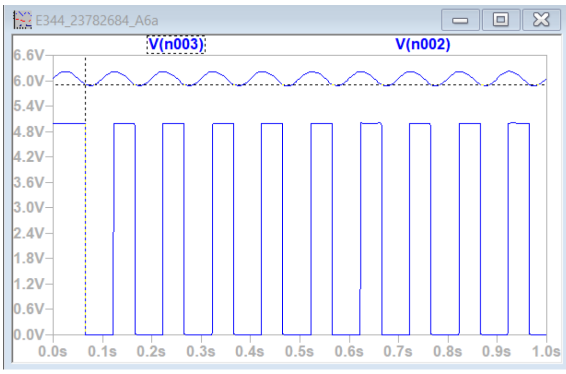
(a) SPICE graph output



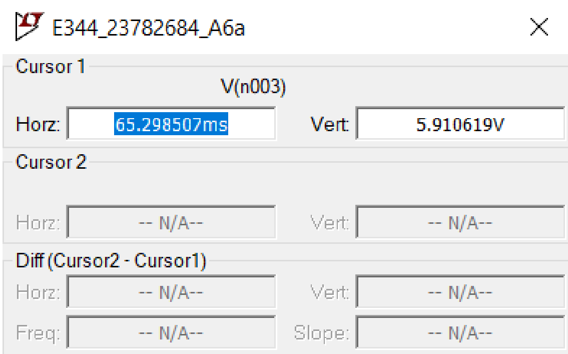
(b) SPICE measurement

Figure 3.18: SPICE simulation measurement of the battery charger at steady state

3.9. Under-voltage protection

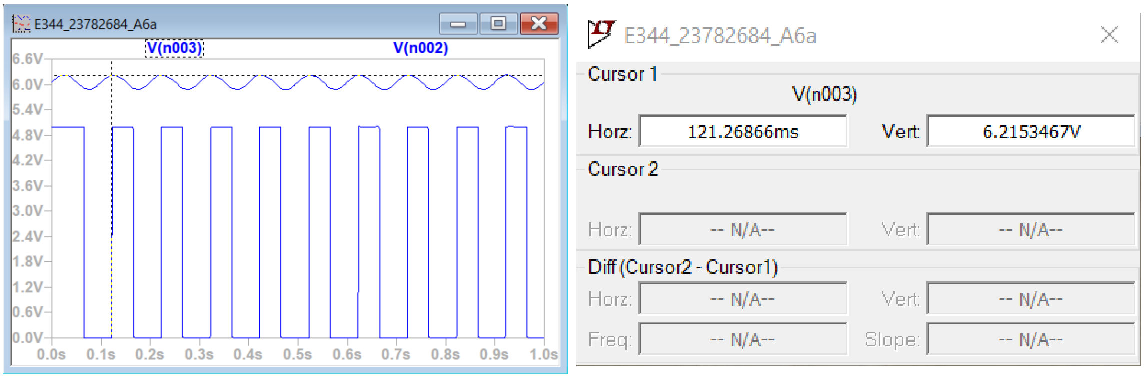


(a) SPICE graph output



(b) SPICE voltage measurement

Figure 3.19: SPICE measurements of the under-voltage protection Schmitt trigger for the lower threshold voltage



(a) SPICE graph output

(b) SPICE voltage measurements

Figure 3.20: SPICE measurements of the under-voltage protection Schmitt trigger for the upper threshold voltage

Note, our Schmitt trigger design is working as intended and is

3.10. signal conditioning

Table 3.8: Measurements of the voltage output of the voltage divider for different input voltages

Input Voltage	Output Voltage
6.2V	3.1V
6.1V	3.05V
6V	3V
5.9V	2.95V

It is working as intended and our input into the Schmitt trigger is well within specification.

Chapter 4

Physical Implementation and Circuit Diagram

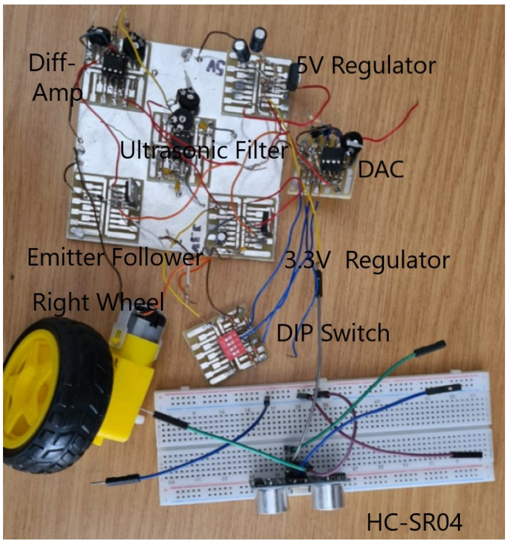


Figure 4.1: All the components built thus far with necessary labels included.

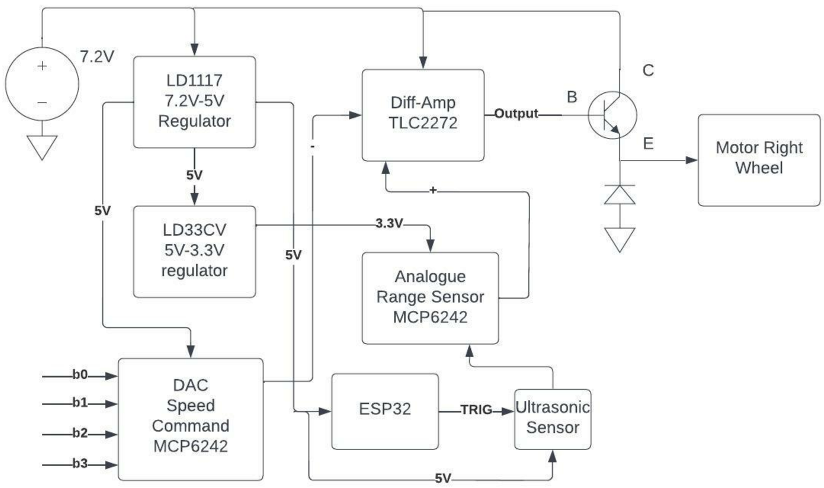


Figure 4.2: Circuit Flow diagram assignments A1-A4

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Appendix A

Social contract

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E-design 344 Social Contract

2022

The purpose of this document is to establish commitment between the student and the organisers of E344. Beyond the commitment made here, it is not binding.

In the months preceeding the term, the lecturer (Thinus Booysen) and a few paid helpers (Rita van der Walt, Keegan Hull, and Michael Ritchie) spent countless hours to prepare for E344 to ensure that you get your money's worth, that you are enabled to learn from the module, and demonstrate and be assessed on your skills. We commit to prepare the assignments, to set the assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344.

I, Cameron Oosthuysen .... have registered for E344 of my own volition with the intention to learn of and be assessed on the principals of analogue electronic design. Despite the potential publication online of supplementary videos on specific topics, I acknowledge that I am expected to attend the scheduled lectures to make the most of these appointments and learning opportunities. Moreover, I realise I am expected to spend the additional requisite number of hours on E344 as specified in the yearbook.

I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing respect towards the University's equipment, staff, and their time.

Prof. MJ (Thinus) Booysen

Signature: MJ Booysen Digitally signed by MJ Booysen Date: 2022.07.02 13:22:09 +02'00'

Date: 1 July 2022

Student number: 23782684

Signature:

Date: 25/07/2022

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Appendix B

GitHub Activity Heatmap