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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.

August 17, 2020

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Contents

List of Figures

List of Tables

Nomenclature

Variables and functions

η	Efficiency
ω_n	Natural Frequency
f_c	Cutoff Frequency
A_v	Gain
t_r	Rise time (90%)
V_{ref}	Reference Voltage

Acronyms and abbreviations

AC	Alternating Current
ADC	Analog-to-Digital Converter
DC	Direct Current

Chapter 1

System design

1.1. System overview

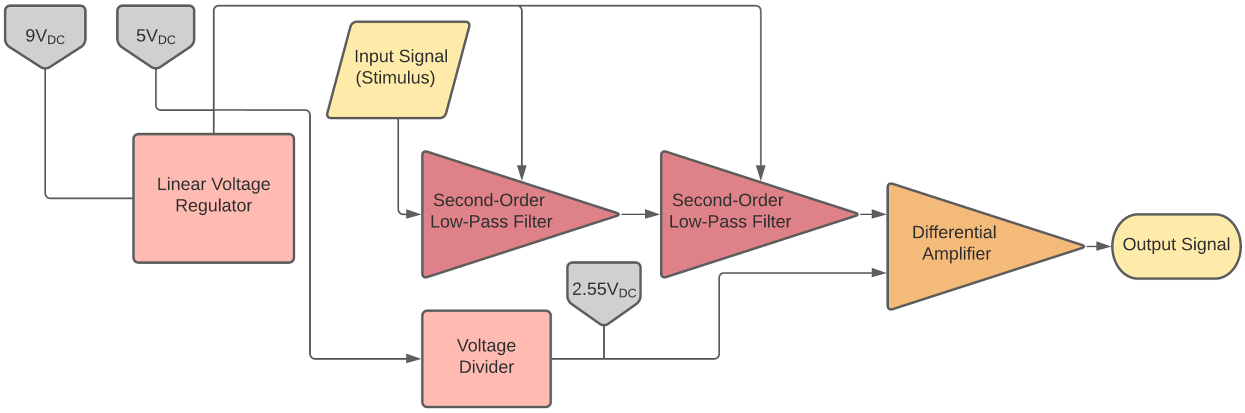


Figure 1.1: System Block Diagram

As part of the health monitoring system, which consists of an analogue temperature sensor and an optic heart rate monitor, a voltage regulation circuit is required, as well as a signal conditioning and amplification system. This report focuses on the design and implementation of the latter components. Figure 1.1 gives an overview of the combined system, where the voltage regulator supplies power to the circuital components responsible for filtering the signal, removing its offset, and then amplifying the signal which is originally received from an analog temperature sensor. Two second-order low-pass filters were cascaded to clear the signal of noise. This may seem excessive at first, but the cascaded setup allows for the use of less costly components (see Section 3.2), as well as producing an output signal subject to very low noise (see Section 3.3). Since the filtered signal still has a DC offset, and the amplifier needs a virtual ground, the voltage divider connects to the amplifier in such a way as to simultaneously remove the input DC offset and add the virtual ground. Finally, the differential amplifier increases the magnitude of the input signal to the degree needed at the input of a microcontroller ADC, which will be used to interpret the temperature sensor output. Note that this circuit design does not include a voltage buffer, as it was decided against upon noting that the desired output was easily obtained without a buffer, and omitting the buffer resulted in much lower current drawn from the battery (see Section 3.2), as well as resulting in lower total cost due to less components present in the circuit. Analysis and simulation of all circuits was done with the simulation software LTSpice.

Chapter 2

Voltage regulation

2.1. Introduction

Given a 9 V_{DC} battery, a voltage regulator is required to reduce the voltage level to 5 V_{DC}, as this is the level required by the operational amplifiers used in the rest of the circuit. Two voltage regulators were considered: the LM7805 linear regulator as well as the LM2595 switchmode regulator, which were both analysed with regards to efficiency and noise by means of calculations and simulations. According to the literature, the linear regulator does not really output noise, but has low power efficiency of around 50% for input and output of 9 V_{DC} and 5 V_{DC} [?] respectively. The switchmode regulator can provide power efficiency of around 85%, but outputs a considerable amount of noise [?]. With the aforementioned in mind, both of the regulators were simulated (Section 2.2) to determine the best trade-off between low noise and efficiency.

2.2. Design

The LM7805 chip and its required peripheral circuit is shown in Figure 2.1. Component values were obtained from the datasheet [?]. For testing purposes, a 50 Ω load was connected to the regulator, drawing 100 mA.

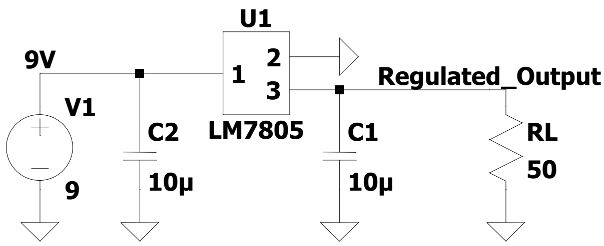


Figure 2.1: Linear Voltage Regulator

The LM2595 chip is shown in figure 2.2, built into the required peripheral circuit. Capacitor and inductor values were obtained from the datasheet [?]. Resistor values were calculated:

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) \qquad \text{where } V_{REF} = 1.23V$$

Selecting R_1 as 1 kΩ, with V_{out} as 5 V gives R_2 as 3065 Ω. For testing purposes, a 50 Ω load was connected to the regulator, drawing 100 mA.

Since the provided circuit includes a resistor (R_{sense}) between the voltage source and the voltage regulator, the voltage drop over the resistor will be $V = IR = (0.01238)(0.01) = 123.8\mu$V. This is negligible, as it is not nearly enough to approach the dropout voltages of the voltage regulators, which are 6.7 V for the LM7805 and 5.8 V for the LM2595 in the case of a 5 V output.

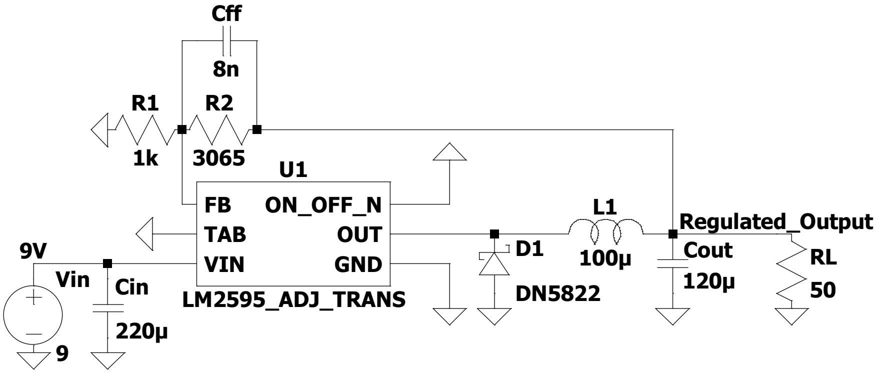


Figure 2.2: Switchmode Voltage Regulator

2.3. Results

The input and output power measurements are displayed in table 2.1. Comparing the efficiency of the respective regulators, it is clear that the switchmode regulator is considerably more efficient. However, simulation results in a settling time of 1.24 ms, which is quite slow. Furthermore, the switchmode regulator creates noise levels of up to 950 μV_{pp} in the output, as can be seen in figure 2.3, whereas the linear regulator produces almost no noise (figure 2.4). Noise is a problem, as the large gain of the differential amplifier will increase the noise levels, which will distort the output.

Table 2.1: Comparison of Voltage Regulators

	I_{in} [mA]	I_{out} [mA]	P_{in} [mW]	P_{out} [mW]	η [%]
LM7805	105.06	100.05	945.54	500.55	52.93
LM2595	57.54	99.65	517.86	496.6	95.89

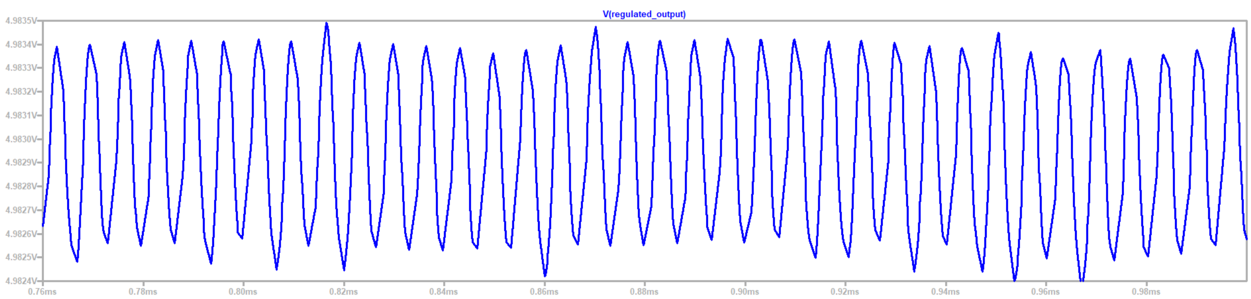


Figure 2.3: Switchmode Voltage Regulator Noise

The output graphs of the voltage regulators are shown in figures 2.4 and 2.5, and clearly demonstrate that both regulators produce the desired output current and voltage. The input current for the switchmode regulator is not shown as it obscures the graph, but it has an average value of 57.54 mA. All relevant values can be found in table 2.1.

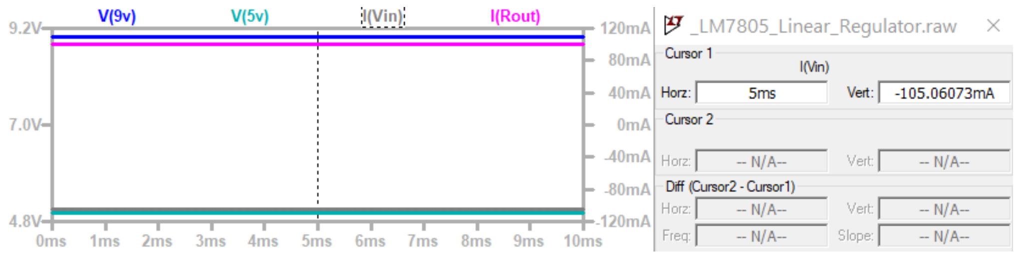


Figure 2.4: Linear Voltage Regulator Output

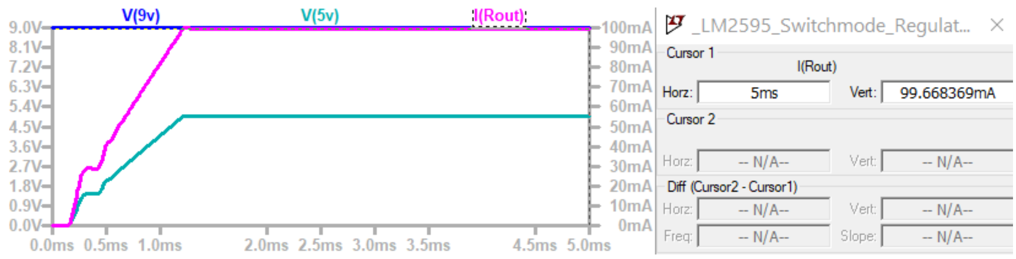


Figure 2.5: Switchmode Voltage Regulator Output

2.4. Summary

Concluding, it has been shown that both regulators behave as expected, but that the levels of noise present in the switchmode regulator make it unsuitable for the design at hand, as input signals, and thus the noise as well, will be amplified to levels of noise in the output signal that are unacceptable for an ADC input. The linear regulator will therefore be used. This choice was made despite the fact that the switchmode regulator is approximately 40% more efficient than the linear regulator. However, since the total current drawn is still very low, the efficiency is not a problem. However, it should be noted that the current drawn should be re-evaluated after the rest of the components have been connected to the regulator, in order to make sure that the current draw requirement still is met, and that the current needed is within the range that the regulator can supply.

Chapter 3

Temperature sensor conditioning circuit

3.1. Intro

The signal obtained from the temperature sensor presents as DC, with 50 Hz AC noise superimposed.The sensor output is too small for a ADC to take as input. Furthermore, the applicable range is only from 34°C to 42°C. The two aforementioned considerations necessitate amplification of the relevant part of the temperature sensor signal to a 0 to 5 V range for an ADC. To this end, a temperature sensor conditioning circuit is required, making use of a filter, an offset removing subcircuit, as well as an amplifier. The filter attenuates the AC signal present in the input signal in order to minimize noise. The offset removing subcircuit removes enough of the DC offset to ensure that the output signal is centered around 2.5 V, to ensure the largest possible output swing. Finally, the amplifier increases the magnitude of the input signal in order to be suitable as input for an ADC.

3.2. Design

The amplifier was designed first, as its gain serves as the determining factor for the amount of noise reduction that is required from the filter. A TLC2272 op-amp was chosen as it allows for an output very close to its rails. Since the output signal has to be centered around 2.5 V, a differential amplifier was decided upon, as the negative input can adjust the output offset. The zero-reference temperature sensor voltage (V_{zero}) is 440 mV, and increases by 35 mV for every 1°C (V_{Δ}). Therefore $V_{temp} = V_{zero} + V_{\Delta} \times$ Temp. As shown in table 3.1, the maximum input voltage swing equals $1.91 - 1.63 = 0.28$V, and has a DC offset of 1.77 V. Amplification is needed to reach an output voltage swing of 5 V, which, combined with a 2.5 V DC offset, will ensure that the circuit uses the input range as specified, and excludes the lower and upper temperature ranges (i.e. below 34°C and above 42°C). Therefore:

Table 3.1: Temperatures and Corresponding Voltage Levels

Temperature [°C]	32	38	42
Voltage [V]	1.63	1.77	1.91

$$A_v = \frac{V_{out}}{V_{in}} = \frac{5}{0.28} = 17.86$$

Considering the current design requirement of 25 mA maximum, the input resistor R is selected as $10\,\text{k}\Omega$, which will therefore, at the highest possible voltage level ($5\,\text{V}$), use $0.5\,\text{mA}$ of current. This gives $R_{feedback} = 178.6\text{k}\Omega$, according to $A_v = \frac{R_{feedback}}{R}$ [?]. R corresponds to R_1 and R_2, and $R_{feedback}$ to R_3 and R_4 in the final design diagram (figure 3.1), which is shown here already to aid with the explanation of the design process.

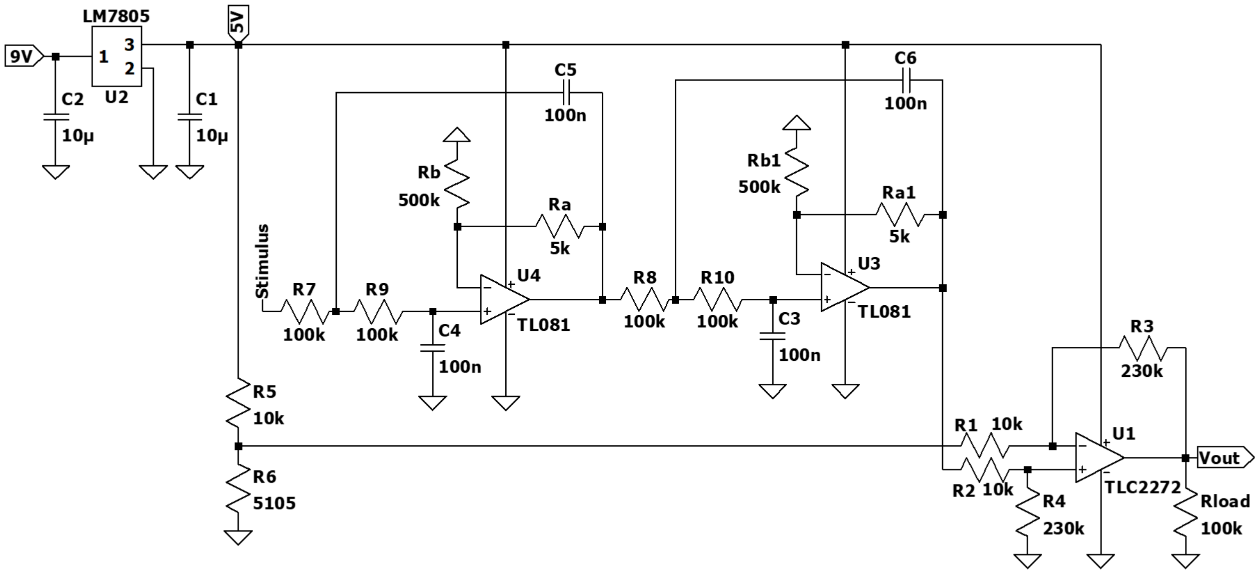


Figure 3.1: Temperature Sensor Circuit

Two points need to be considered:

1. The DC offset of the input signal is undesired and has to be removed in order to obtain a zero-mean input signal. This can be achieved by designing another subcircuit that makes use of another op-amp, for example. This adds to the cost and complexity of the circuit.

2. The output signal has to be centered around $2.5\,\text{V}$. This means that a DC offset has to be added in the form of a virtual ground.

When considered in conjunction with each other, the DC offset alteration can be resolved in one step, thereby reducing cost and complexity significantly. The decision was therefore made to use a differential amplifier, with the input signal connected to the positive input, after which the voltage required at the negative input can be calculated in such a way as to simultaneously subtract the offset and add the virtual ground in one step, thereby producing an output DC offset of $2.5\,\text{V}$. This approach also simplifies the design procedure, as it becomes unnecessary to calculate the virtual ground separately (the lecturer mentions that this is an acceptable approach in Lecture Video 2, minute 11 [?]; this removes the need to perform any virtual ground calculations per se - feel free to double-check with the lecturer). The differential amplifier, however, has to be non-inverting. The calculation thus reduces to a simple differential amplifier gain formula [?]:

$$V_{out} = \frac{R_{feedback}}{R}\left(V_{in+} - V_{in-}\right) \quad \rightarrow \quad 2.5 = \frac{178600}{10000}\left(1.77 - V_{in-}\right)$$

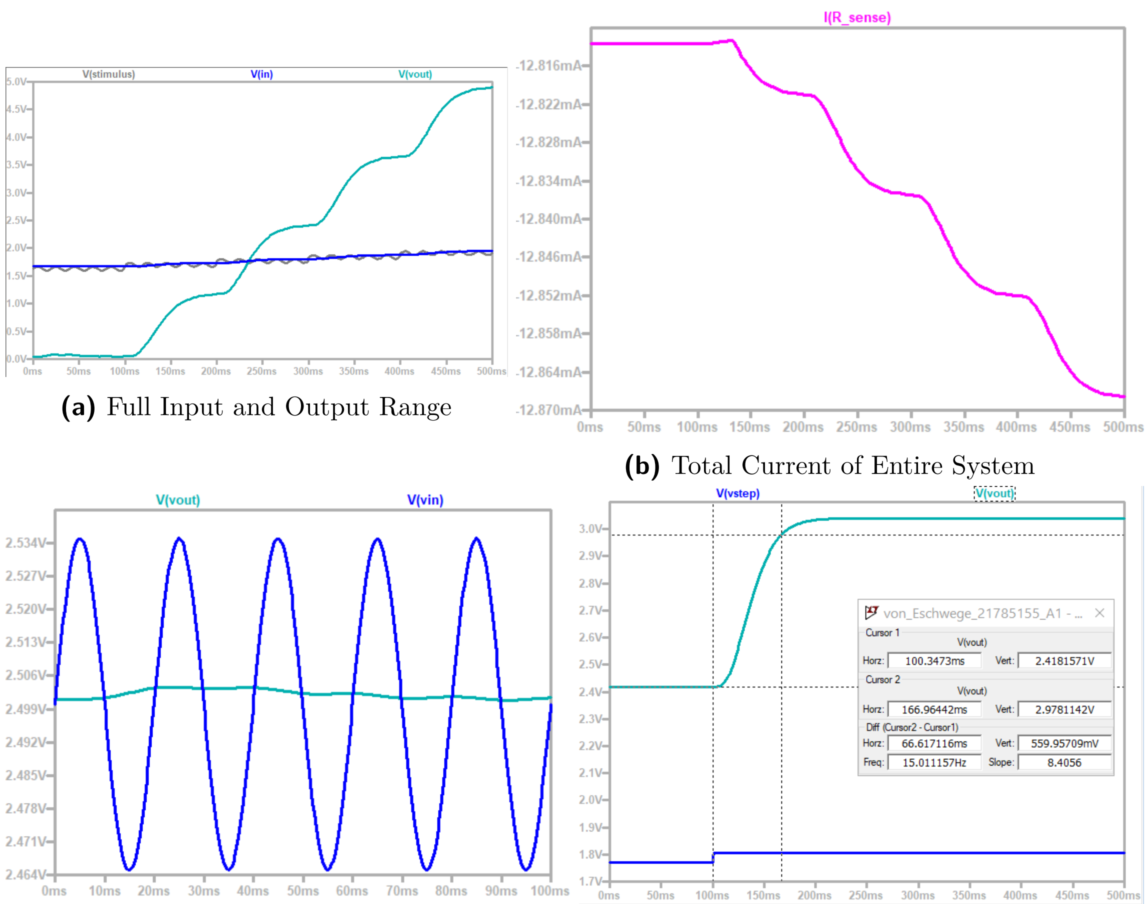
With V_{out} as 2.5 V, V_{in+} as 1.77 V and the resistor values as calculated previously, $V_{in-} = 1.63$ V. The voltage at V_{in-} can be set by means of a voltage divider circuit, which takes 5 V as input and is calculated as follows (resistor names in formulae are selected to conform with Figure 3.1): $V_{in-} = 5(\frac{R_6}{R_6 \times R_5})$. Selecting R_5 as 10 kΩ gives $R_6 = 4.84$ kΩ. Here, the common-mode voltage, V_{IC}, needs consideration; the TLC2272 can operate with a common-mode voltage of V_{DD-} to $V_{DD+} - 1.5$ [?]. Since $V_{in+_{max}}$ is 1.91 V and V_{in-} is 1.63 V, the largest possible common mode voltage is $V_{IC} = \frac{1.91+1.63}{2} = 1.77$ V, which is well below the maximum limit. Since V_{in-} stays constant, the lower limit will never be reached either.

Simulation was used to select a filter, and has shown the following: the RC filter is very simple, but produces too much noise. The passive low-pass filter is relatively simple, but does not meet the settling time requirement. The active low-pass filter meets both the noise and settling time requirements, but requires the TLC2272 op-amp to do so. Since a single TLC2272 op-amp is more expensive than multiple TL081 op-amps, the decision was made to rather use cascaded second order low-pass filters, which make use of the TL081. This is somewhat more complex, but lowers the cost, as the final circuit now only uses three op-amps, two of which are the cheaper TL081 models. The cascaded setup also produces an output signal with extremely low noise. A filter gain of close to unity is desired; for $R_A = 500$ kΩ, a value of 5 kΩ is suitable for R_A, according to the formula [?]: $A_v = 1 + \frac{R_A}{R_B}$
The settling time requirement of 100 ms means that a cutoff frequency of more than 10 Hz is needed, while the attenuation of noise requires a cutoff frequency below 50 Hz. $f_c = 15$ Hz was chosen - the bandwidth thus also is 15 Hz. Choosing R (R_7 and R_9 in the diagram) as 100 kΩ gives C (C_4 and C_5) as 106.1 nF, according to $f_c = \frac{1}{2\pi RC}$. The given cutoff frequency implies a rise time of 19.1 ms according to $t_r \approx \frac{1.8}{w_n} = \frac{1.8}{2\pi(15)}$ [?]. This meets the requirement of 100 ms. After design completion, this filter is then duplicated and connected back-to-back in order to form cascaded second-order low-pass filters, as seen in figure 3.1.

Using the assumption that each resistor is subjected to an average voltage of 2.5 V, while the op-amp draws 3 mA [?], the total temperature sensor current consumption is:
$I_{temp} = (2)\frac{2.5}{10k} + (2)\frac{2.5}{178.6k} + 3mA = 3.53mA$
and the calculated current for the total circuit is:
$I_{total} = (3)\frac{2.5}{10k} + (2)\frac{2.5}{178.6k} + (4)\frac{2.5}{100k} + (2)\frac{2.5}{500k} + (3)\frac{2.5}{5k} + (2)\frac{2.5}{178.6k} + (3)3mA = 11.39mA$

3.3. Results

The designed circuit receives an input signal ranging from 1.67 to 1.94 V for V_{in+}, which is somewhat higher than the calculated values of 1.63 to 1.91 V, and is due to the filter adding some offset. This can easily be overcome by adjusting the voltage divider. V_{in-} receives 1.7 V. Both V_{in-} and V_{in+} thus fall well within the allowable range for the TLC2272, which is from $V_{DD-} - 0.3$ to V_{DD+} [?]. The circuit produces a signal centered at 2.5 V with an output swing of 4.86 V (figure 3.2a), exceeding the required 3.5 V. The absolute maximum amount of noise measured is 25.6 mV (figure 3.2c), and the settling time is 67 ms (figure 3.2d), thereby meeting the requirements of 50 mV and 100 ms respectively. Total current draw is 12.83 mA (figure 3.2b), well below the required 15 mA, and very close to the calculated 11.39 mA. The cutoff frequency, obtained via AC analysis simulation, is 10.48 Hz (figure C.2). Measurements and graphs of settling time, cutoff frequency and current drawn can be seen in Appendix C. It is thus clear that all requirements, as well as all bonus requirements, have been met with a good margin to spare, all the while using only three op-amps, two of which are the cheaper TL081 models. The output signal (light blue) is shown in figure 3.2a.



(a) Full Input and Output Range

(b) Total Current of Entire System

(c) Simulated Noise Suppresion

(d) Simulated Output Rise Time

Figure 3.2: Complete Circuit Output (a) Output Range: 0.1 to 4.85V. Input Range: 1.63 to 1.94 V. (b) Current draw below requirement. (c) Noise suppressed to negligible levels. (d) Settling time within 100 ms.

3.4. Summary

Concluding, the circuit performs very well, and successfully amplifies the temperature sensor output to a level that is readable by the microcontroller ADC, all the while attenuating almost all noise present in the input. The design is somewhat complex, but also cheaper, as it uses less of the TLC2272 op-amps. It meets all requirements and bonus requirements.

Chapter 4

System and conclusion

4.1. System

Considering the system as a whole, it should be easy to integrate it with the rest of the health monitoring system as the design is modular. This can be done by feeding the output of the temperature sensor into the system designed in this report, and then connecting the output of the system to the microcontroller ADC. This requires relatively few connections, and the only setup needed is to calibrate the ADC, using the following formula [?]:

$$\text{ADC} = (2^{10} - 1)\frac{V_{in}}{V_{ref}} \quad \rightarrow \quad V_{in} = \frac{\text{ADC}(V_{ref})}{2^{10} - 1}$$

The slope of the temperature increase is $\frac{42-34}{5-0} = 1.6$. Thus, for 38°C:

$$T = 38 = 1.6V + C = 1.6(2.5) + C \quad \rightarrow \quad C = 34$$

Therefore, the temperature can finally be calculated by

$$T = (1.6)\frac{\text{ADC}(V_{ref})}{2^{10} - 1} + 34$$

Since the noise is 25 mV at maximum, the quantisation error (due to noise) is $T_{err} = (1.6(0.025) + 34) - (1.6(0) + 34) = 0.04$°C. Therefore, the measurement error is less than 4% per 1°C.

Concluding, it has been shown that the combination of the voltage regulator and the temperature sensing circuitry works very well to achieve the desired result. Since the cascaded filters ensure extremely low noise levels, the ADC should be capable of distinguishing the measured temperature to a very high degree of accuracy. The system uses more of the less costly components, and is very power efficient, all the while meeting all of the bonus requirements. It is thus safe to say that the objective of the design has been met successfully.

4.2. Lessons learnt

1. Make sure to understand the instructions before starting to work.
2. Texmaker is a nightmare with citations.
3. Don't go surfing for the entirety of the first week of class.

Bibliography

Appendix A

Social contract

Sign and inlcude.

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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, Daniel von Eschwege .... 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: 16/08/2020

1

Appendix B

GitHub Activity Heatmap

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

Appendix C

Stuff you want to include

A 1°C step input (35 mV), as shown in figure C.1, was used to determine the settling time. The settling time is measured at the point where the output steps to 90% of the final value (622 mV), which is 560 mV. The settling time was thus measured as 62.07 ms, as shown by the cursor difference in figure **??**.

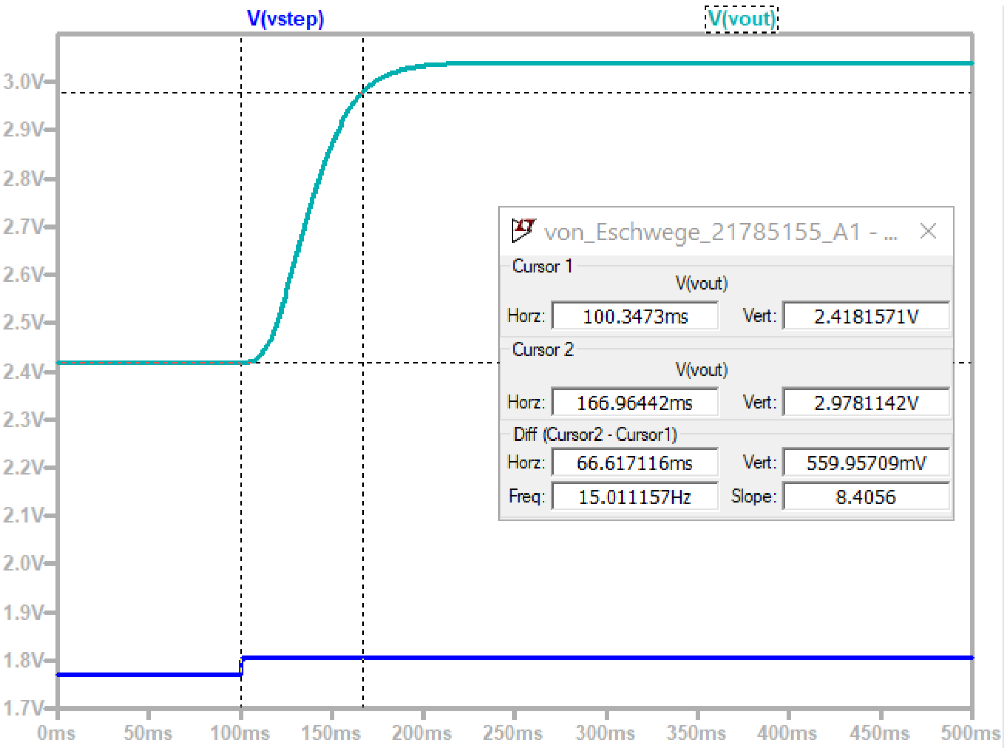

Figure C.1: Settling Time Measurement

The bode plot for the low-pass filter is shown in figure C.2. The -3dB point is lower than calculated, but is still well within the acceptable range.

Please note: It is a good design practice to include a unity gain op-amp to acts as a voltage buffer by clamping V_{in-} against fluctuations. This design practice was considered, but ultimately rejected, as tests with and without the buffer provided outputs of equal quality. This is the case as the signal conditioning circuit already has a very high input resistance. The only notable differences resulting from the inclusion of a buffer were an increase in current drawn, as well as an increase in cost for the circuit components, as another op-amp is required. Therefore, in order to keep the current consumption below 15 mA, as well as to use reduce cost by only using three op-amps, the voltage buffer was omitted in the final design.

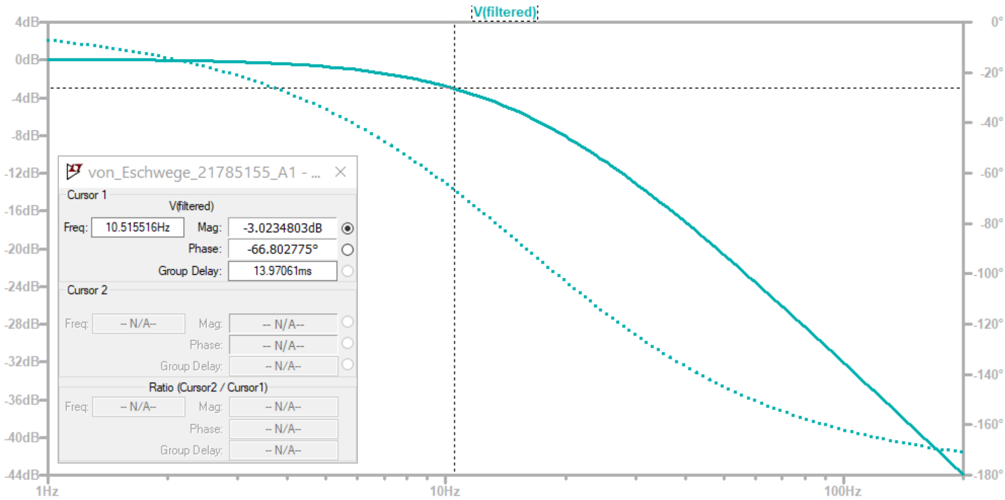

Figure C.2: Cutoff Frequency Measurement