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E344 Assignment 3

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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.

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Nomenclature

update these

Variables and functions

$p(x)$	Probability density function with respect to variable x.
$P(A)$	Probability of event A occurring.
ε	The Bayes error.
ε_u	The Bhattacharyya bound.
B	The Bhattacharyya distance.
s	An HMM state. A subscript is used to refer to a particular state, e.g. s_i refers to the i^{th} state of an HMM.
$\mathbf{S}$	A set of HMM states.
$\mathbf{F}$	A set of frames.
$\mathbf{o}_f$	Observation (feature) vector associated with frame f.
$\gamma_s(\mathbf{o}_f)$	A posteriori probability of the observation vector $\mathbf{o}_f$ being generated by HMM state s.
μ	Statistical mean vector.
Σ	Statistical covariance matrix.
$L(\mathbf{S})$	Log likelihood of the set of HMM states $\mathbf{S}$ generating the training set observation vectors assigned to the states in that set.
$\mathcal{N}(\mathbf{x}\|\mu, \Sigma)$	Multivariate Gaussian PDF with mean μ and covariance matrix Σ.
a_{ij}	The probability of a transition from HMM state s_i to state s_j.
N	Total number of frames or number of tokens, depending on the context.
D	Number of deletion errors.
I	Number of insertion errors.
S	Number of substitution errors.

Acronyms and abbreviations

update this

AE	Afrikaans English
AID	accent identification
ASR	automatic speech recognition
AST	African Speech Technology
CE	Cape Flats English
DCD	dialect-context-dependent
DNN	deep neural network
G2P	grapheme-to-phoneme
GMM	Gaussian mixture model
HMM	hidden Markov model
HTK	Hidden Markov Model Toolkit
IE	Indian South African English
IPA	International Phonetic Alphabet
LM	language model
LMS	language model scaling factor
MFCC	Mel-frequency cepstral coefficient
MLLR	maximum likelihood linear regression
OOV	out-of-vocabulary
PD	pronunciation dictionary
PDF	probability density function
SAE	South African English
SAMPA	Speech Assessment Methods Phonetic Alphabet
PWM	Pulse Width Modulation
LPF	Low Pass Filter
HPF	High Pass Filter
BPM	Beats Per Minute
BJT	Bipolar Junction Transistor

Chapter 1

System design

1.1. System overview

This report documents the design process of both a temperature sensor and heart rate monitor as well as calibration analysis for further Arduino processing.

For the **temperature sensor** we wish to remove a dc offset from the retrieved data and apply amplification via a differential amplifier to allow for further accuracy upon measurement. Alongside this noise reduction is implemented with the use a sufficiently calibrated low pass filter. For the **heart rate monitor** the retrieved signal is first processed via both a low- and high pass filter to remove any excess noise and stabilise the heart rate peaks for further conditioning. The signal is then amplified to allow improved accuracy when placing a threshold. This threshold allows a comparator to transform a heart beat signal into correlating pulses, triggered at every beat. The pulses are then extended to meet the duration requirement as set out by the assignment overview of 150ms and ensure uniformity.This was executed using a monostable multi-vibrator. More on this later. To supply 5V power to both circuits we use a **linear voltage regulator** to step down 9V-5V.

The **available current** of the device is specified as 100 mA - thus the use of large resistors to ensure low current draw and opting only for the use of amplifiers where necessities. From the both assignment 1 and 2 we measure these current draws as 10 mA and 8 mA respectively with is well below this requirement.

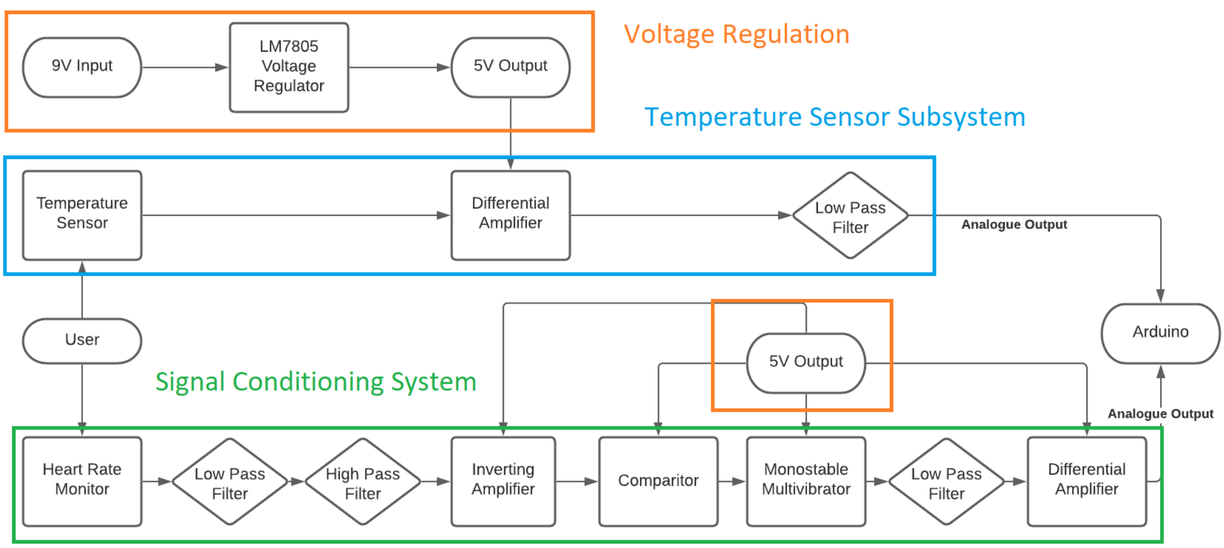


Figure 1.1: System diagram

Chapter 2

Voltage regulation

2.1. Introduction

The goal of this section is to successfully design and test multiple voltage regulator options to step down a 9V battery supply to the 5V output required. We evaluate two of the most common voltage regulators options, namely, a Linear Voltage Regulator [LM7805] and Switchmode Regulator [LM2595]. We gather information for circuitry design from data sheets found in [1] [LM7805] and [2] [LM2595]. `References.bib` file.

2.2. Design

2.2.1. Linear Voltage Regulator

We gauge the typical circuit design for a LM7805 Linear Voltage Regulator from it's data sheet [1] and use the recommended values of $C_1 = 330$ nF and $C_2 = 110$ nF to complete the circuit. See circuit in Appendix C.

We calculate the resistance of the the load from the specifications given as:

$$R_{load} = \frac{V_{out}}{I_{out}} = \frac{5}{0.1} = 50\,\Omega. \tag{2.1}$$

1. We can approximate the current flowing into the regulator as

$$I_{in} = I_{load} + I_{quiescent} = 102mA. \tag{2.2}$$

   where the typical quiescent current can be found as 2mA from the data sheet. [1]

2. By using Ohm's formula we can calculate the power supplied by the 9VDC supply as

$$P_{9V} = V_{in} \times I_{in} = 918mW. \tag{2.3}$$

3. Furthermore the efficiency can be calculated as

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{load}}{P_{9V}} \times 100 = \frac{5 \times 0.1}{0.918} \times 100 = 54.47\%. \tag{2.4}$$

   This is not great but expected.

2.2.2. Switchmode Regulator

This voltage regulator makes use of an switching action and an capacitor to supply an overall average output voltage We design the circuit stated in the data sheet [2].

Starting by choosing a value for R_1 as $1\,\mathrm{k}\Omega$

$$R_2 = (\frac{V_{out}}{V_{ref}} - 1) \times R_1 = 3.065\,\mathrm{k}\Omega. \tag{2.5}$$

taking V_{ref} as 1.23 V - as stated by the data sheet. [2]

From the provided figures in [2] with i_{rated} as 1A we gauge $L_1 = 47\,\mu$H and $C_{out} = 220\,\mu$F. We calculate

$$C_{ff} = (\frac{1}{31 \times 10^3 \times R_2}) = (\frac{1}{31 \times 10^3 \times 3065}) = 10.525nF. \tag{2.6}$$

From the table in [2] we read $C_{in} = 220\,\mu$F. See circuit in Appendix C.

1. We measure the current average flowing into the regulator as 58 mA.

2. By using Ohm's formula we can calculate the power supplied by the 9VDC supply as

$$P_{9V} = V_{in} \times I_{in} = 520\,\mathrm{m}W. \tag{2.7}$$

3. Furthermore the efficiency can be calculated as

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{load}}{P9V} \times 100 = 96.15\%. \tag{2.8}$$

This is very good.

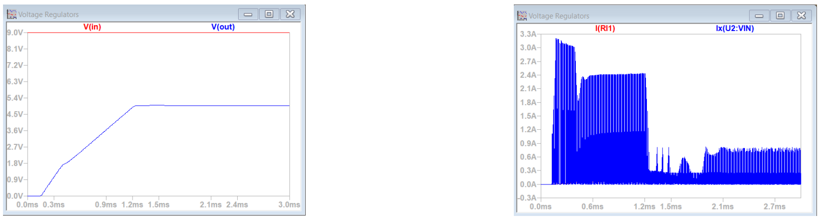
2.3. Results

2.3.1. Linear Voltage Regulator

(a) (b)

Figure 2.1: Simulated result of the Linear Voltage Regulators (a)Graph of measured input and output voltages (b) Graph of measured input and output currents

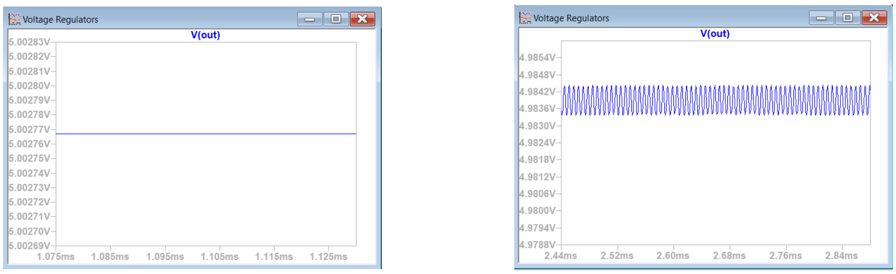
2.3.2. Switchmode Regulator



(a) (b)

Figure 2.2: Simulated result of the Switchmode Voltage Regulators (a)Graph of measured input and output voltages (b) Graph of measured input and output currents

2.3.3. Noise Comparison



(a) (b)

Figure 2.3: Simulated noise result of the Switchmode- and Linear Voltage Regulators (a)Noise output of Linear Voltage Regulator (b) Noise output of Switchmode Regulator

Table 2.1: Comparison of voltage regulators.

Voltage Regulators	Currents		Voltages	
	I_{In} [mA]	I_{load} [mA]	V_{In} [V]	V_{Out} [V]
Linear Voltage Regulator	105	100	9	5
Switchmode Regulator	58	100	9	5

2.4. Summary

From the simulation we can see that both voltage regulators behave very much as predicted. The efficiency is of the Linear Voltage Regulator is quite low with the noise little to non and a voltage drop of 1.7 V.The Switchmode Voltage Regulated provides much better efficiency but at the cost of more noise and a smaller dropout voltage of 0.78 V.Taken these findings into account we settle on the use of the linear regulator. This is due to the resulting noise from the Switchmode regulator simply being insufficiently high. This comes at the cost of efficiency but can be combated by limiting current and thus power consumption.

Chapter 3

Temperature sensor conditioning circuit

3.1. Intro

We wish to design a temperature sensor circuit able to digitise and analyse the temperature of the human body. The temperature sensor in question however consist of measurement range which exceeds that needed for our use (only ranging between 32° to 42° C). Using this full range will lead to unnecessary accuracy loss and we therefore opt for a more specialised approach. Instead, we choose to only work within the predefined range and to amplify the retrieved output. The result of this process will produce an output within optimal range (0 to 5 V) for further ADC Arduino processing.

3.2. Design

3.2.1. Differential Amplifier

Given the temperature sensor specification of a 420mV output at 0°C and a temperature gradient of 50mV/1°C we find:

$$V_{38^\circ} = V_{0^\circ} + T_{gradient} \times T_{38^\circ} = 2.32\,\mathrm{V}. \tag{3.1}$$

We pick 38°C as this represent the midpoint around which we wish to optimise.

$$V_{42^\circ} = V_{0^\circ} + T_{gradient} \times T_{42^\circ} = 2.52\,\mathrm{V}. \tag{3.2}$$

$$V_{34^\circ} = V_{0^\circ} + T_{gradient} \times T_{34^\circ} = 2.12\,\mathrm{V}. \tag{3.3}$$

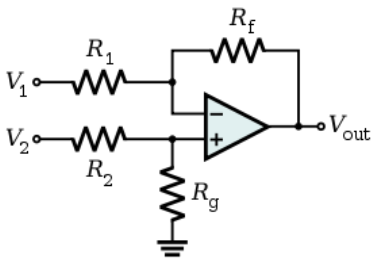


Figure 3.1: Basic Differential Amplifier Diagram

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Assuming:

$$R_f = R_g. \tag{3.4}$$

and

$$R_1 = R_2. \tag{3.5}$$

we obtain and equation

$$V_{out} = \frac{R_f}{R_1} \times (V2 - V1). \tag{3.6}$$

for the midpoint:

$$\frac{V_{max}}{2} = \alpha \times (V_{42^\circ} - V_{38^\circ}). \tag{3.7}$$

$$\frac{V_{max}}{2} = \alpha \times (0.2). \tag{3.8}$$

We notice that choosing an alpha value of 10 will leave use with a range of swing of 2V around the midpoint without getting too close to the rails.

We also know that

$$\alpha = \frac{R_f}{R_1} = 10. \tag{3.9}$$

Thus we choose R1 = 10 kΩ and Rf = 100 kΩ.

V1 will be a constant offset value to linearize the midpoint around 0V. Using equation 3.6.

$$V_{midpoint} = \frac{R_f}{R_1} \times (V_{38^\circ} - V1). \tag{3.10}$$

We calculate $V_1 = 2.07$. Since we only have access to 5V voltage supply we will have to make use of voltage division methods to obtain this (2.07V) value.

$$V_o = (\frac{R_a}{R_a + R_b}) \times V_s. \tag{3.11}$$

Choosing R_a as 3.3 kΩ we find $R_b = 4.671$ kΩ We also add a unity gain buffer to stabilise our 2.07V required input from the voltage divider. We expect the TLC2272 to draw about 3 mA and and the TL081 buffer 2.8 mA.Along with the resistors a small current aswell. This should lead to a total current usage of about 9 mA. See circuit in appendix C.

3.2.2. Low Pass Filter

We decide on a second order low pass filter as this generates a slope of -40dB giving us a sharper and more accurate cutoff.We settle on a RC filter to save cost and simplify the design.

The designed filter is as seen below from [3] :

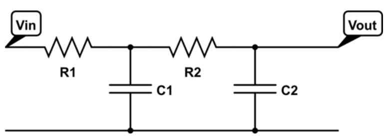


Figure 3.2: Second Order RC Low Pass Filter

.

Choosing $R_1 = R_2$ and $C_1 = C_2$ with our cut-off frequency (f_c) of 50 Hz.

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} = \frac{1}{2\pi RC}. \tag{3.12}$$

and choosing C as $1\,\mu$F we find R $= 3.183\,\mathrm{k}\Omega$.

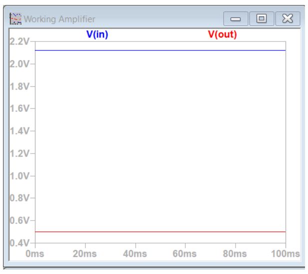
We later find that even further stabilizing of the output is required and find that $R_2 = 7\,\mathrm{k}\Omega$ and $R_1 = 5\,\mathrm{k}\Omega$ deliver a voltage deviation of less than 50 mV. When recalculated , these values give us a cut off frequency of 26.9 Hz - which is still fulfills the set requirement of 50 Hz. See circuit in appendix C.

We calculate the rise time as

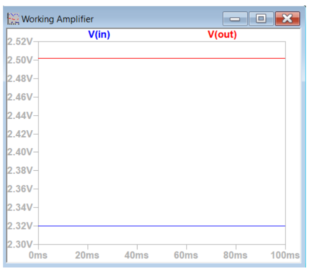
$$t_r = \frac{1.8}{w_r} = \frac{1}{2\pi f_c} = 10.6ms. \tag{3.13}$$

3.3. Results

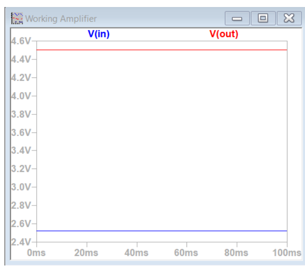
3.3.1. Amplifier



(a)



(b)



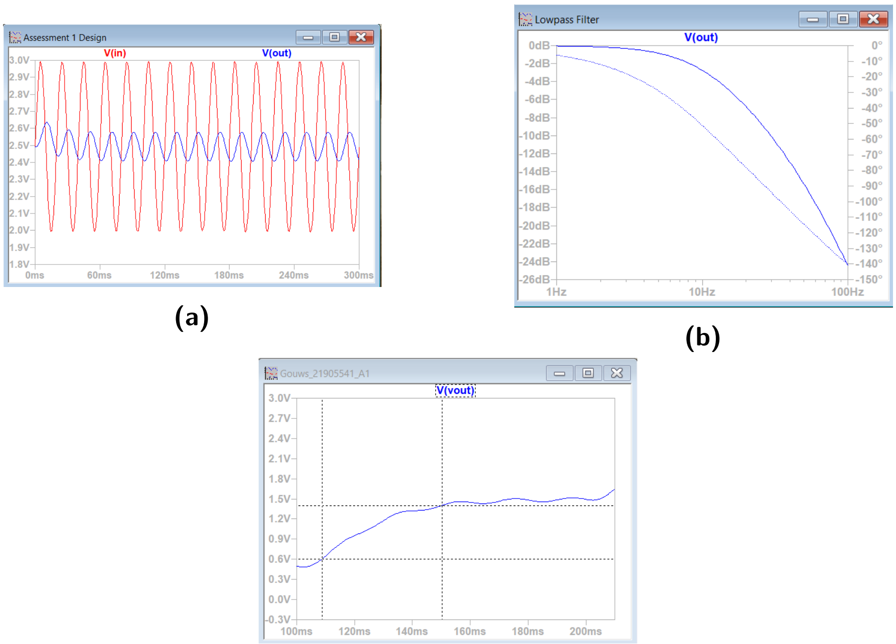
(c)

Figure 3.3: Simulated result of the Differential Amplifier (a) Lower boundary input and output graph (b) Midpoint input and output graph (c) Upper boundary input and output graph

Table 3.1: Amplifier Outputs.

Amplifier Outputs	Voltages		
	V_{sensor}	V_{Out}	[V]
Lower Boundry	2.12	0.5	
Midpoint	2.32	2.5	
Upper Boundry	2.52	4.5	

3.3.2. Low Pass Filter



(a) (b) (c)

Figure 3.4: Simulated result of the second order low pass filter (a) Noise suppression graph (b) Attenuation bode plot (c) Rise time graph

Table 3.2: Low Pass Filter Simulation Results.

Voltage Regulators	Noise		Voltages	
	Before LPF [mV]	After LPF [mV]	Cuttoff Frequency [Hz]	Rise time [ms]
Low Pass Filter	500	76	10.9	41

3.4. Summary

From these simulation we see the amplifier minimum to maximum output ranges from 0.5 to 4.5 V as calculated and that the LPF suppresses the noise to a deviation level of under 80 mV. The LPF also attenuates all frequencies > 10.5 Hz with a rise time of 41 ms. All these values meet the necessary requirements.

Chapter 4

Heart rate sensor

4.1. Introduction

For the heart rate monitor the incoming heart beat signal requires noise conditioning via both a high pass filter [4], low pass filter [5] and amplifier [6] before being converted into finite pulses [7]. These pulses must adhere to a time delay greater than 150ms. The signal also needs to be converted into a correlating analogue output of between 0 to 5 V [8]- compatible for further Arduino processing. In this section we will design, implement and analyse each of these elements.We will also make use of some previously designed elements such as the virtual ground and voltage regulator as designed in Assignment 1. [9]

4.2. Design

Evaluating the frequency spectrum of a heart beat signal (shown in Figure 4.1) we notice that the fundamental frequency of a heart beat (between 50 to 150 bpm) should lie between the range of 1 to 2.5 kHz. Therefore we can denote that the lower frequency peaks seen in Figure 4.1 accounts for the slow changing sinus wave seen in the variation of signal peaks with the higher frequency peaks resulting due to noise.

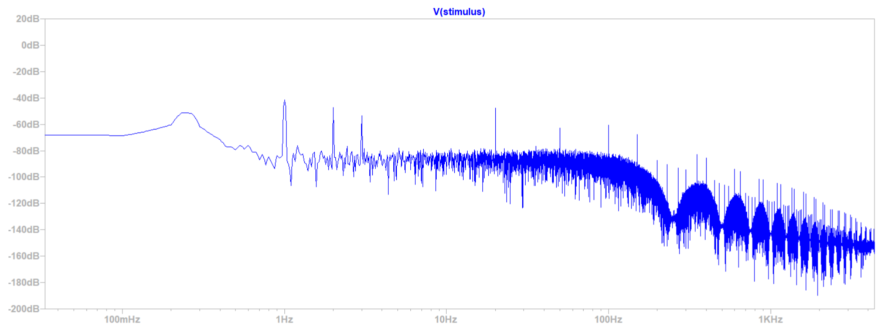


Figure 4.1: Frequency Domain Spectrum of a Unfiltered Heart Signal

4.2.1. Signal Conditioning

Third Order Passive Low Pass Filter

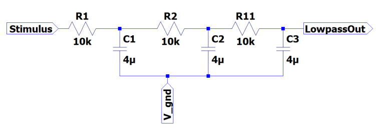


Figure 4.2: Third Order Passive Low Pass Filter

Choosing $R_1 = R_2 = R_3$ and $C_1 = C_2 = C_3$ $4\,\mu$F in Figure 4.2 with a cut-off frequency (f_c) at 4 Hz.

$$f_c = \frac{1}{2\pi\sqrt[3]{R_1 C_1 R_2 C_2 R_3 C_3}} = \frac{1}{2\pi RC}. \tag{4.1}$$

We find R $= 9.95\,\text{k}\Omega \approx 10\,\text{k}\Omega$.

Third Order Passive High Pass Filter

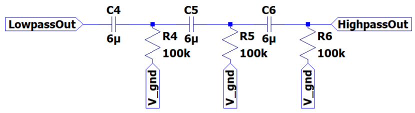


Figure 4.3: Third Order Passive High Pass Filter

Choosing $R_4 = R_5 = R_6$ and $C_4 = C_5 = C_6 = 2\,\mu$F in Figure 4.3 with a cut-off frequency (f_c) at 0.8 Hz.

$$f_c = \frac{1}{2\pi\sqrt[3]{R_4 C_4 R_5 C_5 R_6 C_6}} = \frac{1}{2\pi RC}. \tag{4.2}$$

We find R $= 99.5\,\text{k}\Omega \approx 100\,\text{k}\Omega$.After analyzing the bode plot the capacitance was adjusted to $6\,\mu$F to achieve the desired cut-off frequency. After filtering the signal is amplified using a TL081 amplifier with a $VIN_{min} = 0$V ; $VIN_{max} = 5$V ; $V_{dif} = 30$V placed in a non-inverting amplifier circuit to increase accuracy when placing a threshold. Specifics on the design of the non-inverting amplifier circuit can be found in Appendix C - B.

4.2.2. Thresholding and Pulsed Output

Voltage Comparator

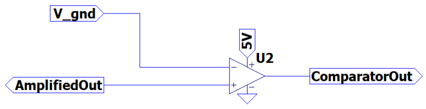


Figure 4.4: Voltage Comparator

Using the amplified signal centred around 2.5V / virtual ground and a threshold voltage (V_{ref}) placed at this centre (2.5V) the comparator will deliver a high pulsed output at the start of an upward peak aka a heart beat.The threshold is chosen in the centre due to the small pk-pk amplitude (100 mA) meaning that slight displacement of the threshold voltage could result in little to no tolerance of noise or deviation. We do however ensure that our amplification is adequate to allow for a 10% pk-pk deviation without any loss of accuracy.For input values > 2.5 V the comparator will output the top rail (5V) and for values < 2.5 V the bottom rail (0V).

Monostable Multi-Vibrator

Due to noise and variations the pulsed output produced by the comparator will not be identical but vary in duration.To ensure a uniform final output we make use a monostable multi-vibrator to extend all pulsed time frames to a duration of our desire.

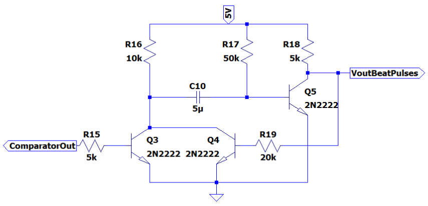


Figure 4.5: Monostable Multi-vibrator

For the circuit seen in Figure 4.5 we chose $R_{15} = 5\text{k}\Omega$ to ensure the BJT's operate in saturation.We make use of 2N2222 NPN transistors as these are easily accessible in the labs. Since $V_{out} = V_{cc} - I_{CQ2} \times \text{R}_{18}$ - we choose $R_{18} = 5\text{k}\Omega$ to ensure $V_{out} > 4\text{V}$ yet minimizing current consumption. The resistor values of R_{16} and R_{19} are of little significance and therefore chosen as $10\text{k}\Omega$ and $20\text{k}\Omega$ respectively.

$$\tau = \frac{R_{12}C_{10}}{1.37} > 150ms. \tag{4.3}$$

Choosing R_{12} as $50\text{k}\Omega$ and $\tau = 180$ ms we find $C_{10} = 5\mu\text{F}$.

4.2.3. Analogue Transducer

Noting that as with PWM a higher frequency of pulses will result in a higher average DC output we wish to produce the required analogue voltage output by scaling and amplifying this DC value. A second order Butterworth filter is used to obtain this value as designed in Appendix C - B. To scale the correlated DC output we use a differential amplifier with the same design process followed in Report 1 [9] section 3.2.1. The specific design for this assignment can also be viewed in Appendix C - B. The differential amplifier is designed to ensure an output range > 3.5V, centered around 2.5V for optimal swing.The final circuitry can be seen in figure 4.6. From the design we expect to see calculated output values of 4.85V @ 150 bpm ; 2,5V @ 100 bpm ; 150 mV @ 50 bpm.

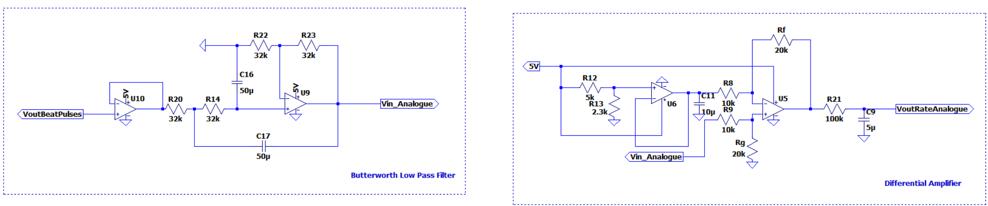
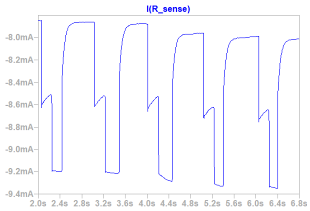


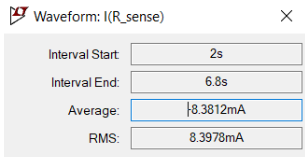
Figure 4.6: Analogue Transducer Circuit

4.3. Results

Current Draw



(a)



(b) Current Draw of Circuit

Figure 4.7b shows the the current draw of the circuit is well below the assignment specification of 50mA.

Frequency Response

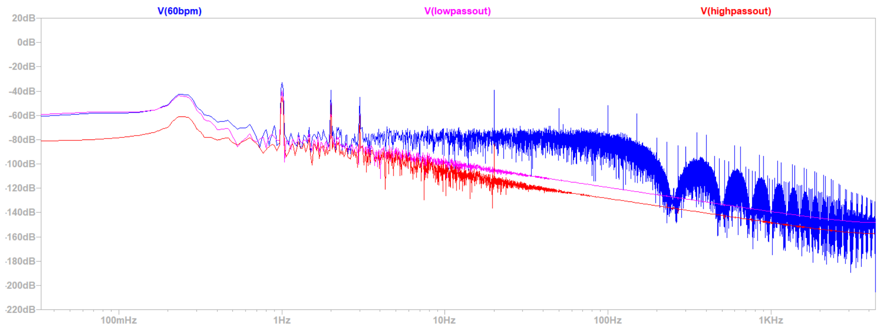
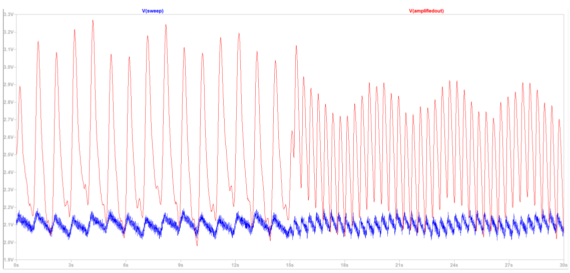


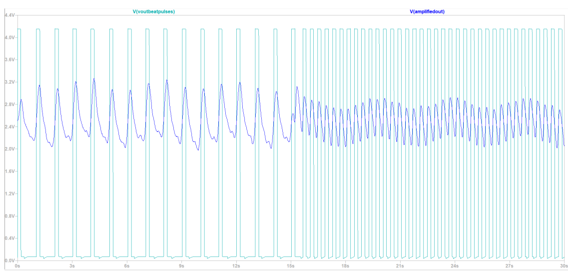
Figure 4.8: Frequency Response of Filter Output

Figure 4.8 shows the suppression the higher noise frequency by the LPF (pink graph) and the dampened curve at around 0.8 Hz due to the HPF (red graph).

Full Range Input and Output



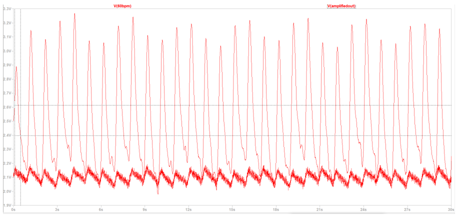
(a) Full Range Conditioned Output



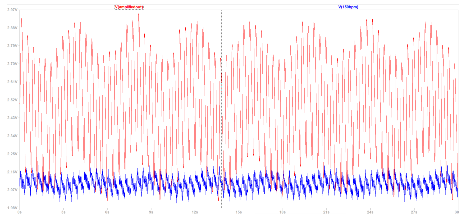
(b) Full Range Pulsed Output

From Figure 4.9a and Figure 4.9b we can see that the circuit behaves correctly.

Thresholding and Deviation



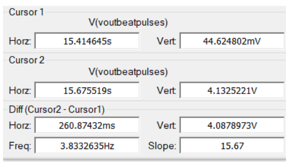
(a) 60 bpm threshold placement and variation



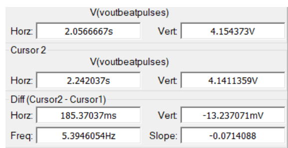
(b) 150 bpm threshold placement and variation

In Figure 4.10a and Figure 4.10b the cursors indicate a 10% pk-pk deviation allowable, showing that even with these deviations accurate results will still be generated.

Pulsed Output Specification



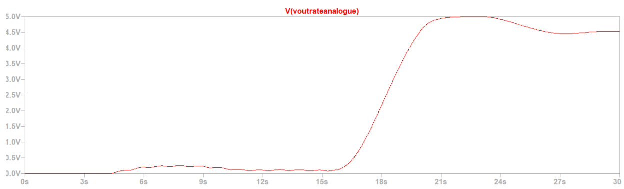
(a) Measured output voltage range.



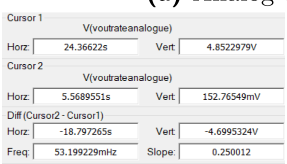
(b) Measured output duration

Therefore the measured output can be seen to meet the design requirement of high > 4V , low < 0.1 V (Figure 4.11a) with duration > 150 ms(4.11b).

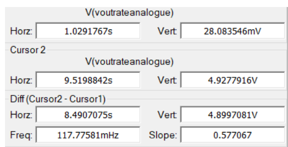
Analogue Transducer Output



(a) Analog output from 50 bmp and to 150 bpm



(b) Measured analogue output voltage range



(c) Measured analogue 5% settling time

The circuit meets the requirement of $V_{range} > 3.5$V and a response time of no more than 10s.

4.4. Summary

The circuit performs very much as expected and meets all necessary requirements

Chapter 5

Calibration and digitisation

5.1. Temperature sensor

Include flow diagram of code or pseudocode as a list.

5.1.1. Analytical Design

Analytical expectations (calculations of what you expected the calibration to be) Please include a 10-bit make-believe ADC in your calculations

5.1.2. Empirical Design

Based on measurements, calculate calibration (to adapt or replace analytic design. Compare analytic solution to empirical solution (plot?)
Include assessment of your calibration.

5.2. Heart rate sensor

No need to include the 10-bit ADC in this section.

Bibliography

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[9] E. Gouws, "Temperature Sensor," in *E344 Assignment 1 (ITSC 2020)*, July 2020, pp. 1–14.

Appendix A

Social contract

Sign and inlcude.

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

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, ... 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.

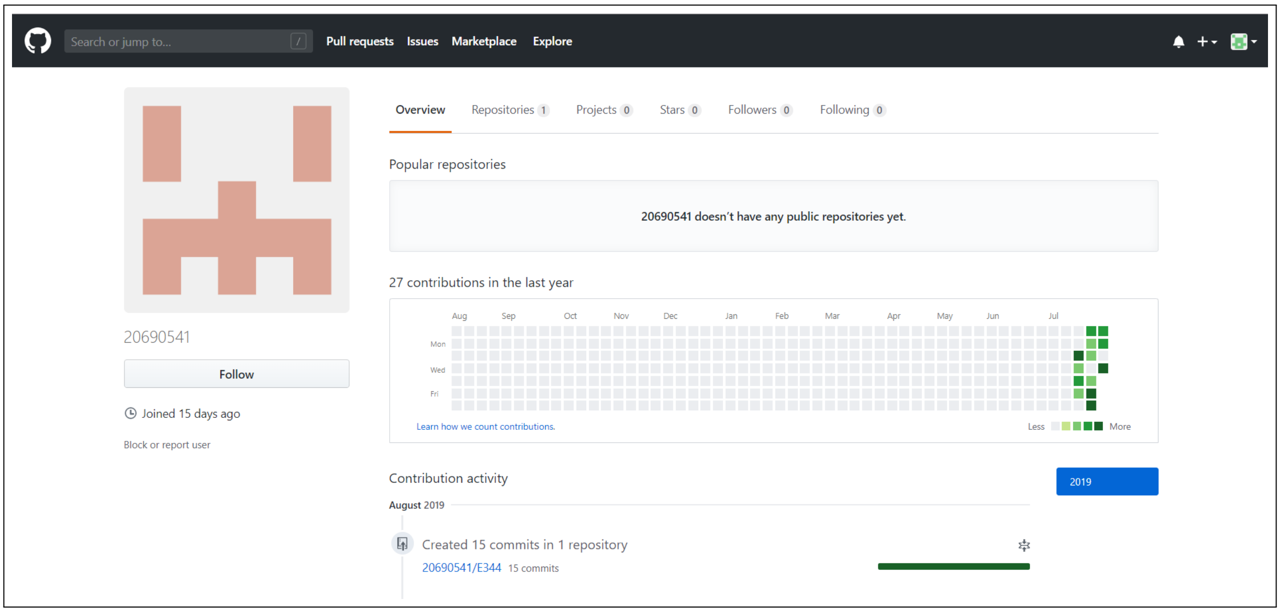
Signature: .... Date: ....

1

Appendix B

GitHub Activity Heatmap

Take a screenshot of your github version control activity heatmap and insert here.



Appendix C

A. Temperature sensor circuitry

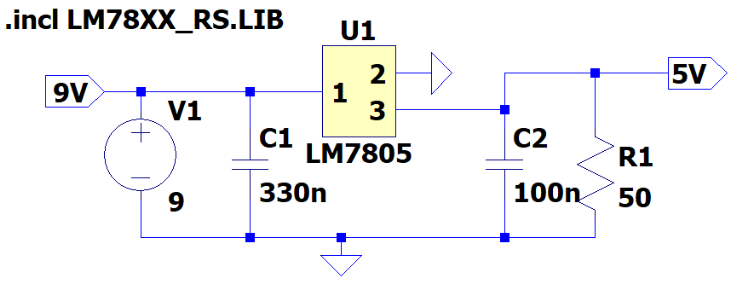


Figure 1: Linear Voltage Regulator LTSpice Circuit Diagram

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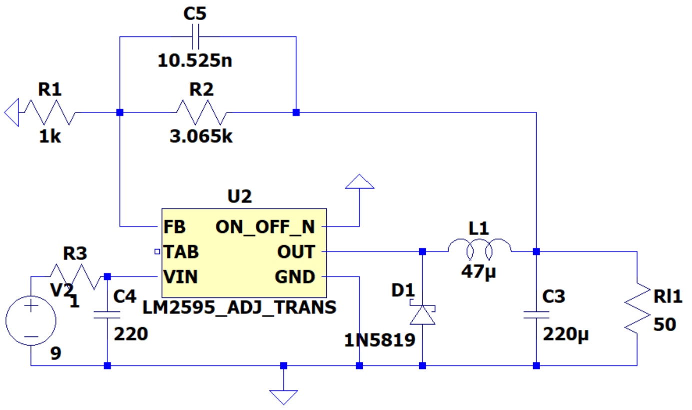

Figure 2: Switchmode Voltage Regulator LTSpice Circuit Diagram

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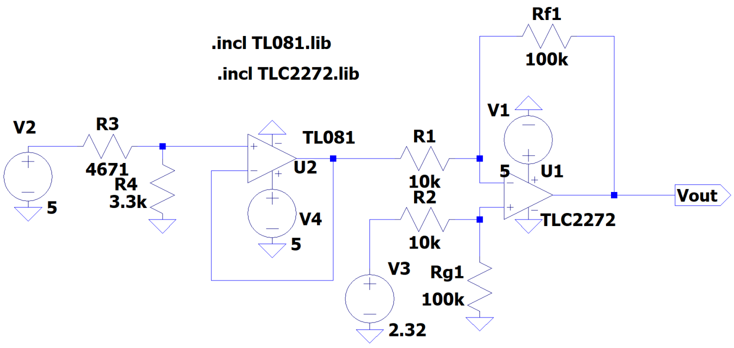

Figure 3: Amplifier Circuit

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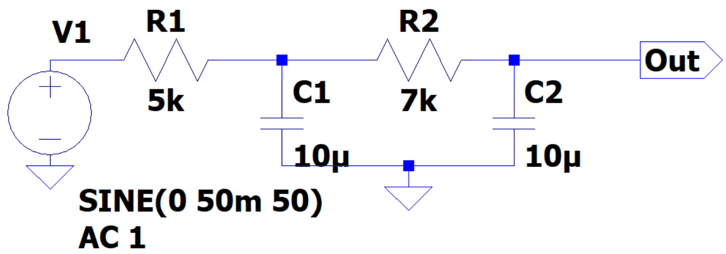

Figure 4: Low Pass Filter Circuit

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B. Non-Inverting Amplifier

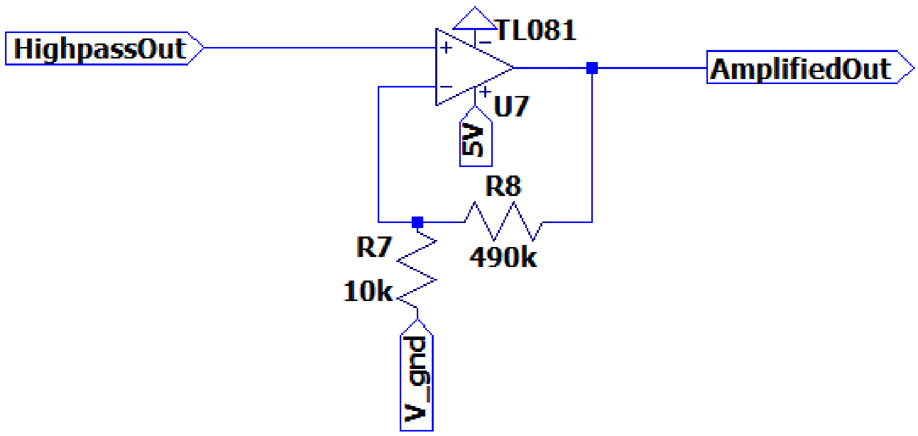

Figure 5: Non-Inverting Amplifier

Since the current pk-pk of the signal is 2 mV we wish to increase this quite significantly, opting for a gain (A_v) of 50.

$$A_v = 1 + \frac{R_8}{R_7} = 1 + \frac{490\,\mathrm{k}\Omega}{10\,\mathrm{k}\Omega} = 50 \tag{1}$$

C. Second Order Butterworth Filter

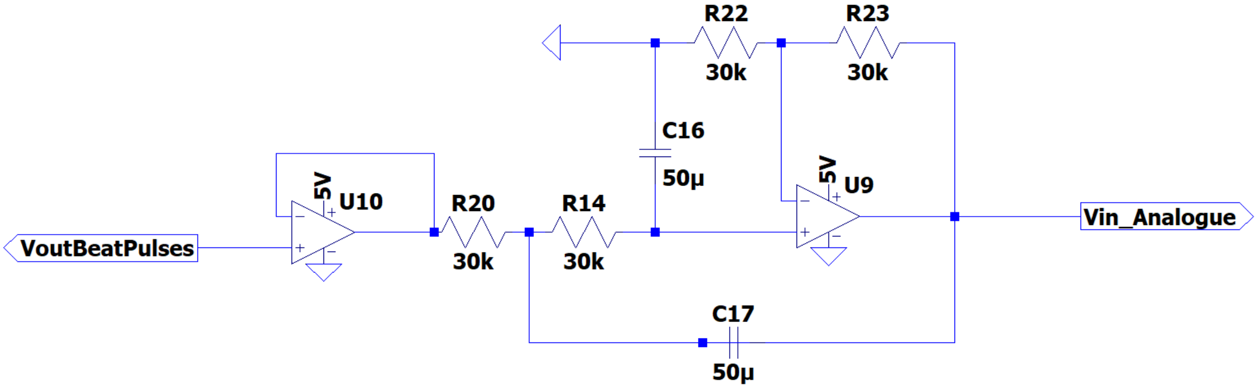

Figure 6: Second Order Butterworth Filter

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

With C = 50 μF and a cutt- off frequency of 0.1 we find R = 31.8 kΩ = 32 kΩ

D. Differential Amplifier

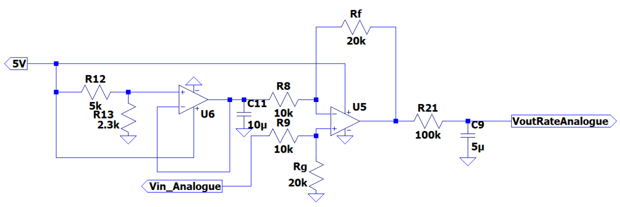

Figure 7: Differential Amplifier Circuit

Finding V_{out} at 50 bpm as 1.65V and V_{out} at 150 bpm as 4V we derive a midpoint voltage as 2.825V. Choosing $R_f = R_g$ and $R_1 = R_2$ we get

$$V_{out} = \frac{R_f}{R_1} \times (V2 - V1). \tag{3}$$

$$\frac{V_{max}}{2} = \alpha \times (V_{150} - V_{mid}). \tag{4}$$

$$2.5 = \alpha \times (1.175). \tag{5}$$

Choosing a gain of 2 will result in a swing of 2.35V. Therefore we choose Rf = 20 kΩ and R1 = 10 kΩ.

$V_1 = V_{mid}$ will be a constant offset value to linearize the midpoint around 2.5V. Using equation 3.6.

$$V_{midpoint} = \frac{R_f}{R_1} \times (V_{150} - V1). \tag{6}$$

We calculate $V_1 = 1.575$. We make use of a 5V supply and voltage division to achieve this value. A unity buffer is added for further stability around this point.

Based our final formula of

$$V_{out} = 2 \times (V_{in} - 1.575). \tag{7}$$

From the design We expect to see output values of 4.85V @ 150 bpm ; 2,5V @ 100 bpm ; 150 mV @ 50 bpm.