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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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Nomenclature

Variables and functions

$rate_{bpm}$	Heart-rate in bpm.
f	Base frequency.
V_{gnd}	Virtual ground voltage.
V^+	Positive supply voltage.
V^-	Negative supply voltage.
R	Resistor.
C_{LPF}	Low-pass filter capacitor.
C_{HPF}	High-pass filter capacitor.
f_{LPF}	Low-pass filter cutoff frequency.
f_{HPF}	High-pass filter cutoff frequency.
α	Op-amp gain
V_{amp}	Amplification stage output voltage.
V_{out}	Output voltage.
T	Period of heartbeat signal.
I_{tot}	Total current drawn.
R_{sense}	Internal resistance of sensor.
$V_{IN_{max}}$	Maximum rated input voltage.
$V_{IN_{min}}$	Minimum rated input voltage.
V_{ID}	Maximum rated differential input voltage.
ΔI	Current dissipation.

Acronyms and abbreviations

AC	alternating-current
bpm	beats per minute
DC	direct-current
FFT	fast Fourier transform
GND	ground
HPF	high-pass filter
LPF	low-pass filter
VDC	direct-current voltage

Chapter 1

System design

1.1. System overview

The block diagram for a temperature and heartbeat sensor conditioning system is shown in Figure 1.1. The system is supplied with 9 VDC. It performs the conditioning of temperature and heart-rate sensor data to produce an output signal which can be more easily interpreted by the user in accordance with the specifications in [1] and [2]. The output from this system will allow a micro-controller to derive the temperature and heart-rate from the sensor input.

The heartbeat conditioning section of this system is designed, analysed and discussed in this report. Any measured heart-rate from 50 bpm to 150 bpm generates a defined output signal. Details regarding the voltage regulation and temperature conditioning can be found in [3]. Taking into consideration the system current limit of 100 mA and the current draw of the temperature conditioning subsystem, there remains 85.3 mA for further functionality of the system, including the heartbeat sensor conditioning subsystem.

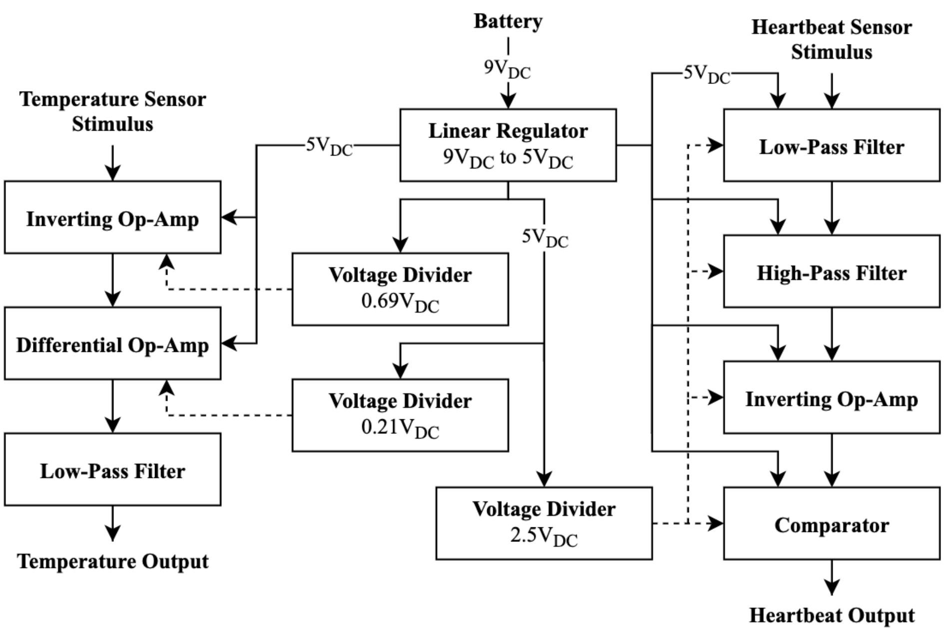

Figure 1.1: System diagram

Chapter 2

Heart rate sensor

2.1. Introduction

The conditioning circuit is given an output signal from a heartbeat sensor (the ”stimulus”). This signal represents any heart-rate from 50 bpm to 150 bpm, but contains significant noise and DC disturbance. The purpose of the conditioning circuit is to interpret the sensor output and return distinct pulses for each heartbeat so that the heart-rate can be determined.

There are three stages to the conditioning circuit: a filtering stage, an amplification stage, and a comparator stage. The filtering stage comprises of a third-order Butterworth low-pass filter and a second-order Sallen-Key high-pass filter. Both of these configurations were built in accordance with [4]. The inverting op-amp used for the amplification stage was configured using the theory in [5] and for the comparator, [6] was consulted.

The technical requirements of each component need to be considered in the design of the signal conditioning system. Particularly, the voltage limitations of each op-amp stipulated in [7] need to be carefully considered.

2.2. Design

Appendix C shows the LTSpice model of the heartbeat sensor conditioning circuit. This circuit was designed for a heartbeat signal with a DC component of 1.5 V and amplitude of 33.30 mVpk, and allows for a variation in these specifications of ±0.2 VDC and ±3.33 mVpk. TL081 op-amps were used for all op-amp applications of this design. This is because the TL081 is cost-effective, simple, and allows for efficient simulation for the circuit in LTSpice [7].

Table 2.1: Heartbeat signal frequency components.

$rate_{bpm}$	f	$2f$	$3f$	
50 bpm	0.83	1.67	2.50	[Hz]
60 bpm	1.00	2.00	3.00	[Hz]
90 bpm	1.50	3.00	4.50	[Hz]
120 bpm	2.00	4.00	6.00	[Hz]
150 bpm	2.50	5.00	7.50	[Hz]

Upon analysis of the given heartbeat signals using the FFT, it was determined that the heartbeat itself is comprised of three separate signals: one at the ”base” frequency determined by the heart-rate in bpm ($f = \frac{rate_{bpm}}{60}$), and two additional signals at double and triple the base frequency. This is detailed in Table 2.1. The frequency information for a heart-rate of

50 bpm is also deduced, as this heart-rate also needs to be designed for. All other frequency components in the heartbeat signal are noise or disturbance components. These unwanted components are observed around 250 mHz, 20 Hz, 50 Hz and further even higher frequencies. All of this frequency information is considered in the conditioning circuit design below.

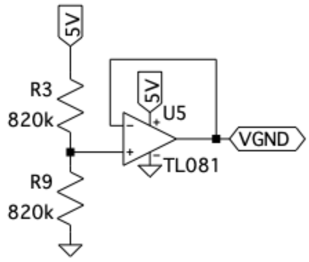

Figure 2.1: Virtual ground circuit.

In order to account for the 1.5 V DC offset of the heartbeat sensor signal, and to simplify the thresholding process in the comparator stage of the circuit, a **virtual ground** level is selected at half of the supply voltage. $V_{gnd} = \frac{V^+}{2} = 2.5\,\mathrm{V}$. This virtual ground is created using voltage division and a voltage-follower op-amp as shown in Figure 2.1. Large common-value resistors $R = 820\,\mathrm{k\Omega}$ are chosen to reduce the current usage of the circuit. Equation 2.1 explains how V_{gnd} is obtained.

$$V_{gnd} = \frac{R_3}{R_9} \times V^+ = \frac{820\,\mathrm{k\Omega}}{820\,\mathrm{k\Omega}} \times 5 = 2.5\,\mathrm{V} \tag{2.1}$$

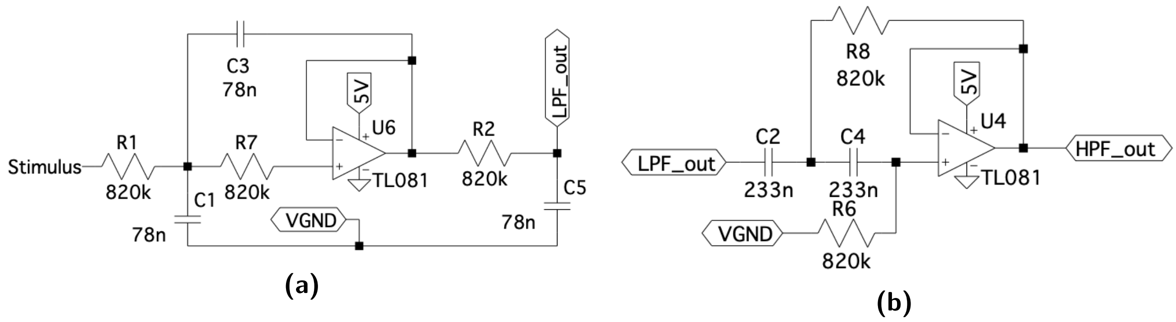

Figure 2.2: Filter stage. (a) Third-order Butterworth low-pass filter. (b) Second-order Sallen-Key high-pass filter.

The **filter stage** removes noise and DC disturbance from the heartbeat signal. Only the base frequencies (f) of each heart-rate were considered in the filter design. This is because sufficient information can be gathered from the base frequencies for further conditioning, and the design complexity of the filter stage will be reduced. Large common-value resistors $R = 820\,\mathrm{k\Omega}$ are chosen to reduce the current usage of the circuit. As seen in Table 2.1, the highest allowable frequency is 2.5 Hz. The third-order Butterworth low-pass filter configuration [4] shown in Figure 2.2a is designed for this frequency. The capacitor values are calculated by Equation 2.2.

$$C_{LPF} = \frac{1}{2\pi R f_{LPF}} = \frac{1}{2\pi \times 820\,\mathrm{k\Omega} \times 2.5\,\mathrm{Hz}} = 78\,\mathrm{nF} \tag{2.2}$$

As seen in Table 2.1, the lowest allowable frequency is 0.83 Hz. The second-order Sallen-Key high-pass filter configuration [4] shown in Figure 2.2b is designed for this frequency. The capacitor values are calculated by Equation 2.3.

$$C_{HPF} = \frac{1}{2\pi R f_{HPF}} = \frac{1}{2\pi \times 820\,\mathrm{k\Omega} \times 0.83\,\mathrm{Hz}} = 233\,\mathrm{nF} \tag{2.3}$$

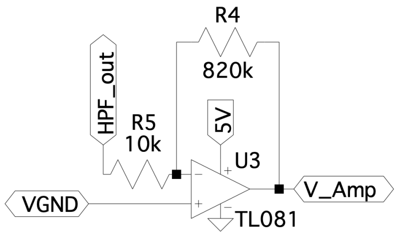

Figure 2.3: Inverting op-amp with gain.

The **amplification stage** applies a gain to the filtered heartbeat signal in order to allow for easier thresholding in the comparator stage. A large common-value feedback resistor $R_4 = 820\,\mathrm{k\Omega}$ is chosen to reduce the current usage of the circuit. An analysis of the filtered signal shows that there is only a small AC variance ranging from 2.5 mVpk to 3.6 mVpk for the given heart-rates. To remain consistent in using common-value resistors and to prevent using too small of a resistor so as not to draw too much current, an input resistor $R_5 = 10\,\mathrm{k\Omega}$ is chosen. The gain factor of this amplifier configuration is calculated by Equation 2.4 [5].

$$\alpha = -\frac{R_4}{R_5} = -\frac{820\,\mathrm{k\Omega}}{10\,\mathrm{k\Omega}} = 82 \tag{2.4}$$

This gain should return a heartbeat signal with an AC variance ranging from 0.205 Vpk to 0.295 Vpk for the given heart-rates. This range is sufficient for the thresholding functionality of the comparator stage.

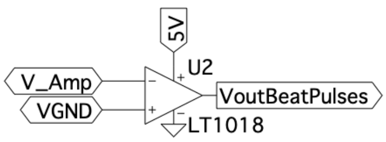

Figure 2.4: Op-amp comparator.

The **comparator stage** implements a simple op-amp comparator [6], shown in Figure 2.4, to output distinct square pulses for each heartbeat from the sensor signal. A reference voltage $V_{gnd} = 2.5\,\mathrm{V}$ is compared to the filtered and inverse-amplified sensor signal V_{amp}. If $V_{amp} < V_{gnd}$, then $V_{out} = V^{+} = 5\,\mathrm{V}$. If $V_{amp} > V_{gnd}$, then $V_{out} = V^{-} = 0\,\mathrm{V}$.

In accordance with [1], the pulse duration for each heartbeat needs to be 150 ms or longer. Table 2.2 indicates the period for each signal determined by the heart-rate in bpm ($T = \frac{60}{rate_{bpm}}$). From this, it is found that the smallest period is that of the 150 bpm signal, and so this signal needs to be most closely considered when designing the pulse length of the output. Notably, one can deduce that as long as the comparator identifies around half of the

Table 2.2: Period of each heartbeat signal.

$rate_{bpm}$	T	$\frac{1}{2}T$	
50 bpm	1.20	0.60	[s]
60 bpm	1.00	0.50	[s]
90 bpm	0.67	0.33	[s]
120 bpm	0.50	0.25	[s]
150 bpm	0.40	0.20	[s]

signal as surpassing the reference voltage, the pulse should be longer than 150 ms. This is because $\frac{1}{2}T_{150_{bpm}} = 200\,\text{ms} > 150\,\text{ms}$. For this reason, the reference voltage is chosen as the value around which the filtered and amplified signal is centered, i.e. 2.5 V. This threshold voltage should also account for the allowed specification deviations mentioned in Section 2.2.

The total current of the conditioning circuit can now be calculated using Equation 2.5. The current draw of the virtual ground stage is not included as this stage is present in the temperature sensor conditioning circuit from [3] and so has already been accounted for.

$$I_{tot} = \frac{V^+}{R_1 + R_2 + R_4 + R_5 + R_6 + R_8} = 1.22\,\mu\text{A} \tag{2.5}$$

2.3. Results

Figure 2.5 shows that the **full range** of heart-rates from 60 bpm to 150 bpm can be measured and conditioned by the system in Appendix C. One can note in Figure 2.5c and Figure 2.5d that the **pulse duration** of both the 60 bpm and 150 bpm conditioned signals is longer than 150 ms, which is in accordance with [1].

Upon simulation of the circuit in Appendix C, the current through R_{sense} is determined to be 15.3 mA. This current represents the **total current of the circuit**, and is well within the specifications in [1].

All **op-amps** perform as expected. The input signal for the virtual ground voltage divider, filter stage and amplification stage remains within the TL081 common-node voltages (1 V to 4 V) [7]. The datasheet does not specify a value for $V_{IN_{min}}$ but at 15 V, $V_{IN_{max}}$ is significantly larger than our signal which is centered tightly around 2.5 V. The differential input voltage $V_{ID} = 30\,\text{V}$ is also far larger than any of the voltage values being handled in this system.

Figure A.1 in Appendix A depicts the **frequency response** of the filter stage. It is clear when analysing the cursor values that the noise and disturbance of the heartbeat signal is sufficiently filtered.

The **thresholding** of the comparator stage was measured and is shown in Figure B.1 in Appendix B. The maximum and minimum allowable specification deviations as mentioned in Section 2.2 were applied to the 60 bpm and 150 bpm signals respectively to obtain these plots. From this, it is clear that even with the most extreme deviations from the original heartbeat sensor signal, the thresholding around 2.5 V proves successful.

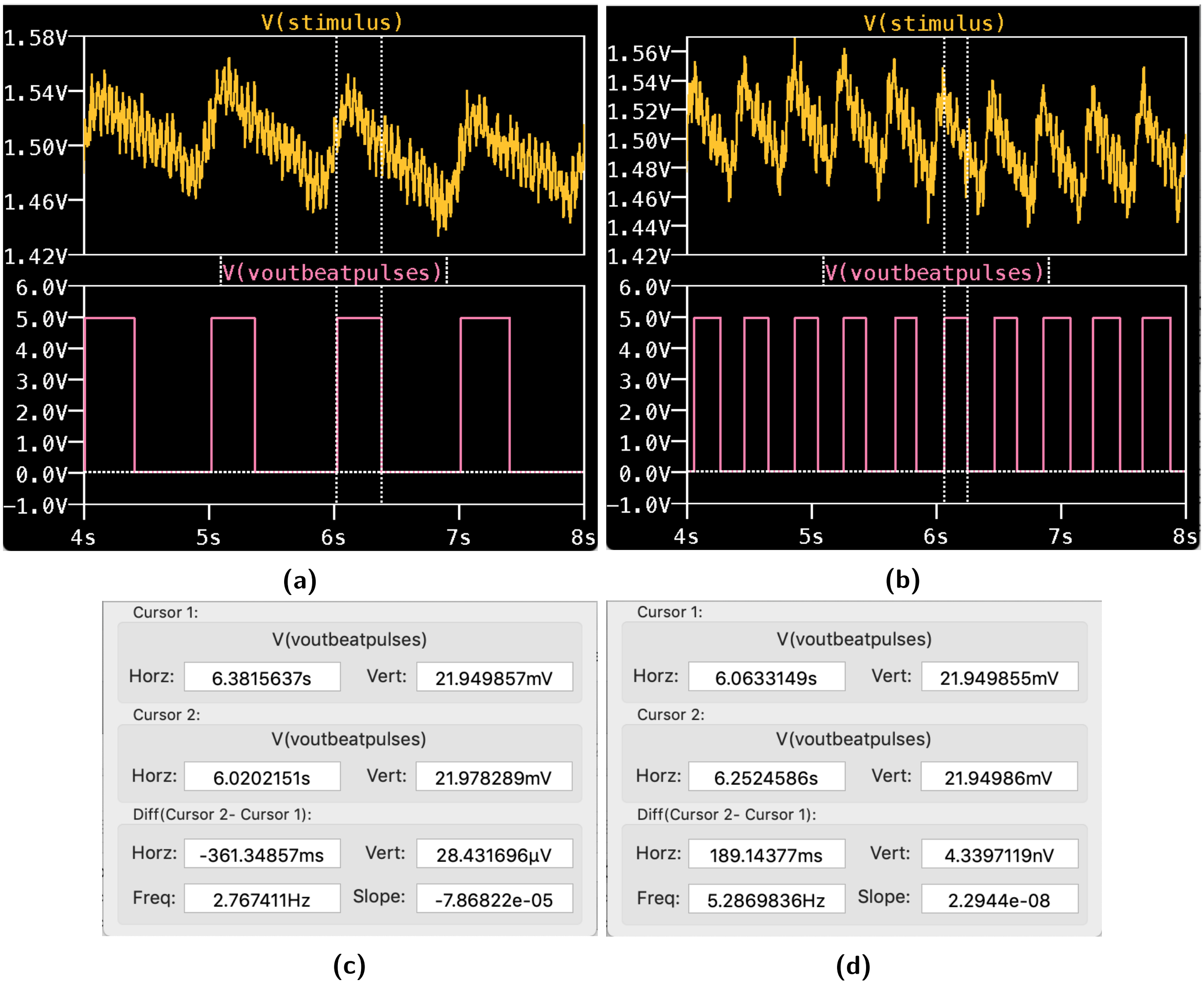

Figure 2.5: Conditioning circuit input and output simulation results. (a) Input and output at 60 bpm. (b) Input and output at 150 bpm. (c) Pulse duration at 60 bpm. (d) Pulse duration at 150 bpm.

2.4. Summary

The conditioning circuit in Appendix C performs as expected, and within the specifications of [1]. This includes the allowable specification variations of ±0.2 VDC and ±3.33 mVpk on the heartbeat sensor signals.

The circuit has been designed to be able to process all heart-rates from 50 bpm to 150 bpm. Although simulation and testing was only done on heart-rates as low as 60 bpm, theoretical calculations do support the same functionality for a heart-rate of 50 bpm. In practical applications this will need to be further investigated before implementation.

After simulation, the total current drawn from the conditioning circuit, while well within specifications, is significantly higher than the calculated value. This is likely due to assumptions made in the theoretical calculation, but could be due to a design/component error. This also would require further investigation before practical application.

Chapter 3

System and conclusion

3.1. System

The circuit in Appendix C meets all design specifications in [1]. Given the overall current limitation of 100 mA [2], the current draw of 14.7 mA for the temperature sensor conditioning system [3], and the current draw of 15.3 mA for the heartbeat sensor conditioning system, there remains $\Delta I = 100 - 14.7 - 15.3 = 70\,\text{mA}$. This current may be needed for further interfacing with the sensors or a micro-controller for further processing.

The full range of heart-rate values are measured and returned as distinct pulses for each heartbeat. These pulses can potentially be used to determine an analogue heart-rate using a transducer. Each pulse has a duration of 150 ms or higher.

This conditioning system was designed for a very particular type of sensor input, and might need significant adjustment to accommodate sensor input which does not have a DC component of 1.5 V or a heartbeat signal amplitude of 33.30 mVpk. Additionally, if there is a new noise signal which falls in the range of 0.8 Hz to 2.5 Hz, it is likely to distort the signal and may prevent accurate conditioning and interpretation of the heart-rate.

3.2. Lessons learnt

1. Sometimes the more component which has more functionality is the less ideal option for the simple application at hand.

2. Just because others aren't following a certain method, doesn't mean the method isn't correct.

3. Asking for help when you're stuck can save you a significant amount of time.

Bibliography

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[6] Electronics Tutorials, *Op-Amp Comparator*, 2018. [Online]. Available: https://www.electronics-tutorials.ws/opamp/op-amp-comparator.html

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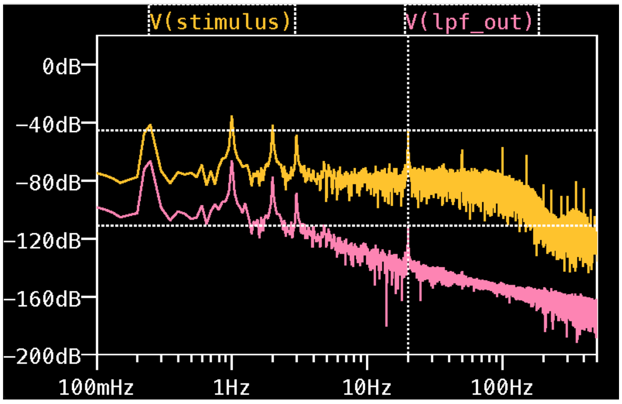
Appendix A

Simulation results: frequency analysis



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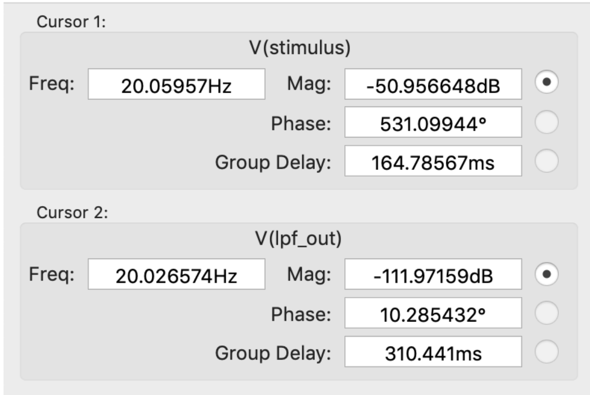

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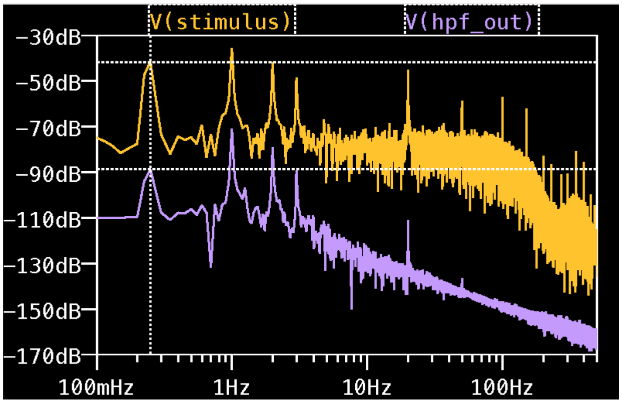

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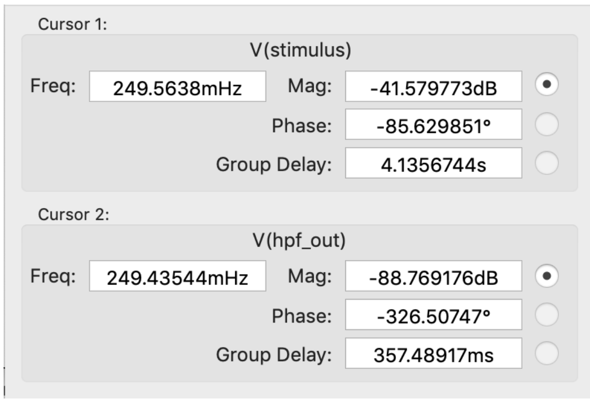
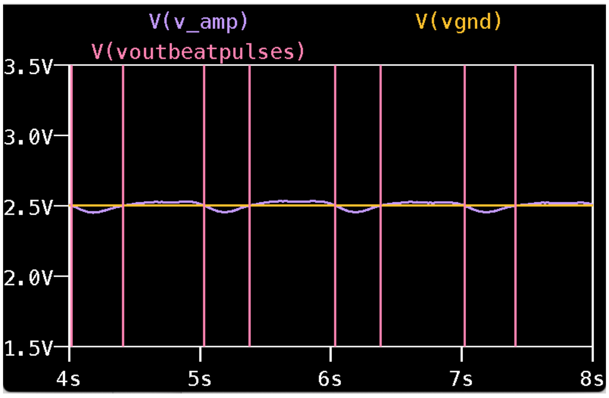


(d)

Figure A.1: Frequency analysis of low-pass and high-pass filters. (a) Frequency response of low-pass filter. (b) Plot values at 20 Hz. (c) Frequency response of high-pass filter. (d) Plot values at 250 mHz.

Appendix B

Simulation results: thresholding analysis



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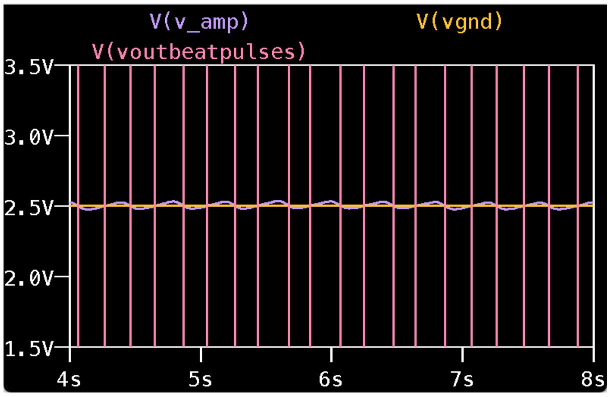

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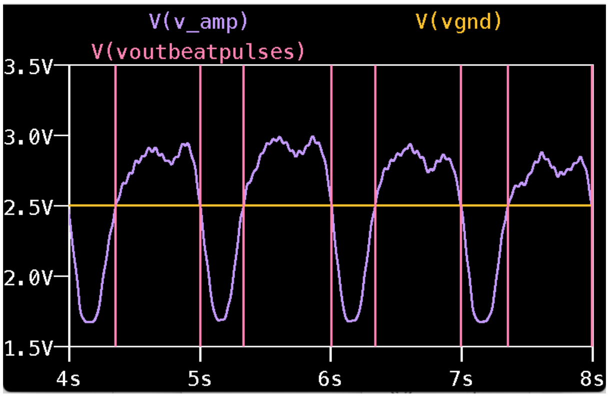

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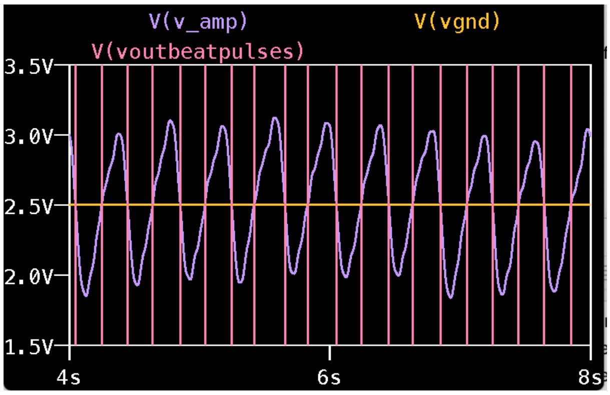
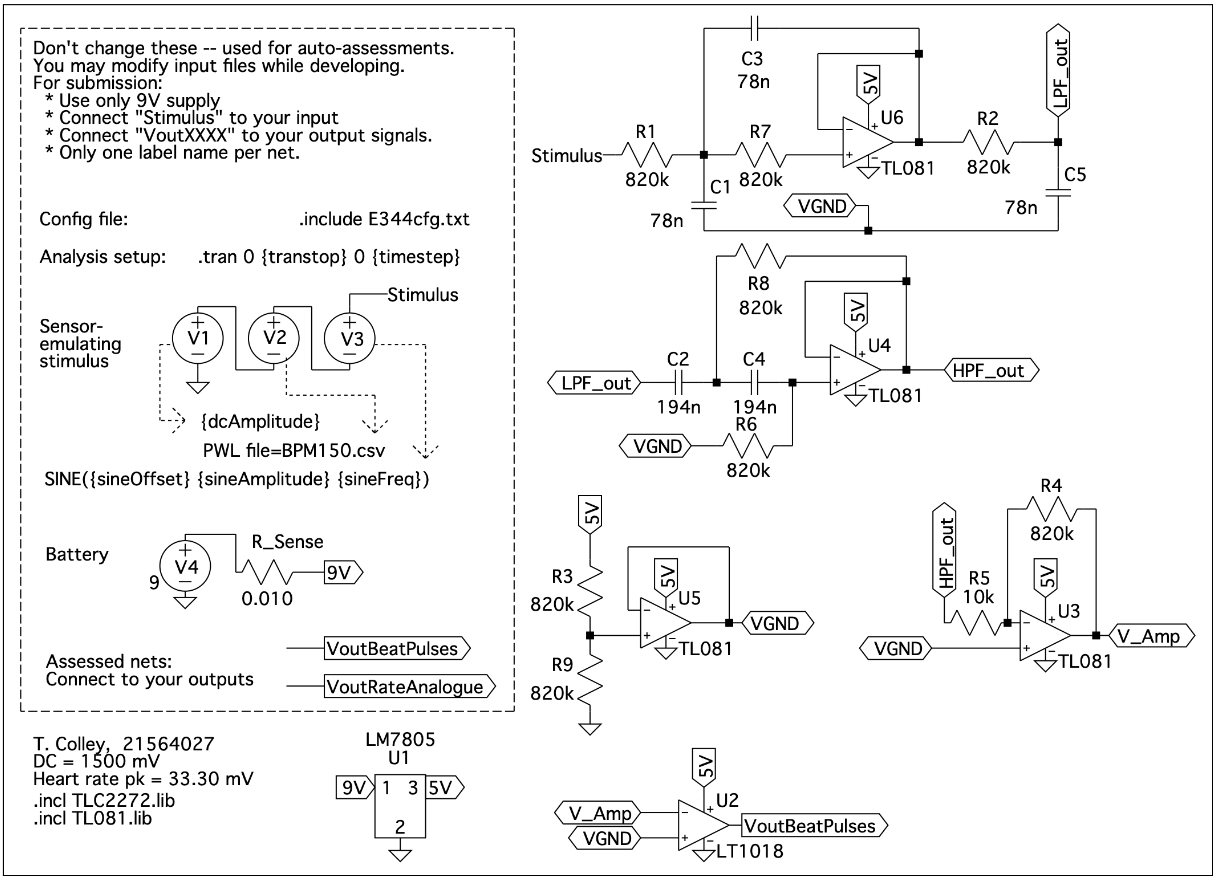


(d)

Figure B.1: Thresholding demonstration with specification deviations. (a) Negative deviation applied at 60 bpm. (b) Negative deviation applied at 150 bpm. (c) Positive deviation applied at 60 bpm. (d) Positive deviation applied at 150 bpm.

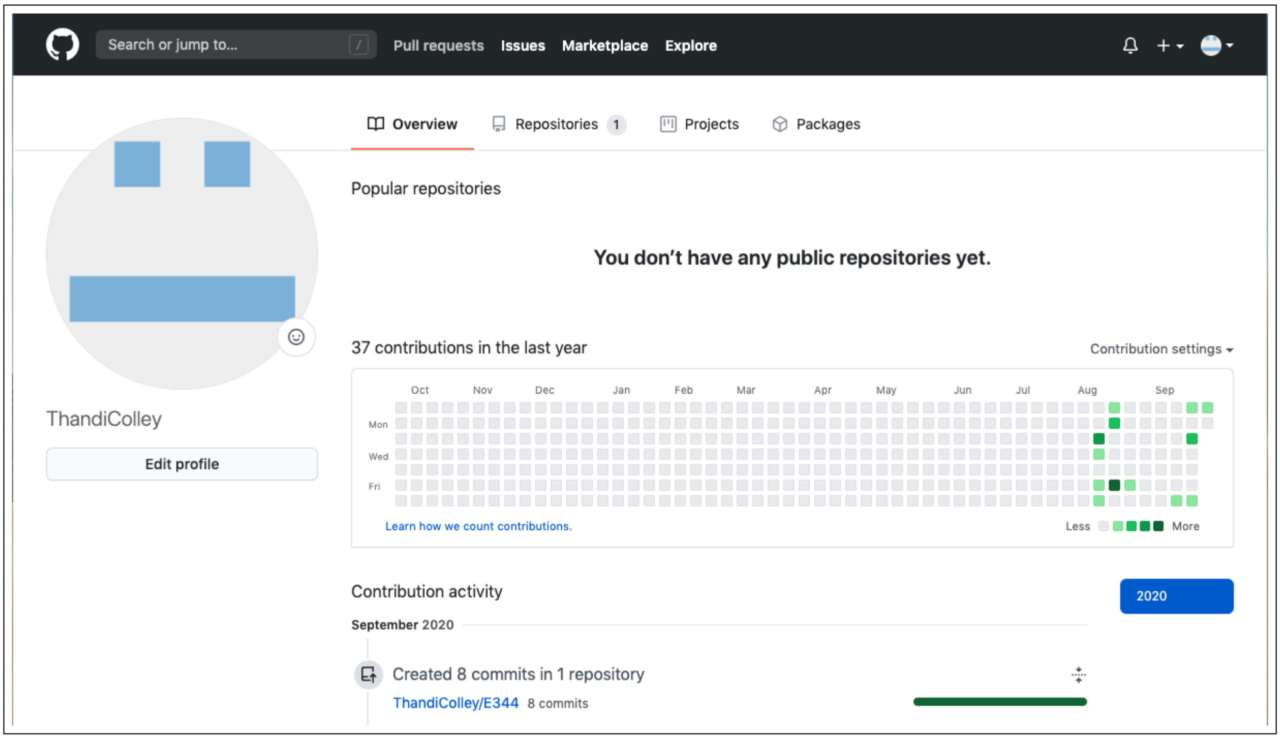
Appendix C

Circuit diagram



Appendix D

GitHub Activity Heatmap



Appendix E

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, Thandi Colley 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: 29 September 2020

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