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E344 Assignment 2

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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 29, 2020

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21642818 Studentenommer / *Student number*	GMarais Handtekening / *Signature*
G.M. Marais Voorletters en van / *Initials and surname*	September 29, 2020 Datum / *Date*

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Nomenclature

Variables and functions

A	Gain
A	Ampere, unit for current
dB	Decibel, logarithmic value
F	Farad, unit of capacitance
Hz	Hertz, unit of frequency
n	Order of filter
Ω	Ohm, unit of resistance
Q	Quality factor
s	Second, unit of time
V	Volt, unit of voltage potential
f_C	Corner frequency

Acronyms and abbreviations

BPM	Beats Per Minute
DC	Direct Current
FFT	Fast Fourier Transform
HPF	High Pass Filter
LPF	Low Pass Filter
MCU	Micro Controller Unit

Chapter 1

System design

1.1. System overview

The system (Fig. 1.1) contains a voltage regulator [1] to supply power, a heartbeat sensor as input, filters and amplifier as signal conditioning, comparator to create the desired 5V pulse and a one shot timer to condition the pulse signal. The end circuit did not need a one shot timer, as it meets the requirements with the comparator.

For signal conditioning, a Sallen & Key high pass filter is used to filter any heart beat above 50 BPM while also amplifying the signal to easily use with the comparator. The Sallen & Key filter also allows the signal to be centred around a given virtual ground no matter the signal offset. The HPF is coupled to a second order passive LPF to filter any heart beat below 150 BPM and to smooth out the signal. The comparator can now more easily threshold the signal, as it is smoothed out and amplified. The threshold point is designed for the highest frequency signal to have a pulse larger than 150 ms.

The regulator supplies ± 100 mA, while the temperature sensing circuit [1] uses ± 10 mA. This leaves 90 mA for the rest of the circuit design, however the heartbeat sensing circuit will be designed to use less than 50 mA.

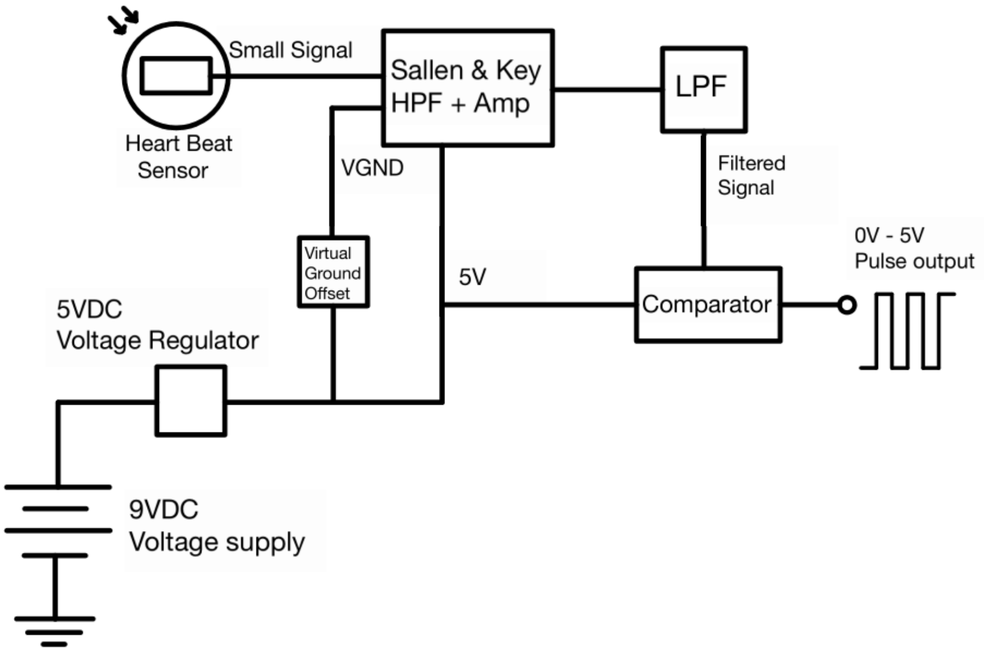


Figure 1.1: System diagram

Chapter 2

Heart rate sensor

2.1. Introduction

In this chapter, the design for the Sallen & Key HPF, passive LPF and comparator will be explained and what sources where consulted in the designed process.

The Sallen & Key HPF design [2] can be used to not only filter the signal above a desired frequency, but by adding a resistor feedback the signal can also be amplified. Amplification reduces the quality of the signal (Q), thus the amplification must not be too large . This method is used in the design to make it easier for thresholding in a later stage. In order to minimise design expenses, the LPF design is based on a passive filter [3]. A single order filter does enough to filter excess noise to a degree, but in order to smooth out the signal further, a second phase is added to the design to create a second order passive LPF.

2.2. Design

Before designing the filter, the frequency response must first be inspected to determine which frequencies are desired and which are not. In Fig 2.1 a 150 BPM heart beat is drawn in `LTSpice` using its built in FFT function, and shows 3 prominent frequencies between 0.8 Hz and 4 Hz and numerous spikes above 10 Hz. From this it can be concluded that the frequencies from 0.8 to 4 Hz is desired signal while anything above or below this range is noise.

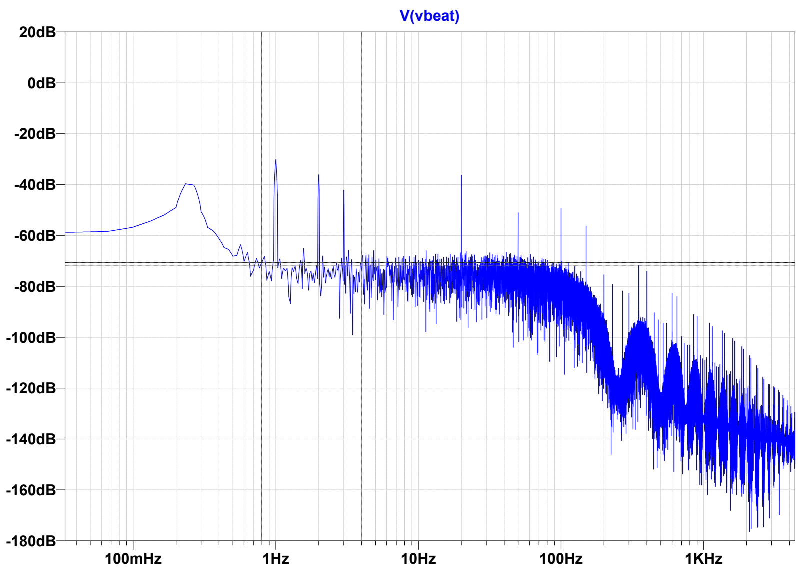
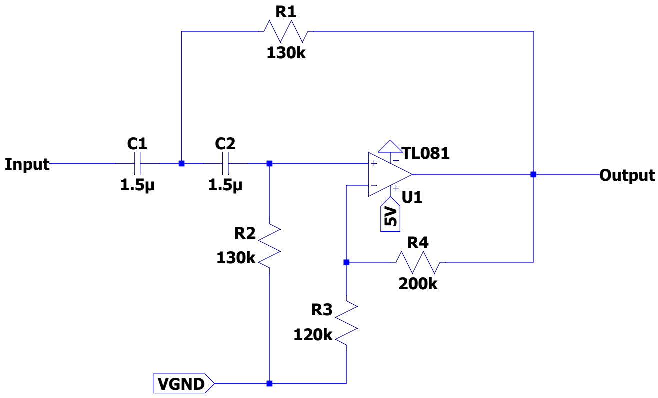
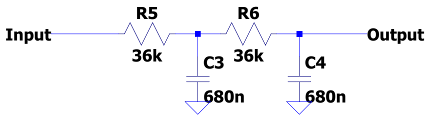


Figure 2.1: FFT of a 150BPM heart beat signal



(a) Sallen & Key HPF circuit diagram



(b) Passive LPF circuit diagram

Figure 2.2: Circuit Diagrams of a Sallen & Key HPF and passive LPF

The HPF will thus be designed to suppress all frequencies below 0.8 Hz. The design layout will look like Fig. 2.2a. The HPF will be designed for a corner frequency (f_c) of 0.8 Hz. One can assume $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then Eq. 2.1 becomes Ep. 2.2. Using a standard capacitor value of 1.5 µF for C, a resistor value can be approximated.

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \tag{2.1}$$

$$f_c = \frac{1}{2\pi RC} \tag{2.2}$$

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 0.8 \times 1.5\mu} = 132\,629\,\Omega \approx 130\,\text{k}\Omega$$

To finish off the design of the HPF, the amplification factor must be designed. As noted in [2] the amplification is dependant on the quality factor, Q, which determines the amplification. Designing for a moderate quality factor of 3 gives the amplification and resistor values for R_3 and R_4 as follows in Eq. 2.3 and Eq. 2.4. Assume $R_4 = 200\,\text{k}\Omega$.

$$A = \frac{3Q-1}{Q} = \frac{3(3)-1}{3} = 2.66667 \tag{2.3}$$

$$A = 1 + \frac{R_4}{R_3} \implies \frac{R_4}{R_3} = 1.66667$$

$$R_3 = \frac{R_4}{1.66667} = 119.9998\,\text{k}\Omega \approx 120\,\text{k}\Omega \tag{2.4}$$

The LPF will be designed to suppress all frequencies above 4 Hz. The design layout will look like Fig. 2.2b. A second order passive LPF has to be designed for a different cutoff frequency than a normal first order LPF, which is usually the 3 dB point. Using [3] as reference, the new cutoff frequency is derived from Eq. 2.5 where n is the order of the filter and the 3 dB point is 4 Hz. Now the resistor values for the LPF can be designed using 2.6, assuming that $R_5 = R_6 = R$ and $C_3 = C_4 = C = 680\,\text{nF}$.

$$f_{(-3\,\mathrm{dB})} = f_C\sqrt{2^{\left(\frac{1}{n}\right)} - 1} \tag{2.5}$$

$$f_C = \frac{f_{(-3\,\mathrm{dB})}}{f_{(-3\,\mathrm{dB})}} = \frac{4\,\mathrm{Hz}}{\sqrt{2^{\left(\frac{1}{2}\right)} - 1}} = 6.215\,\mathrm{Hz}$$

$$f_C = \frac{1}{2\pi\sqrt{R_5 R_6 C_3 C_4}} = \frac{1}{2\pi RC} \tag{2.6}$$

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 6.215 \times 680\mathrm{n}} = 37.66\,\mathrm{k\Omega} \approx 36\,\mathrm{k\Omega}$$

A simple comparator design, seen in Fig. 2.3, that only uses an op-amp will be used to push the signal from 0 to 5 V. The threshold value is determined by R_7 and R_8. As the signal through the HPF is already centred around 2.5 V, any deviation in the DC component of the signal is neglected. Assuming the filtered response of a heartbeat will approximate a sawtooth signal centred around 2.5 V, the comparator must be designed for the highest frequency as it will have the shortest pulse. A 150BPM signal will subsequently have a period of 400 ms. For simplicity, the thresholding can be designed for 200 ms, or approximately 2.5 V. To achieve this, R_7 and R_8 must be equal. The thresholding should be large enough to allow for a deviation of ±10 mV in amplitude, while also eliminating the need for a One Shot component. The resistors must also be large enough to limit current draw. Thus $R_7 = R_8 = 330k$.

Regarding op-amps, the HPF handles a small input voltage with a relatively small swing. For this stage, the op-amp will never reach the 0 to 5 V rails, and can therefore use a TL081 op-amp [4]. The comparator however, will receive an larger, amplified signal and will need to push the voltage between the 5 V and 0 V rails, therefore needing a much stronger op-amp, such as the TLC2272 op-amp [5].

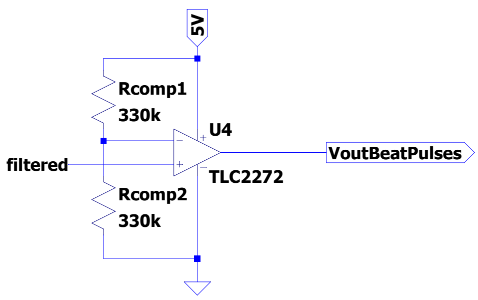


Figure 2.3: Op-amp comparator circuit

2.3. Results

Fig. 2.4 shows the results of the filter responses. The HPF reactes as expected, giving an amplification at around 0.8 Hz that can be seen in Fig. 2.4a. Fig. 2.4b shows that the −3 dB and −6 dB point of the LPF is very close to the designed cutoff frequencies. The combined system response is seen in Fig. 2.4d

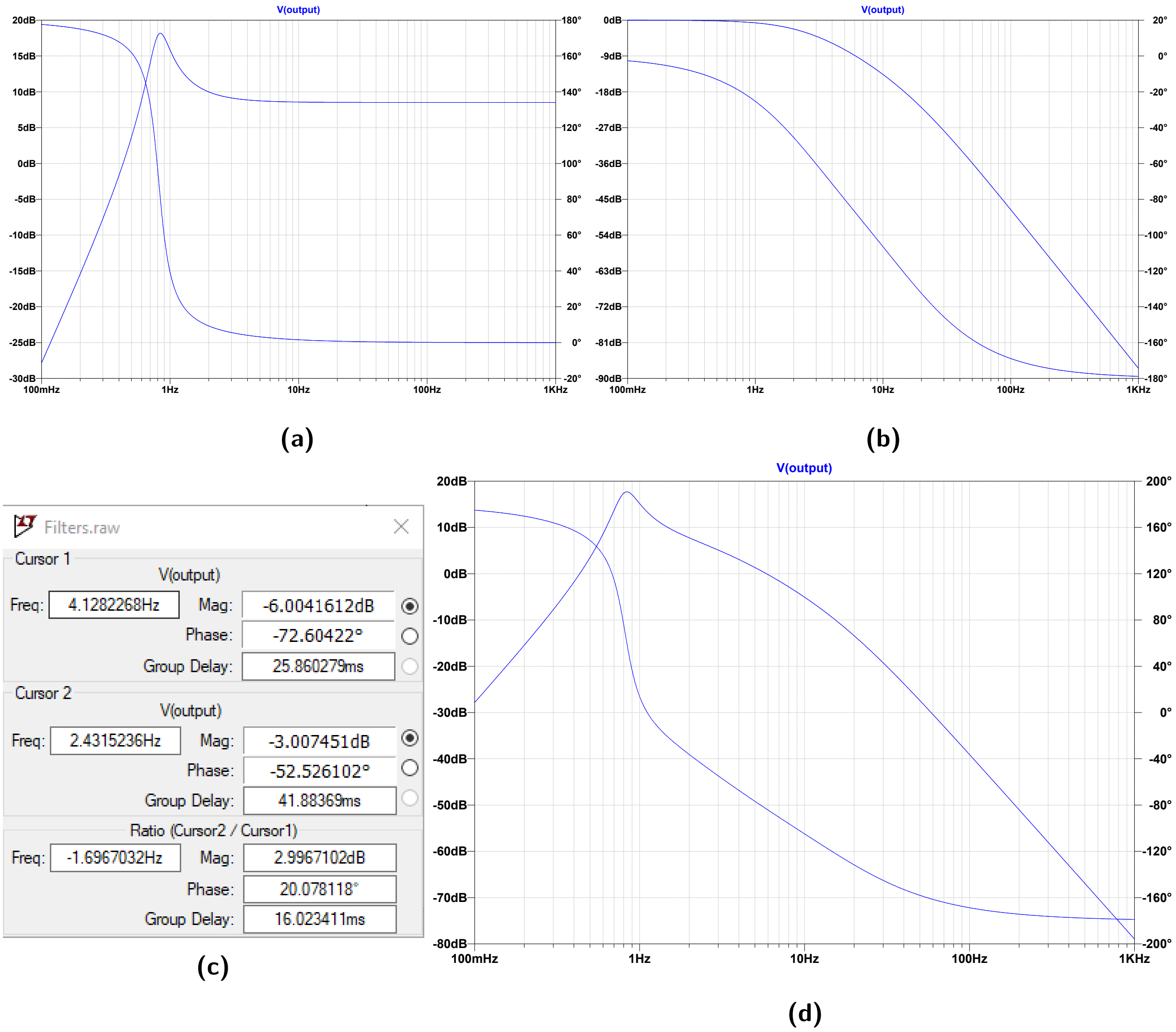


Figure 2.4: Bode plots of filter stages. (a) HPF Sallen Key bode plot (b) LPF passive bode plot (c) LPF bode plot cursors (d) Combined stages bode plot

The analysis for the thresholding of the comparator and and pulse duration is seen in Fig. 2.5. The output filtered signal is measured at the threshold voltage at which the comparator will trigger shown Fig. 2.5d and the output signal at 60 BPM in Fig. 2.5a as well as 150 BPM in Fig. 2.5b.

The current draw from the power supply is measured at 60 BPM and 150 BPM and shown in Tabel 2.1.

Table 2.1: Table of current usage.

Test frequency $[BPM]$	Current through R_{sense} [mA]
60	-12.4942
150	-12.4942
Average	-12.4942

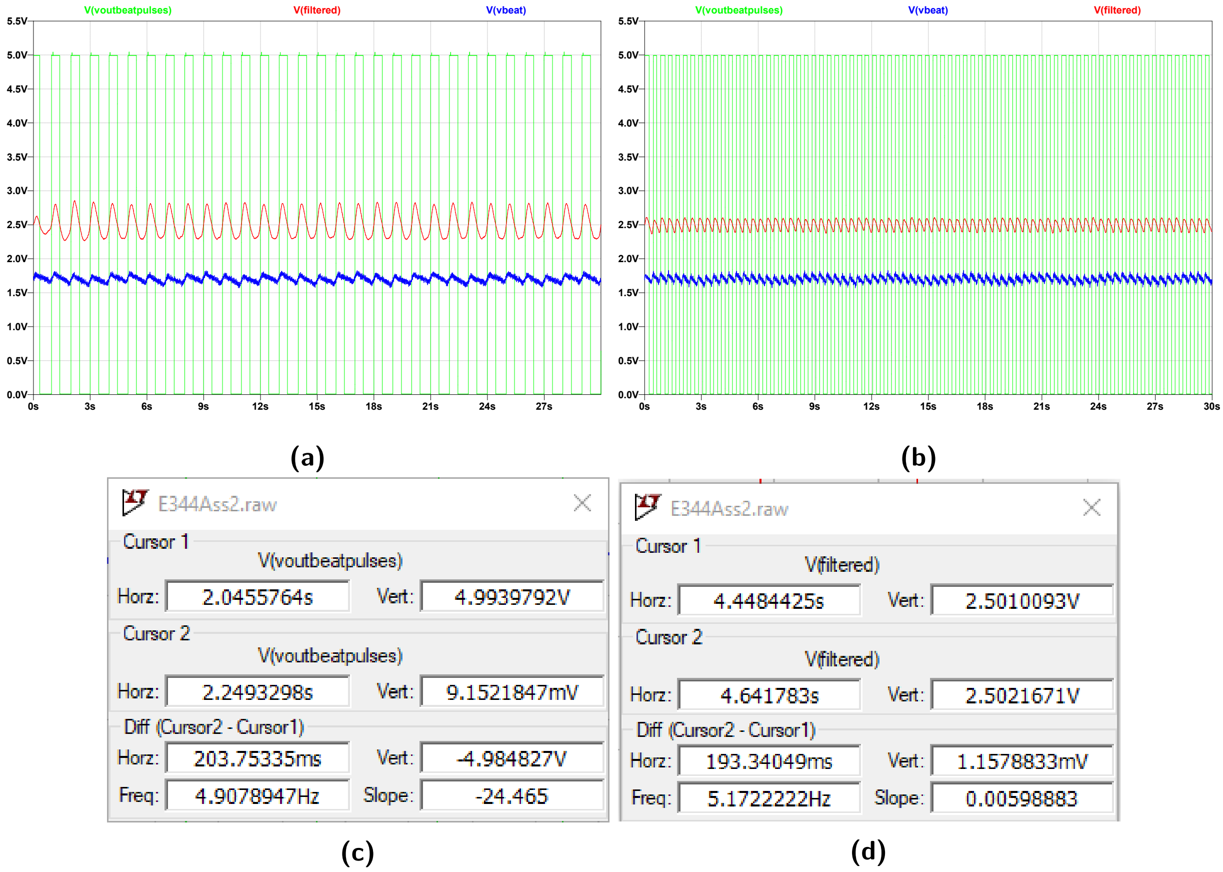


Figure 2.5: (a) 60 BPM signal with pulse output (b)150 BPM signal with pulse output (c) Cursor position for pulse duration in Fig. 2.5b (d) Cursor position for threshold values

2.4. Summary

The circuit performed as expected. The pulse duration for the shortest wavelength still exceeds 150 ms and the comparator pushes the signal to reach 5 to 0 V at its highest and lowest. Small deviations in amplitude and in DC offset is also limited which ensures the signal is stable. The circuit is limited to only work efficiently between the ranges of 50 to 150 BPM, as any BPM lower or higher might be filtered out. One must keep in mind that the circuit is only accurate after the 1 s at 50 BPM as the capacitors need to be charged.

Chapter 3

System and conclusion

3.1. System

The circuit works as expected. This heart rate sensor conditioning circuit will fit nicely into the system. The MCU can easily read the pulse inputs and count every high pulse for a duration of time and then relate that to BPM. This will only need one pin from the MCU, while also using very little current. The circuit is effective and make accurate pulses. In the way the circuit is built, it also allows it to be used with any DC offest from the heart beat sensor, given that it is between the ranges of 0 to 5 V.

It is not a very difficult circuit to implement, except when one wants to introduce a transducer to convert frequency signals to an analog output. It is quite difficult to find proper sources for this implantation online, let alone in stander Engineering textbooks. Once a source is found however, it can be even more difficult given `LTSpice` struggles with timestep errors.

3.2. Lessons learnt

Things that I learned in assignment 2:

- Most importantly, I feel much more confident in my knowledge of LaTeX and `LTSpice` and have learned how to use them properly, while also finding out how they are limited in certain aspects.
- I learned how to implement filters in a more effective way,and how different filters can be used for different use cases.
- I learned that you can build a lot of simple components like One-Shot timers, comparators, transducers and filters only by using op-amps, resistors and capacitors.
- I learned that it is always wiser to start early and not procrastinate. Also, write down while you are designing so that you can always backtrack and find your steps.

If I had another chance, I would spend more time working on the transducer. I spent almost 20 hours, if not more, on that part of the designed, but still could not get it working. I decided not to implement the transducer after I realised that if I do keep working on this single part of the design, which is only necessary for distinction, I will never finish on time.

Bibliography

[1] G. M. Marais, “E344 Assignment 1,” August 2020.

[2] Electronics Tutorials, “Sallen and Key Filter Design for Second Order RC Filters,” 2018. [Online]. Available: https://www.electronics-tutorials.ws/filter/sallen-key-filter.html

[3] ——, “Low Pass Filter - Passive RC Filter Tutorial.” [Online]. Available: https://www.electronics-tutorials.ws/filter/filter{_}2.html

[4] Texas Instruments, “TL08xx JFET-Input Operational Amplifiers,” vol. 082, 2015.

[5] ——, “TLC227x , TLC227xA : Advanced LinCMOS Rail-to-Rail Operational Amplifiers PACKAGE,” 2016.

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, Gerhardus 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: 27/09/2020

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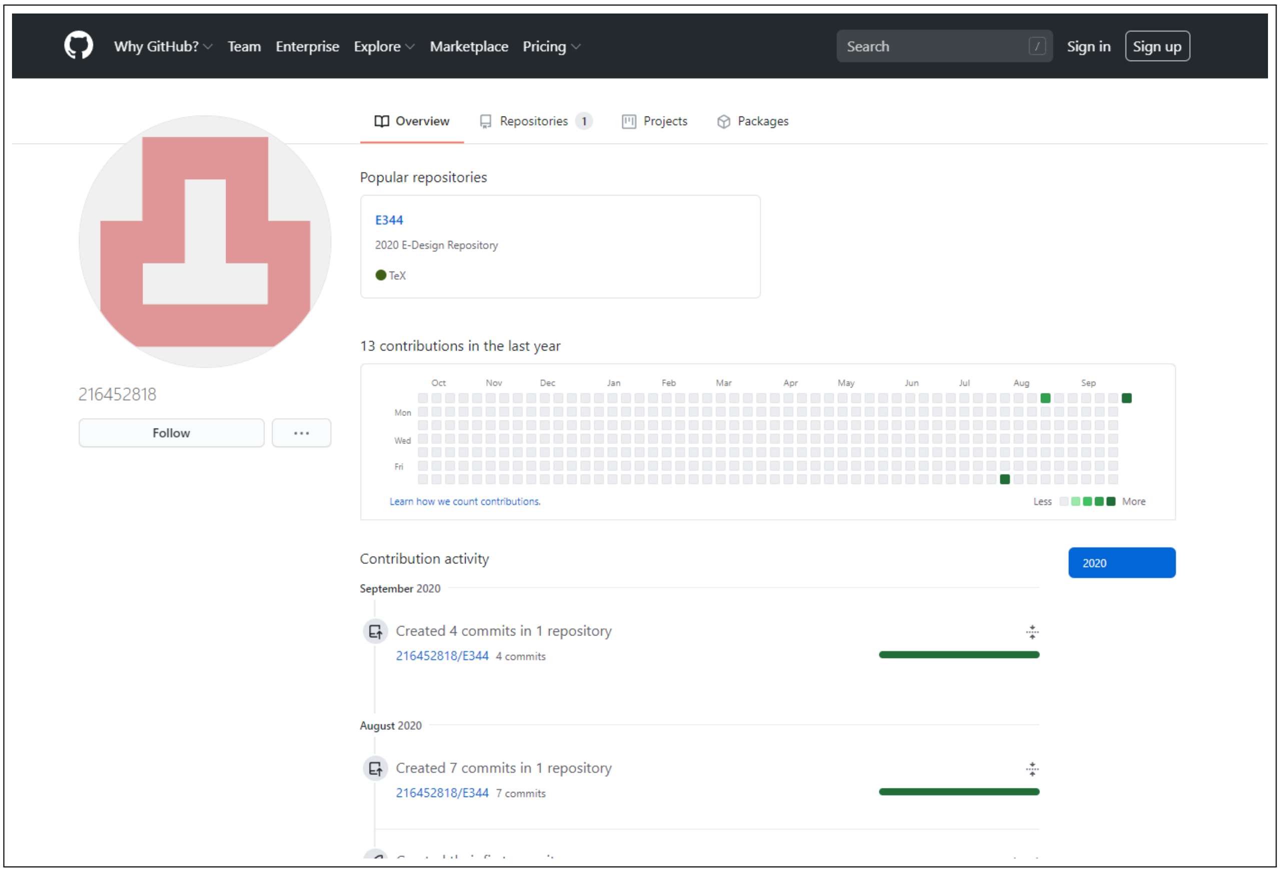
Appendix B

GitHub Activity Heatmap



Appendix C

Stuff you want to include

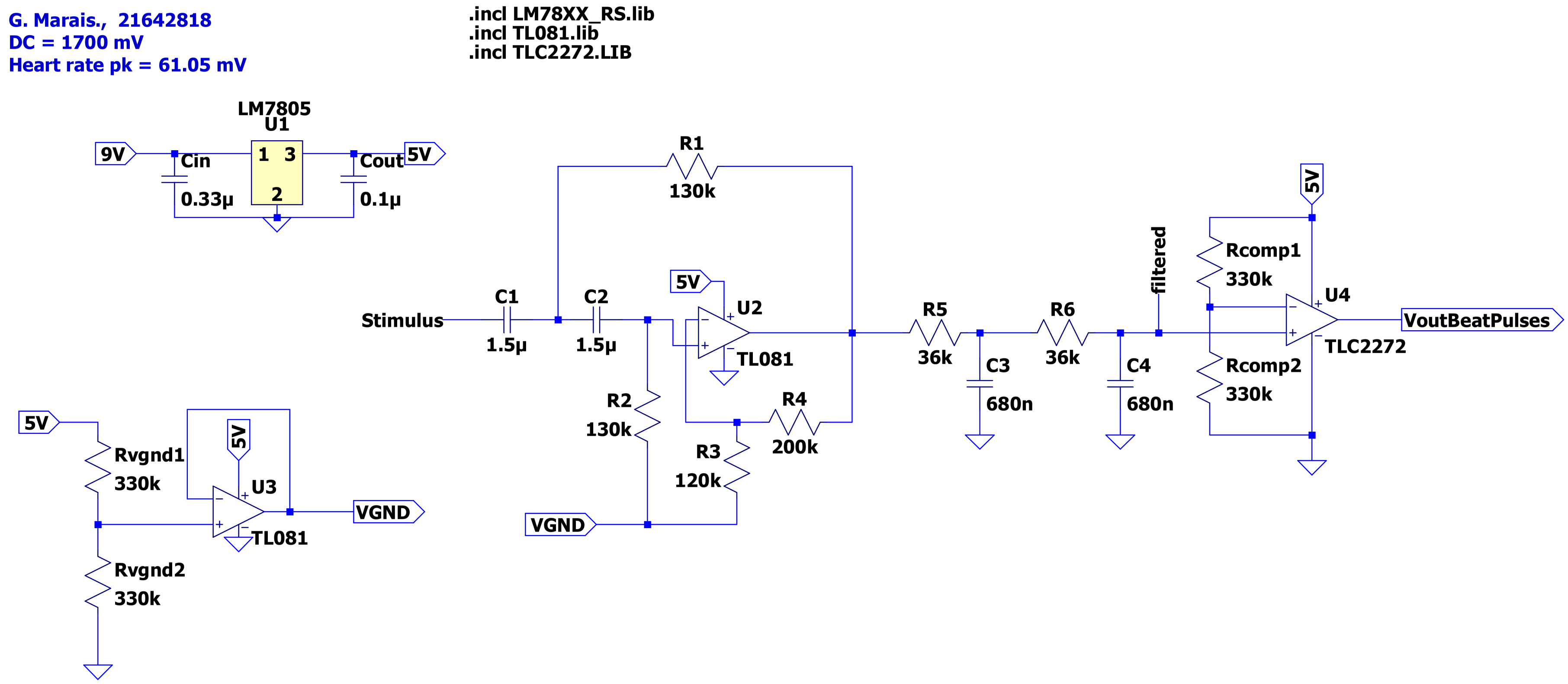


Figure C.1: Full Circuit Diagram