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E344 Assignment 1

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Report submitted in partial fulfilment of the requirements of the module
Design (E) 344 for the degree Baccalaureus in Engineering in the Department of Electrical
and Electronic Engineering at Stellenbosch University.

August 7, 2022



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Nomenclature

Variables and functions

A_v	Gain
V_0	Output Voltage
R_x	Resistor of arbitrary name
f_c	Corner frequency

Acronyms and abbreviations

CMRR	Common Mode Rejection Ratio
PWM	Pulse Width Modulation
LPF	Low-Pass Filter
MCU	Micro-controller (unit)
RC	Resistor and Capacitor

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 V_{cc} . 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 $CMMR = 20\log|\frac{A_{DM}}{A_{CM}}|$. 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. [1]

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	$V_{SS} - 0.3V \text{ to } V_{DD} + 0.3V$
All other inputs	$V_{SS} - 1V \text{ to } V_{DD} + 1V$

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 $V_O = A_d(V_1 - V_2)$ [2]

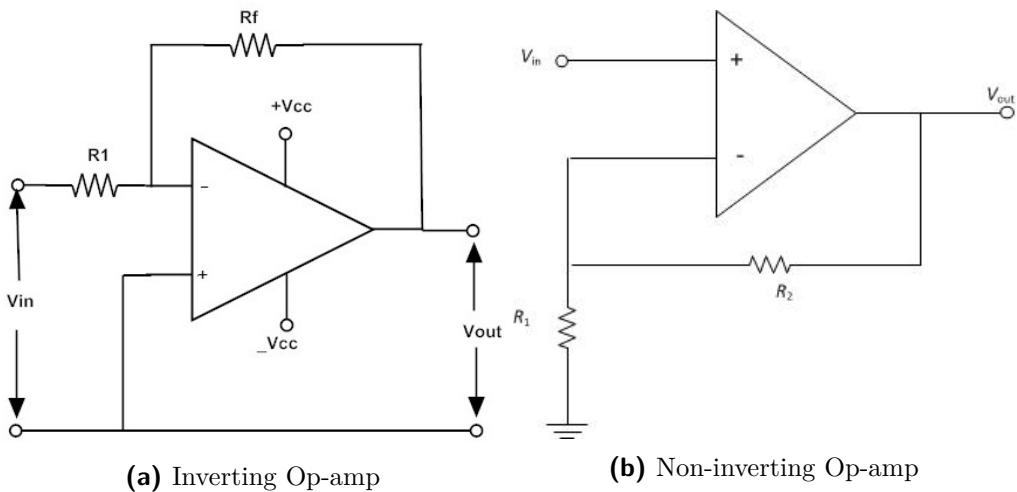


Figure 1.1: Inverting and non-inverting op-amp schematics

1.2. Current sensing

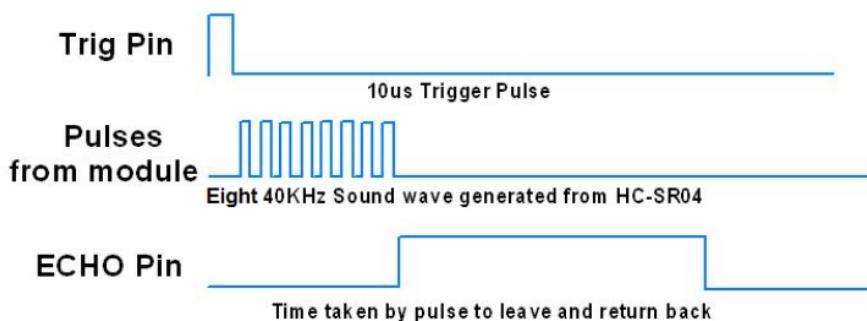
A few examples where current sensing circuits are current control, current limiting, and remaining battery level detection circuits. We will make use of a low-side current sensing circuit since our load is connected to a voltage rail. A high-side current sensing circuit will have its load connected to 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 and 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 moves out of harm's 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 $10\mu s$ to the sensor. It receives it and responds by sending an 8-cycle sonic burst signal at 40KHz and raises 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 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 $\frac{\text{microseconds}}{58} = \text{answer in centimeters}$ [3].



(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

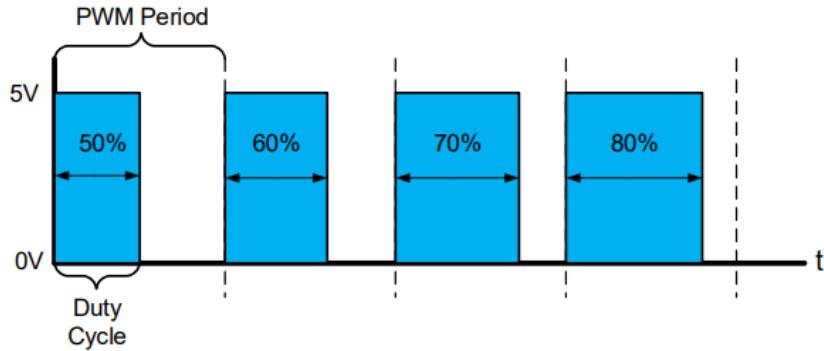
The output voltage of a PWM signal can be calculated as:

$$V_{out} = Amplitude \cdot Duty cycle \quad (1.1)$$

To verify this, a voltage measurement was taken at the output of the first LTSpice pulse output which was $6000\mu s$ and our max period is $60000\mu s$ so it is 10% duty cycle. With a gain of zero, the output voltage was $\approx 500\text{mV}$, 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

As stated previously, we can convert this PWM signal to a analog signal using $V_{out} = Amplitude \cdot Duty cycle$. 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 3.6 because we do not want to blow the pin no MCU. For the lowest measurement of distance (5cm) we need our voltage to be below 0.3 (almost unreadable by the MCU pin) [4].

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 $\approx 16Hz$, 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)" [5].

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 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 $10\mu s$ 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 [6].

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.

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 $150\mu\text{A}$ 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:

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

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

$$R = 16k\Omega$$

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 $3.0V < Pin < 3.6V$ [3] 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:

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

$$A_v = 275V/V$$

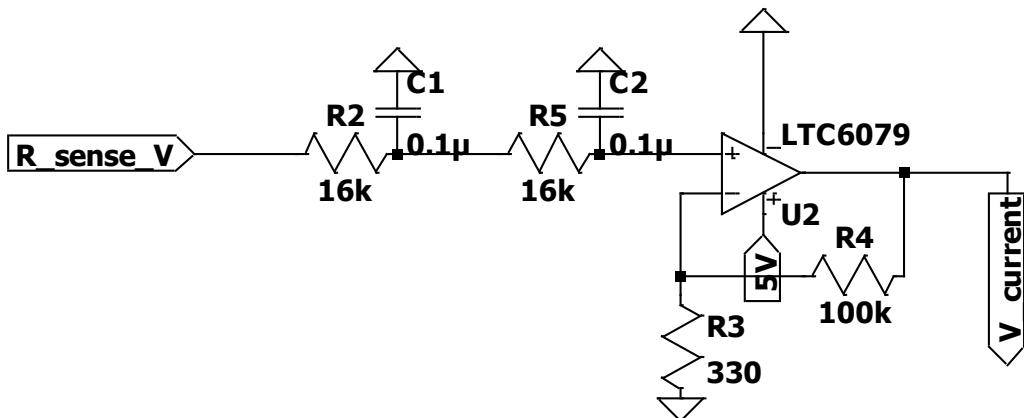
Now we know that our resistor feedback network must be in a ratio that produces a gain of 275V/V. I will choose the first resistor. The larger the better since we want to sink as much current as possible. I will choose $R_f = 100k\Omega$. Now all we need is the resistor to ground R_g .

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

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

$$R_g \approx 330\Omega$$

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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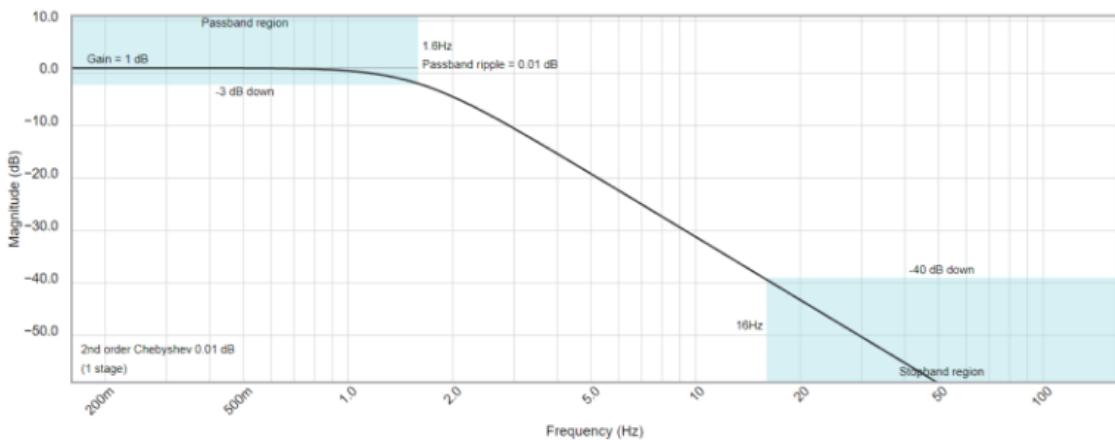
Figure 2.1: This figure shows the circuit built in spice

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 $\approx 16\text{Hz}$. The duty cycle range of the PWM signals on the echo pin will be $116\mu\text{s}(2\text{cm}) \leq t \leq 23200\mu\text{s}(4\text{m})$ which can be calculated using the $\frac{\text{microseconds}}{58} = \text{answer in centimeters}$ formula. For our specifications, we need to measure $\geq 1\text{m}$ and output a voltage $\geq 3\text{V}$, but no more than 3.6V (otherwise we pop a pin), and for a $\leq 5\text{cm}$ measurement, we need to output a voltage of $\leq 0.3\text{V}$. 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.

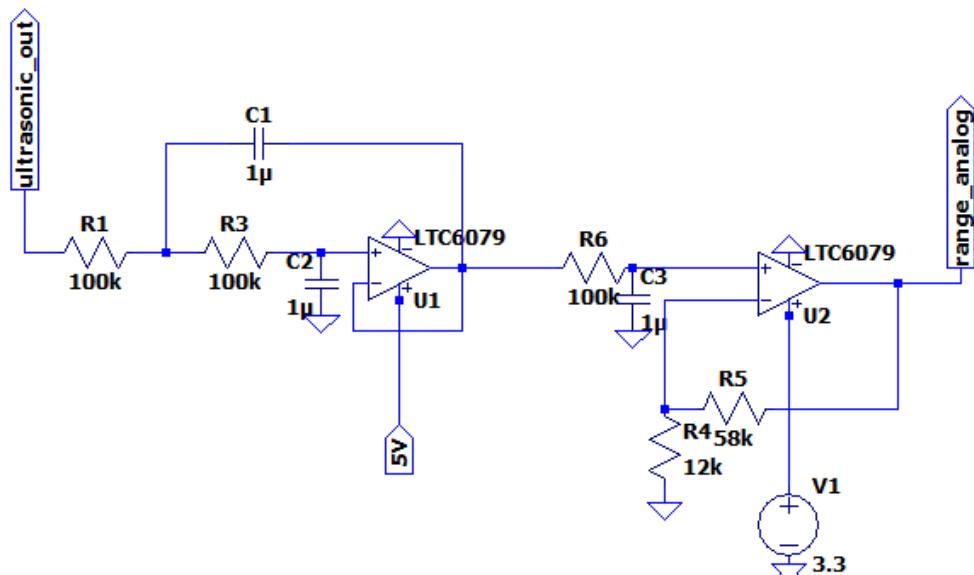
A second-order active low pass was chosen for this. Refer to Section 1.4 as motivation for this was discussed. To design a 2nd-order active LPF you will make use of one of two equations. If you are willing to keep both resistors and capacitors the same size in the filter section you can use the simplified 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 $f_c = 1.6\text{Hz}$ or even lower if we wish. A capacitor will be chosen first (low capacitance $\approx 1\mu\text{F}$), 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

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

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.

Chapter 3

Results

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	$3.33V$

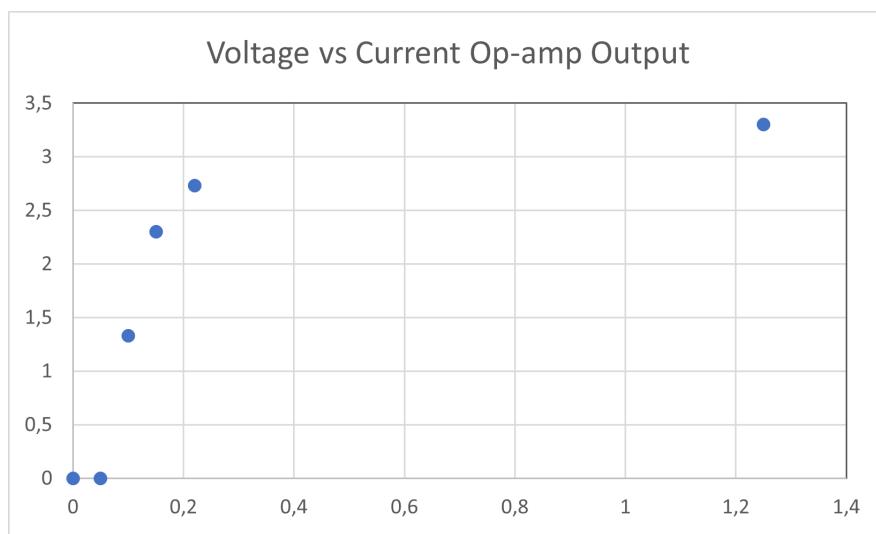


Figure 3.1: Voltage vs current for the op-amp with motor connected to the circuit

3.1. Current sensor

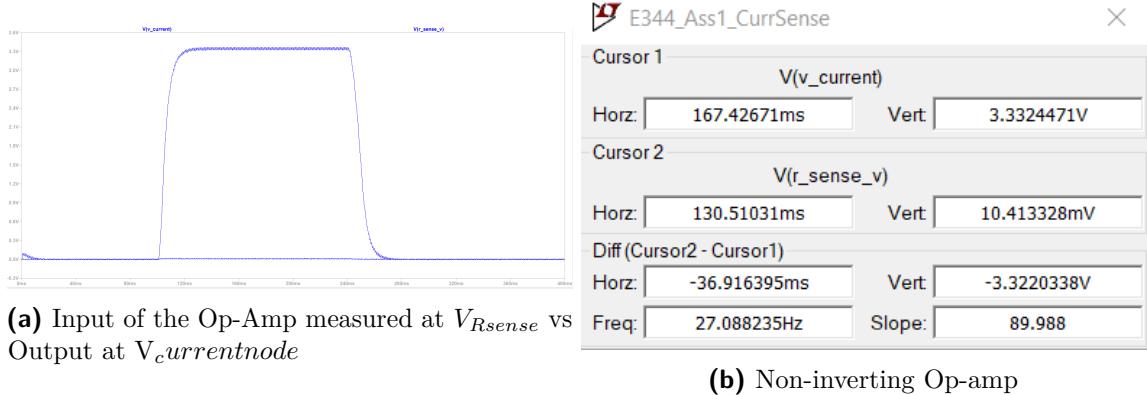


Figure 3.2: Input of the Op-Amp measured at V_{Rsense} vs Output at $V_{currentnode}$

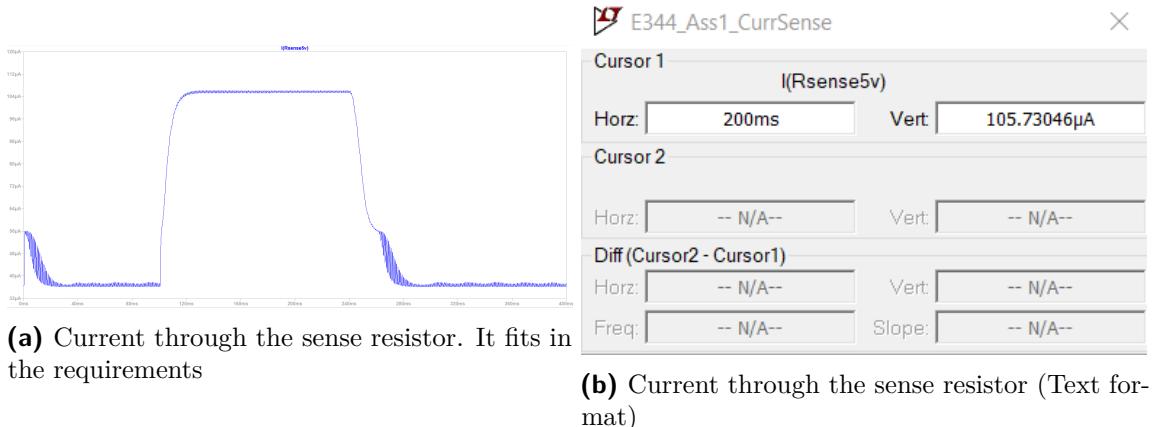


Figure 3.3: Current measured through the sense resistor

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:

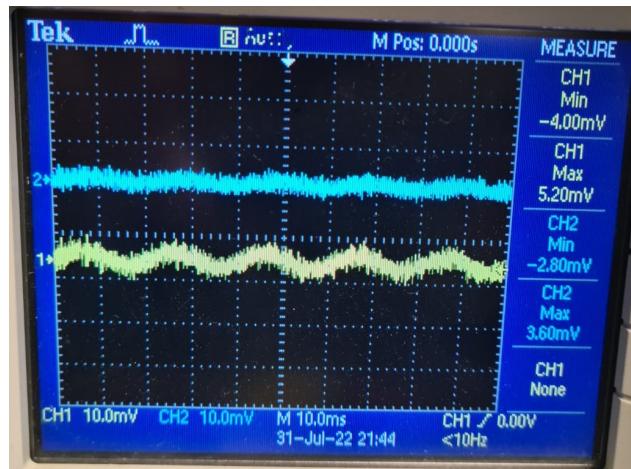
- Connected 5V supply to the op-amp
- Connected signal generator probes to the circuit. The configuration was square wave, 6mV pk-pk, 10Hz (100ms), and a duty cycle of 70% so the wave is easier to visualise.
- Connected a oscilloscope probe to the the output of the op-amp. The output was measured.



(a) Step response of the op-amp measured

Figure 3.4: The figure shows the step response measured after a square wave was inputted into the op-amp

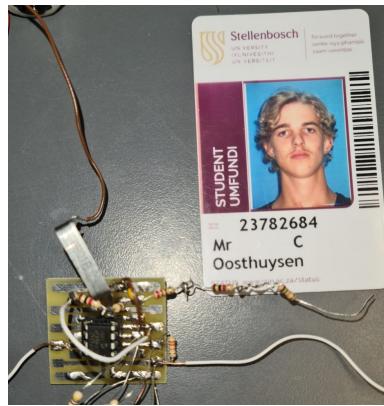
Note, the noise channel was just removed for clarity as one could not really see the graph when the noise was present on the oscilloscope. The time measured to reach 90% of the final value was 7ms. This is fast and was well within the requirements.



(a) Noise measured on oscilloscope

Figure 3.5: Natural noise being amplified by the circuit

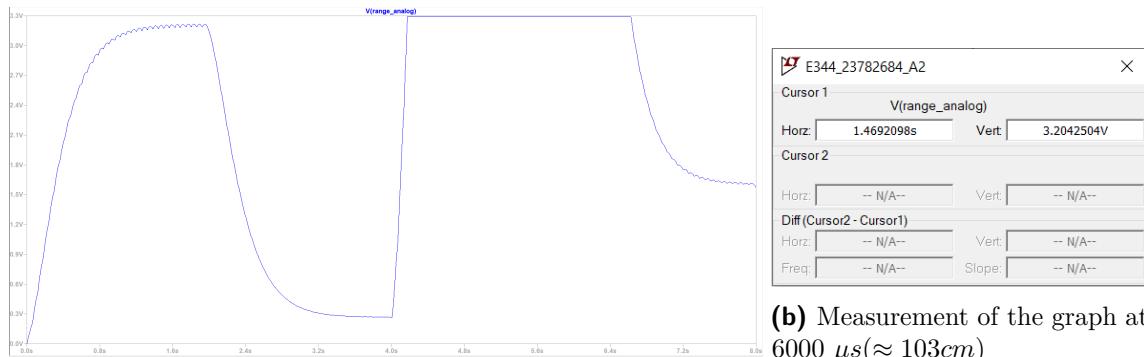
There was a slight gain in noise when natural noise was passed through the op-amp. This was a good indication of how well my op-amp deals with noise. Some artificial noise was then added to the circuit by using a signal generator and connecting it to the circuit. 10mV at 1000Hz was supplied to the input 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.



(a) Built circuit

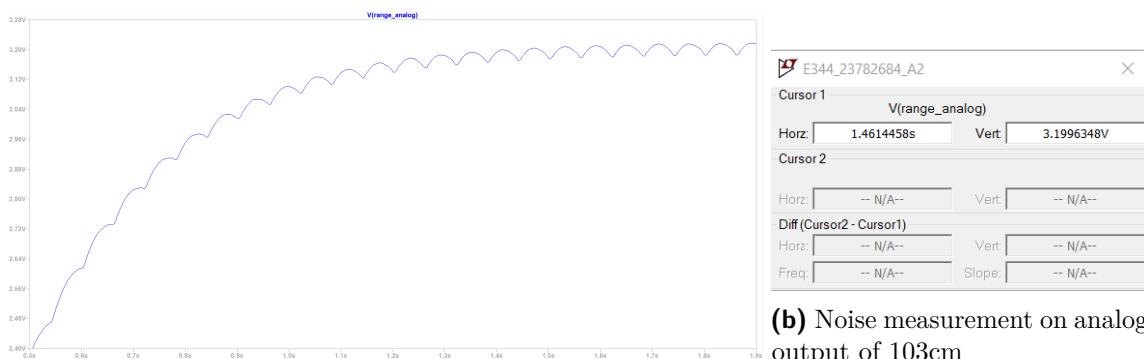
Figure 3.6: Built Circuit with respective student card next to it

3.2. Ultrasonic Range Sensor



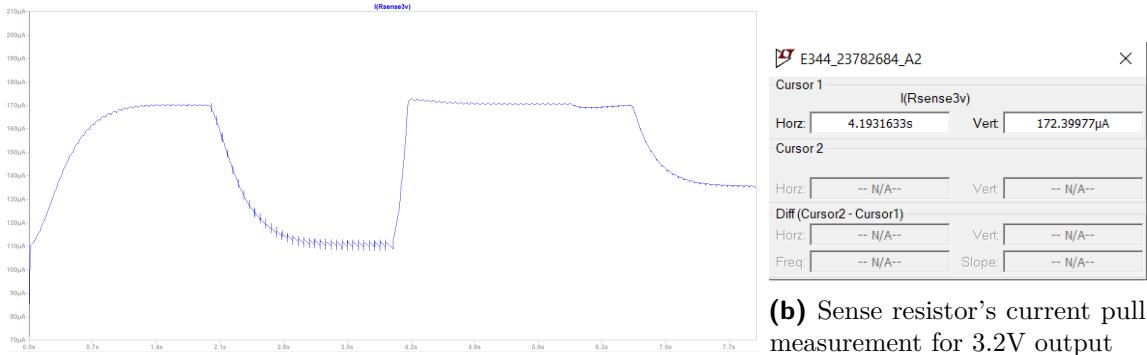
(a) Full range LTSpice graph output of ultrasonic sensor

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



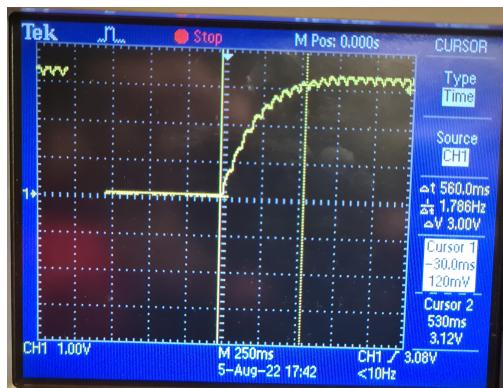
(a) Noise on the analog output of our ultrasonic sensor

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

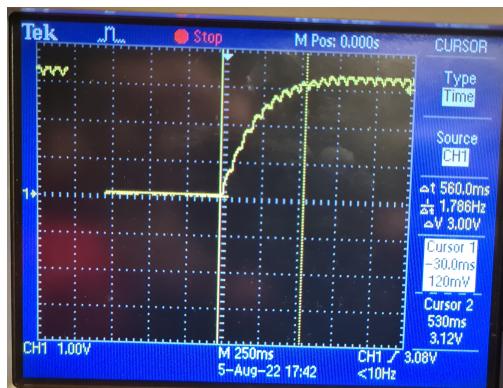


(a) Sense resistor's current pull graph output for full range

Figure 3.9: Current measured on the sense resistor ensuring that it is indeed below $750\mu\text{A}$. $\approx 170\mu\text{A}$ 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

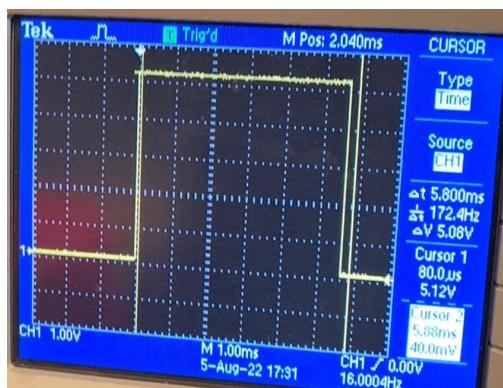


(b) Sense resistor's current pull measurement for 3.2V output



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

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

Bibliography

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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 preceding the term, the lecturer (Thinus Booyens) 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) Booyens

MJ Booyens
Signature:

Digital signature by MJ Booyens
Date: 2022.07.02
13:22:09 +02'00'

Student number: 23782684

A handwritten signature of Cameron Oosthuysen.

Signature:

Date: 1 July 2022

Date: 25/07/2022

Appendix B

GitHub Activity Heatmap

