Stellenbosch
UNIVERSITY
IYUNIVESITHI
UNIVERSITEIT

E344 Assignment 1

Cameron Oosthuysen
23782684

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.

July 31, 2022

Stellenbosch
UNIVERSITY
IYUNIVESITHI
UNIVERSITEIT

forward together
sonke siya phambili
saam vorentoe

Plagiaatverklaring / *Plagiarism Declaration*

1. Plagiaat is die oorneem en gebruik van die idees, materiaal en ander intellektuele eiendom van ander persone asof dit jou eie werk is.
   Plagiarism is the use of ideas, material and other intellectual property of another's work and to present is as my own.

2. Ek erken dat die pleeg van plagiaat 'n strafbare oortreding is aangesien dit 'n vorm van diefstal is.
   I agree that plagiarism is a punishable offence because it constitutes theft.

3. Ek verstaan ook dat direkte vertalings plagiaat is.
   I also understand that direct translations are plagiarism.

4. Dienooreenkomstig is alle aanhalings en bydraes vanuit enige bron (ingesluit die internet) volledig verwys (erken). Ek erken dat die woordelikse aanhaal van teks sonder aanhalingstekens (selfs al word die bron volledig erken) plagiaat is.
   Accordingly all quotations and contributions from any source whatsoever (including the internet) have been cited fully. I understand that the reproduction of text without quotation marks (even when the source is cited) is plagiarism

5. Ek verklaar dat die werk in hierdie skryfstuk vervat, behalwe waar anders aangedui, my eie oorspronklike werk is en dat ek dit nie vantevore in die geheel of gedeeltelik ingehandig het vir bepunting in hierdie module/werkstuk of 'n ander module/werkstuk nie.
   I declare that the work contained in this assignment, except where otherwise stated, is my original work and that I have not previously (in its entirety or in part) submitted it for grading in this module/assignment or another module/assignment.

23782684 Studentenommer / *Student number*	Handtekening / *Signature*
C. Oosthuysen Voorletters en van / *Initials and surname*	July 31, 2022 Datum / *Date*

Contents

List of Figures

List of Tables

Nomenclature

Variables and functions

A_v	Gain
V_0	Output Voltage
R_x	Resistor of arbitrary name

Acronyms and abbreviations

CMRR	Common Mode Rejection Ratio

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. [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	$V_{SS} - 0.3V to V_{DD} + 0.3V$
All other inputs	$V_{SS} - 1V to V_{DD} + 1V$

Operational amplifier configurations

Inverting Op-Amp:

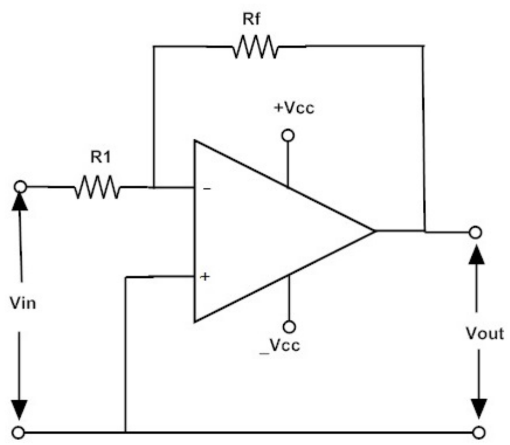
This op-amp will produce an output which is out of phase with respect to its input by 180° and its gain can be calculated as $A_v = \frac{-R_f}{R_i}$

Non-inverting Op-amp:

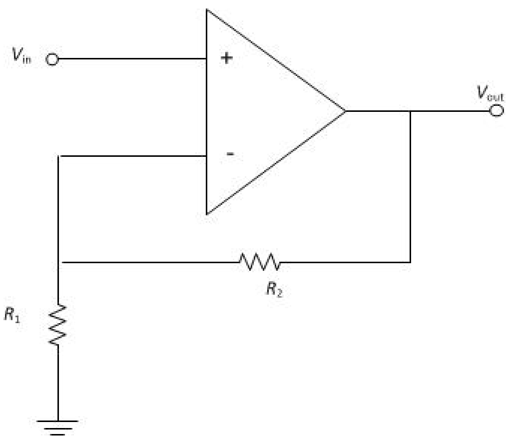
In contrast to the inverting op-amp, as the name suggests, will produce an output with respect to its input with no phase shift. Its gain can be calculated as $A_v = \frac{R_f}{R_i}$

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



(a) Inverting Op-amp



(b) Non-inverting Op-amp

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 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.

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 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:

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

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

$$R = 16k\Omega$$

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:

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

$$A_v = 275V/V$$

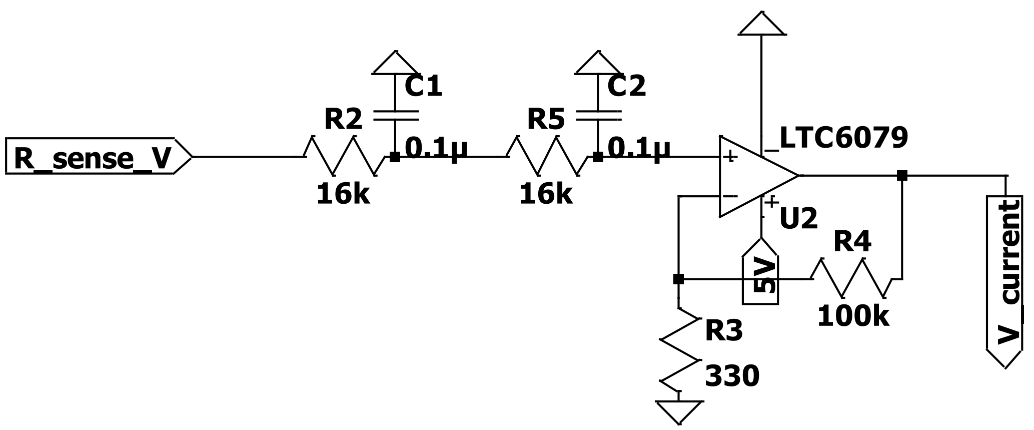
Now we know that our resistor feedback network must be in a ratio that produces a gain of 275V/V. I will choose the first resistor. The larger the better since we want to sink as much current as possible. I will choose $R_f = 100k\Omega$. Now all we need is the resistor to ground R_g.

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

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

$$R_g \approx 330\Omega$$

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

h

Figure 2.1: This figure shows the circuit built in spice

.

Chapter 3

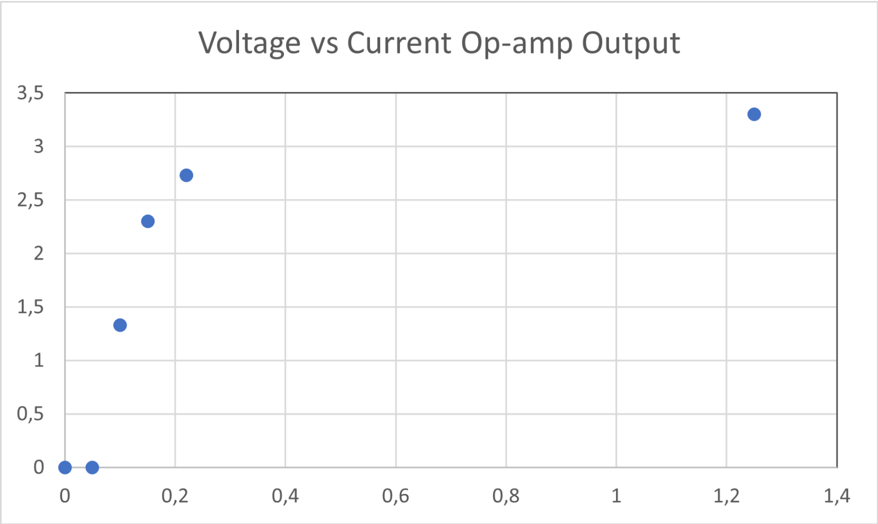
Results

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	$1.2A$	$3.33V$

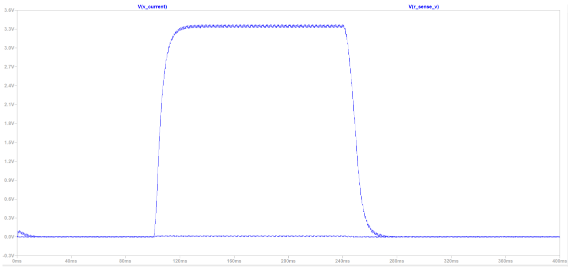


(a) Voltage vs current

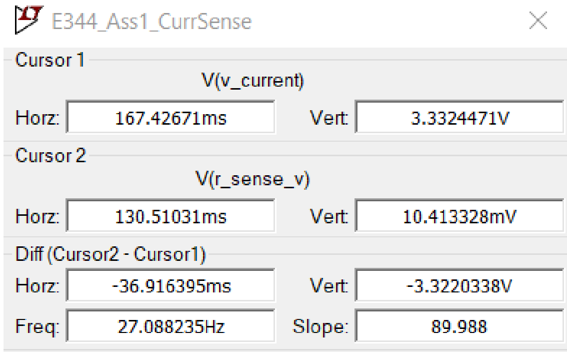
Figure 3.1: Voltage vs current for the op-amp with motor connected to the circuit

.

3.1. Current sensor



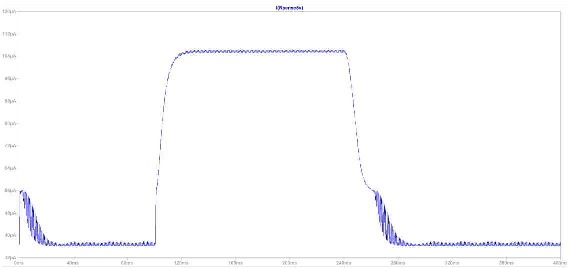
(a) Input of the Op-Amp measured at V_{Rsense} vs Output at V$_{c}urrentnode$



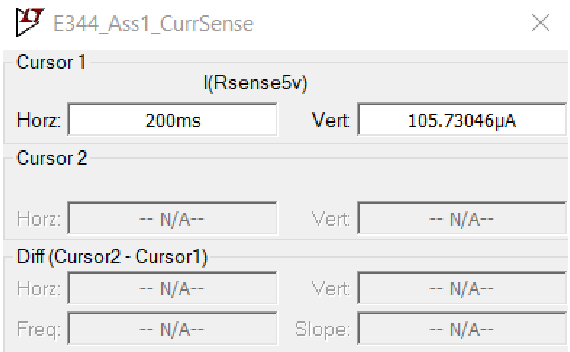
(b) Non-inverting Op-amp

Figure 3.2: 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



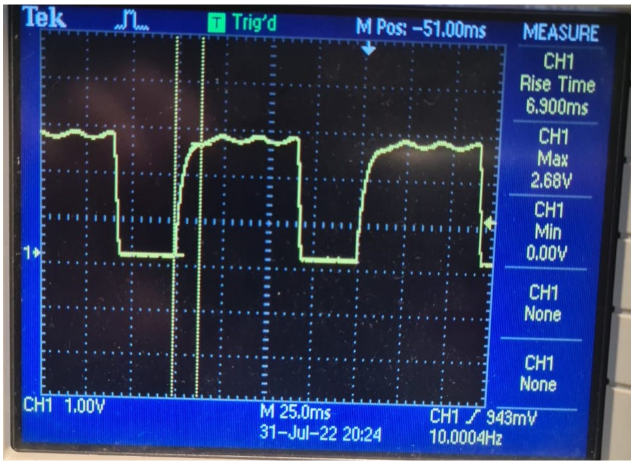
(b) Current through the sense resistor (Text format)

Figure 3.3: 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.

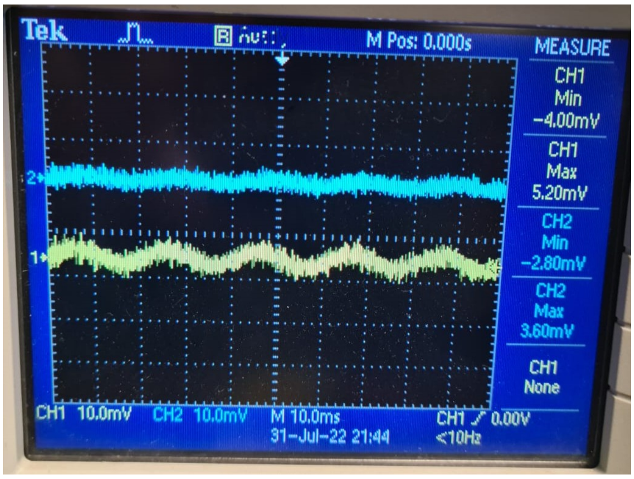


(a) Step response of the op-amp measured

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.

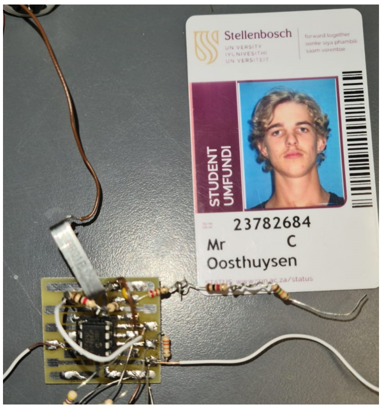


(a) Noise measured on oscilloscope

Figure 3.5: Natural noise being amplified by the circuit

.

There was a slight gain in noise when natural noise 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.



(a) Built circuit

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

.

Bibliography

[1] "Analog sensor conditioning circuits - an overview - microchip technology," 2009. [Online]. Available: https://ww1.microchip.com/downloads/en/AppNotes/00990a.pdf

[2] A. Administrator, "First order and second order passive low pass filter circuits," Sep 2021. [Online]. Available: https://www.electronicshub.org/passive-low-pass-rc-filters/#:~:text=Thesecondorderlowpass,80dBFoctaveandsoon.

[3] C. NA, "Esp32 series - espressif," 2022. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

Appendix A

Social contract

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

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	Student number: 23782684
Signature: MJ Booysen (Digitally signed by MJ Booysen Date: 2022.07.02 13:22:09 +02'00')	Signature:
Date: 1 July 2022	Date: 25/07/2022

1

Appendix B

GitHub Activity Heatmap