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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.

September 22, 2020

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Nomenclature

Variables and functions

$V(0\,^{\circ}\mathrm{C})$	Voltage of temperature sensor at $0\,^{\circ}\mathrm{C}$.
$\triangle V(1\,^{\circ}\mathrm{C})$	Change of voltage at $1\,^{\circ}\mathrm{C}$ change.

Acronyms and abbreviations

ADC	Analog to Digital Converter
LPF	Low Pass Filter
VDC	Voltage DC

Chapter 1

System design

1.1. System overview

The system diagram of the voltage regulation and signal conditioning system can be seen in Fig. 1.1, as well as the definitions of the signal lines.
A linear voltage regulator is chosen to supply the circuit with power. Though inefficient in comparison to a switch mode regulator, the motivation of this design choice is further explained in a later chapter. The differential amplifier was chosen in order to minimise the need for more than one op-amp for signal conditioning. A summing amplifier could just as well be used, however it would require two or more op-amps. To ensure that the 5 VDC source is not affected by the amplifier, a buffer is used in between the voltage regulator and the differential amplifier. This circuit does not allow the use of negative voltages at the negative power supply pin, which means the amplifier can only swing between $5V$ and ground. A virtual ground offset of $2.5V$ is therefore used to center the temperature response. The last conditioning of the signal is a Low Pass Filter that suppresses signals of 50 Hz to 50 mV inaccuracy. In order to meet the total current requirement, all if not most resistors in the circuit network will be in the order of kΩ to minimise current flow.

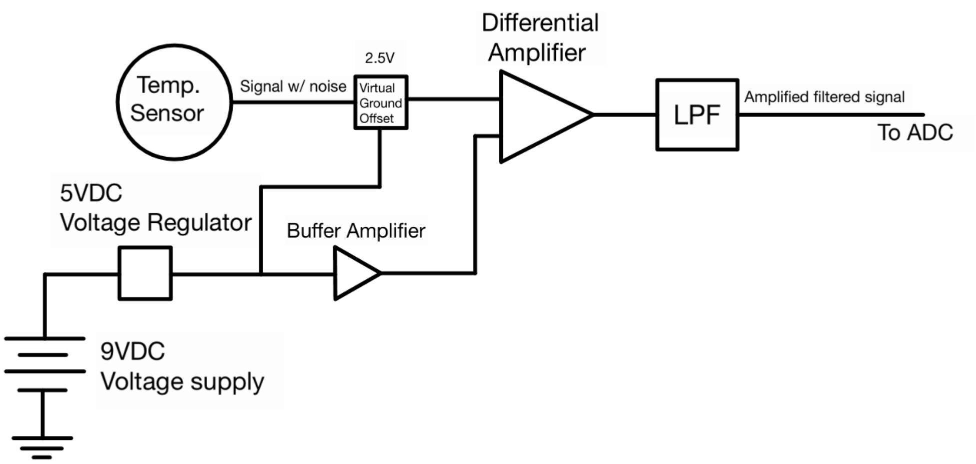


Figure 1.1: System diagram

Chapter 2

Voltage regulation

2.1. Introduction

The advantages and disadvantages of a linear regulator and a switchmode regulator will be explored in this chapter. While designing the regulator circuits, the specific datasheets for the LM7805 linear voltage regulator [1] and the LM2595 switchmode voltage regulator [2] was used to ensure the regulators are used with the correct capacitance, inductance, and resistance values. The variable voltage circuit required by the switchmode regulator [2] is a very intricate circuit, the calculations of which is described in the next section.

2.2. Design

The voltage regulator must regulate a 9 VDC supply to a stable 5 V with little to no noise.

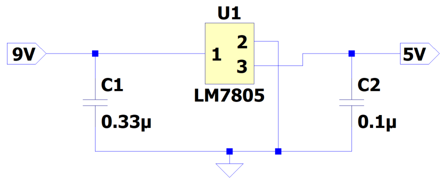
The LM7805 linear regulator circuit, as shown in Fig.2.1a, is fairly simple. It is specified in [1] that the regulator requires an input capacitance of 0.33 µF and an output capacitance of 0.1 µF to improve the transient response. Bypass capacitors are recommended to improve stability, but is not necessary if the response of the regulator is favourable enough.

The LM2595 switchmode regulator circuit, as shown in Fig.2.1b, is more complex and requires more components. The chosen circuit as stated by [2] section 9.2.2 is a series buck regulator with adjustable output, of which the values of C_{IN}, C_{OUT}, L_1, and D1 are specified as 120 µF 25-V electrolytic, 120 µF 50-V electrolytic, 100 µH and a 1N5822 3-A, 40-V Schottkey diode. The regulator is coupled with a Post Ripple filter, comprised of a series inductor of 3 µH and a 15-V bypass capacitor of 180 µF, to reduce the ripple to half. This section includes the formulas needed to work out the values of the other components. R_1 is chosen as 1 kΩ and V_{REF} is specified as 1.23 V.

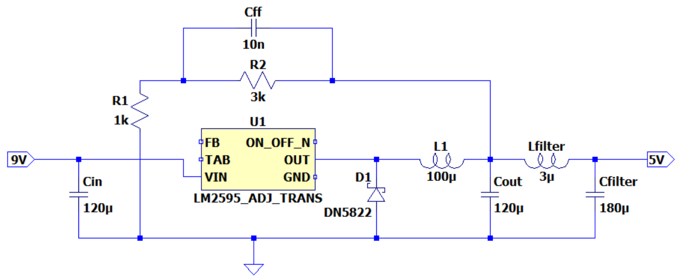
$$R_2 = R_1(\frac{V_{OUT}}{V_{REF}} - 1) = 1\,\mathrm{k\Omega}(\frac{5\,\mathrm{V}}{1.23\,\mathrm{V}} - 1) = 3.06\,\mathrm{k\Omega} \approx 3\,\mathrm{k\Omega}$$

$$C_{FF} = \frac{1}{31 \times 10^3 \times R_2} = \frac{1}{31 \times 10^3 \times 3\,\mathrm{k\Omega}} = 10.75\,\mathrm{nF} \approx 10\,\mathrm{nF}$$

To measure the voltage, current, power, and efficiency, the `LTSpice` function `.meas` is used (Fig.2.3).



(a) Linear voltage regulator.



(b) Switchmode voltage regulator.

Figure 2.1: Circuit diagrams of the two voltage regulators

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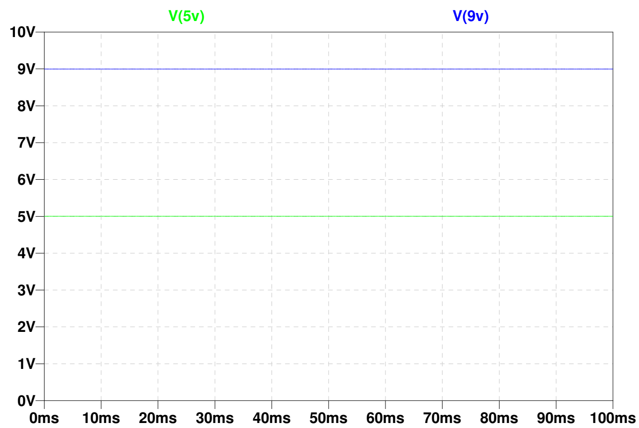
2.3. Results

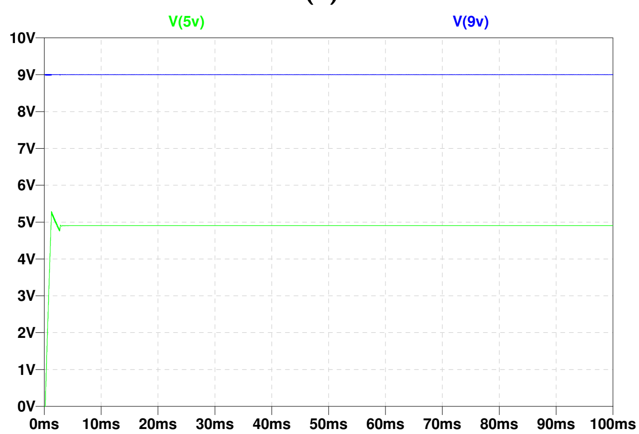
The voltage response for the two voltage regulators can be seen in Fig. 2.2. The results are compared in Table 2.1



(a)

```
pout: AVG(v(5v)*i(r_load))=0.500554 FROM 0 TO 0.1
pin: AVG(-v(9v)*i(r_sense))=0.945436 FROM 0 TO 0.1
eff: pout/pin=0.529442
iout: AVG(i(r_load))=0.100055 FROM 0 TO 0.1
iin: AVG(-i(r_sense))=0.105061 FROM 0 TO 0.1
```

(b)



(c)

```
pout: AVG(v(5v)*i(r_load))=0.473501 FROM 0 TO 0.05
pin: AVG(-v(9v)*i(r_sense))=0.587227 FROM 0 TO 0.05
eff: pout/pin=0.806335
iout: AVG(i(r_load))=0.0968337 FROM 0 TO 0.05
iin: AVG(-i(r_sense))=0.0652632 FROM 0 TO 0.05
```

(d)

Figure 2.2: Voltage regulation, comparing the linear and switchmode regulators... (a) Linear regulator voltage response (b) Linear Regulator `.meas` results. (c) Switchmode regulator voltage response (d) Switchmode regulator `.meas` results.

```
.meas Pout AVG V(5V)*I(R_load)
.meas Iout AVG I(R_load)

.meas Pin AVG -V(9V)*I(R_sense)
.meas Iin AVG -I(R_sense)

.meas Eff param Pout/Pin
```

Figure 2.3: `.meas` arguments used in `LTSpice`

Table 2.1: Table of current, power and efficiency.

	Current		Power		Efficiency
	Supplied [mA]	Draw [mA]	Supplied [mW]	Draw [mW]	[%]
LM7805 Linear	105	100	945.44	500.55	52.94
LM2595 Switchmode	65.26	96.83	587.23	473.5	80.63

Table 2.2: Table of Absolute maximum ratings.
Based on the datasheet of LM7805 in [1] and LM2595 in [2]

	Maximum Allowed Input [V]	Dropout Voltage at 25 °C [V]	Maximum Power Dissapation [W]
LM7805 Linear	30	1.7	≤ 0.75
LM2595 Switchmode	45	0.88	Limited Internally

From the figures and tables it is seen that both regulators have advantages and disadvantages.
The LM7805 regulator has a more favourable response, a higher dropout voltage, and less expensive components, but is not very efficient in terms of power.
The LM2595 regulator is much more efficient and has a higher maximum allowed input, but is much more expensive in terms of components and circuit real estate, and only allows the circuit to reach the desired output after a certain time. As for maximum ratings, the LM7805 linear regulator has a high enough power ceiling that it won't cause any problems for the circuit.

2.4. Summary

From the results, the chosen design is the LM7805 linear regulator. Although not as efficient, it is less expensive, has a higher dropout voltage and better voltage response, which is important for it's use with a temperature sensor, where noise is already a big problem.

Chapter 3

Temperature sensor conditioning circuit

3.1. Intro

A temperature sensor needs a conditioning circuit that will allow the output of the sensor to be read by a micro-controller's ADC. This chapter will explain in detail how this circuit will be designed to meet the specific requirements of the temperature sensor and the ADC. The design process is aided by the formulas found in [3] and circuit descriptions in [4].

3.2. Design

The following parameters of the temperature sensor are specified as:

$$V(0\,^{\circ}\mathrm{C}) = 620\,\mathrm{mV}; \quad \triangle V(+1\,^{\circ}\mathrm{C}) = +20\,\mathrm{mV}$$

There are a couple of design requirements that must be adhered to. The circuit shall:

- measure the output through the full range of 34 to 42 °C which corresponds to a swing of greater than 3.2 V
- suppress 50 Hz noise of 10 mV amplitude to an accuracy of less than 80 mV
- use less than 25 mA
- have a step response of less than 100 ms for a ±1 °C change.
- simulate under 2 minutes in `LTSpice`.

From the parameters and the requirements, a linear equation can be formulated to used with [3] to design the first steps of the differential amplifier circuit. Choosing R_f as 82 kΩ.

$$y = 20x + 1.38$$

$$m = 1 + \frac{R_f}{R_g}; \quad R_g = \frac{R_f}{m-1} = \frac{82\,\mathrm{k}\Omega}{20-1} \approx 4.3\,\mathrm{k}\Omega$$

To determine the values of the voltage divider before the buffer, a divider circuit must be calculated from R_g as if the buffer is not there. From these values, R_1 and R_2 can be calculated. V_{ref} is equal to 5 V

$$R_{g2} = \frac{R_g}{10} \approx 430\,\mathrm{k}\Omega; \quad R_{g1} = R_g - R_{g2} \approx 3.8\,\mathrm{k}\Omega$$

$$V_{ref'} = \frac{|b| \times R_{g1}}{R_{g1} + R_f} = 62\,\text{mV}; \quad R_1 = \frac{R_{g2}(V_{ref} - V_{ref'})}{V_{ref'}} \approx 33\,\text{k}\Omega$$

$$R_2 = \frac{V_{ref'} \times R_1}{V_{ref} - V_{ref'}} \approx 430\,\Omega$$

The main op-amp is required to have a full swing around 5 to 2 V, thus the TLC2272 Op-Amp is best suited for this part of amplification as it can properly go between the rails as specified in [5]. As for the buffer, it isn't necessary to swing at all and only has a unity gain, thus the TL081 would suffice as it has high slew rates [6].

To use the whole swing of the amplifier, a virtual ground must be applied to the temperature signal. A simple voltage divider using 2 resistors of 82 kΩ can be used to achieve this, along with a capacitor and tuning resistor that will allow the amplified response to center around the virtual ground more effectively. The voltage divider network should give a 2.5 V virtual ground. The capacitor also helps to slightly filter the input going into the differential amplifier, but is not necessary for filtering the signal, only to store the voltage drop.

Lastly the output must be filtered to achieve the desired noise suppression. The noise of 10 mV is now amplified 200 mV. The noise needs to be suppressed by at least −7.9 dB in order to achieve the 80 mV accuracy. Fortunately, a standard Low Pass Filter can be designed in `LTSpice` and adjusted to achieve the desired suppression. After the suppression is achieved, the filter will be tested to see if it still meets the step response requirement. For 50 Hz and $R_o = 20\,\text{k}\Omega$ the capacitance is calculated as:

$$C_o = \frac{1}{2\pi \times f_c \times R_o} = \frac{1}{2\pi \times 50 \times 20\text{k}} \approx 160\,\text{nF}$$

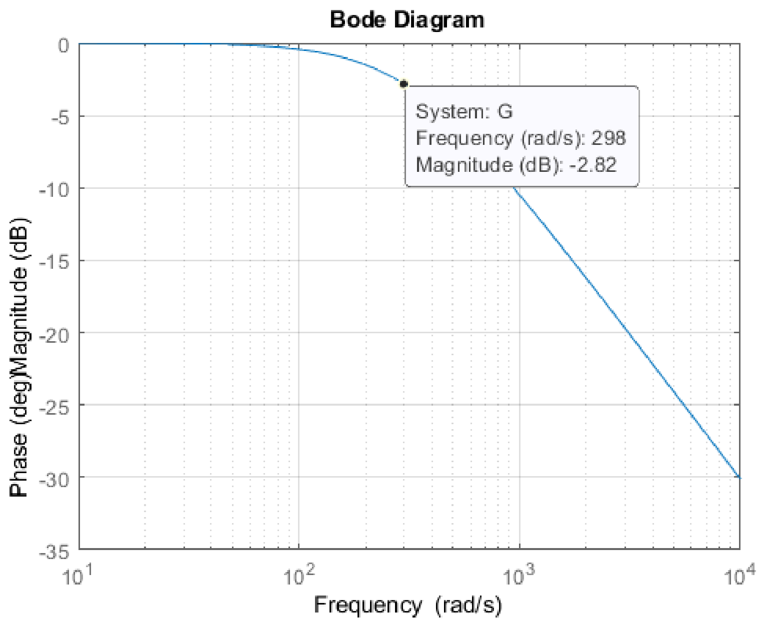


Figure 3.1: LPF Bode Plot

3.3. Results

The response of the system can be seen in Fig.3.3. Once again, the current draw is measured using the `.meas` command in `LTSpice`.

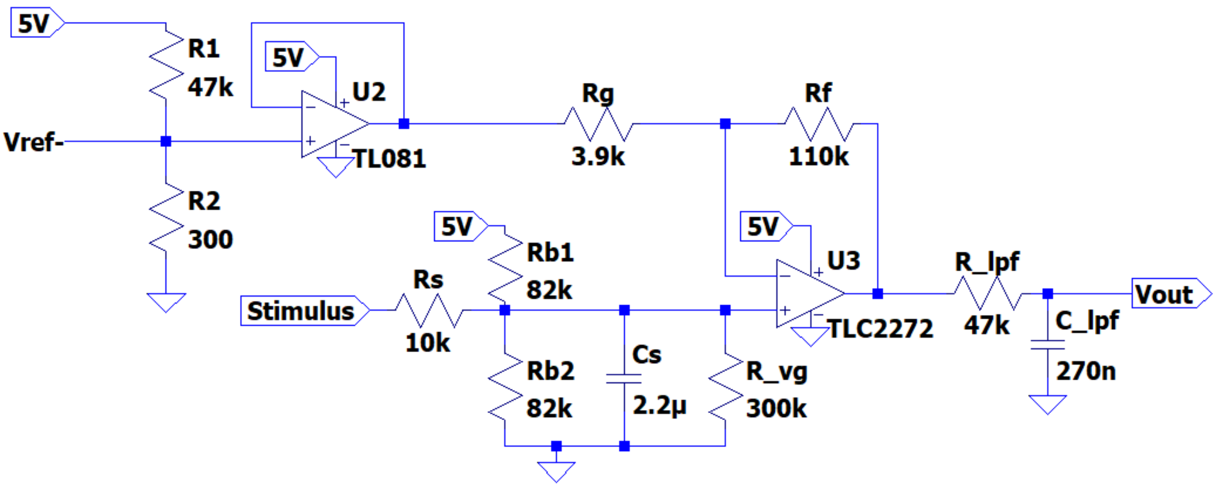
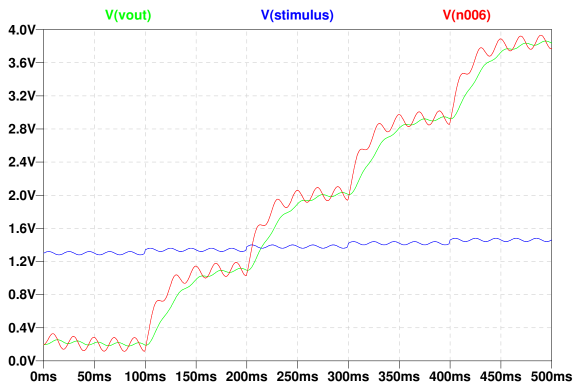
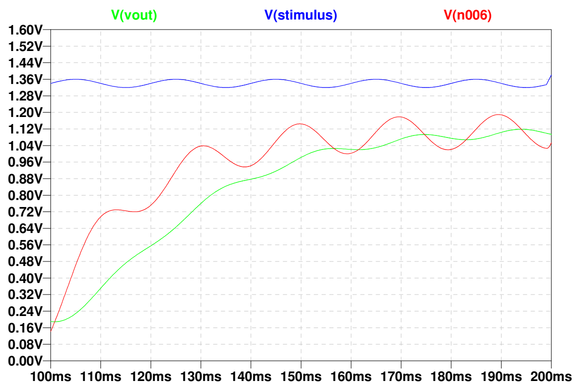


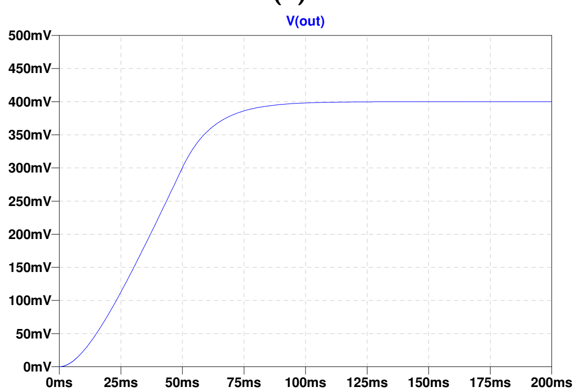
Figure 3.2: Final Differential Op-amp circuit



(a)



(b)



(c)

```
pin: AVG(-v(9v)*i(r_sense))=0.0909459 FROM 0 TO 0.50005
iin: AVG(-i(r_sense))=0.0101052 FROM 0 TO 0.50005
```

(d)

Figure 3.3: Temperature Condition Circuit outputs..(a) Output vs Input vs Unfiltered Output (b) Zoomed 100ms partition of 3.3a (c) Simulated LPF response (c) Circuit total current draw `.meas` results

Table 3.1: Table of time taken to finish simulation

Simulation Time-frame	Total Simulation Elapsed Time
500 ms	3.954 s

From the results it can be seen that the circuit meets the requirements. From Fig.3.3a it can be seen that the circuit takes advantage of the full swing of the op-amp. allowing a response between roughly 3.8 to 0.2 V. In Fig.3.3b it can be seen that the circuit achieves the 100ms rise time as set out bu the requirements. The LPF adheres to the step response as well in Fig.3.3c. The circuit draws less than 15 mA on average and simulates under 2 minutes on the machine used.

3.4. Summary

In summary, the circuit adheres to the requirements, while also improving on some. The output swing is greater than the designed 3.2 V and only uses 10.1 mA. Although the rise time of the LPF could be designed to be more responsive, it meets the requirements without the need of a more complex LPF like a Butterworth-filter. This circuit meets the requirements all while only using 2 op-amps.

Chapter 4

System and conclusion

4.1. System

Report on the integration of the voltage regulator and temperature sensing circuitry. Report on noise levels and how the temperature sensor will fit into the system (E.g. what the calibration will look like and what the the measurement error will be given the range, quantisation error and noise).

The system performs as expected. The voltage regulator is not influenced by the temperature conditioning circuit, given the buffer, which will allow the addition of more components if needed. The noise levels are suppressed to almost 40 mV which will make calibration much quicker and less quantisation errors. The sensor will need to be calibrated around the center of its response, 38 °C which will give a 2 V output to the ADC of the micro-controller.

4.2. Lessons learnt

- Better power efficiency equals more components and more expensive circuitry.
- You can have a circuit that has a super accurate response, but a less complicated circuit that still meets the requirements will also get the job done.
- You don't have to over-design everything.

Bibliography

[1] Fairchild Semiconductors, *MC78LXXA / LM78LXXA 3-Terminal 0 . 1 A Positive Voltage Regulator*, 2013.

[2] Texas Instruments, *LM2595 SIMPLE SWITCHER Power Converter 150 kHz 1A Step-Down Voltage Regulator SIMPLE SWITCHER ® Power Converter 150 kHz 1A Step-Down Voltage Regulator*, 1999.

[3] B. Carter, "Designing Gain and Offset in Thirty Seconds," *Design*, no. February, pp. 1–15, 2002.

[4] Electronics Tutorials, "Operational amplifiers archives," 2020. [Online]. Available: https://www.electronics-tutorials.ws/opamp

[5] Texas Instruments, *TLC227x , TLC227xA : Advanced LinCMOS Rail-to-Rail Operational Amplifiers PACKAGE*, 2016.

[6] ——, *TL08xx JFET-Input Operational Amplifiers*, 2015.

Appendix A

Social contract

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E-design 344 Social Contract

2020

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 the Teaching Assistant (Michael Ritchie) spent countless hours to prepare for E344 to ensure that you get your money's worth and that you are enabled to learn from the module and demonstrate and be assessed on your skills. We commit to prepare for the module, to set the tests and 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.

Signature: .... Date: 13 July 2020

....

I, Gerthardus Magnus Marais 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 of supplementary videos on specific topics, I acknowledge that I am expected to attend the lectures and lab sessions 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.

Signature: .... Date: 14/07/2020

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Appendix B

GitHub Activity Heatmap