Chapter 1

System design

1.1. System overview

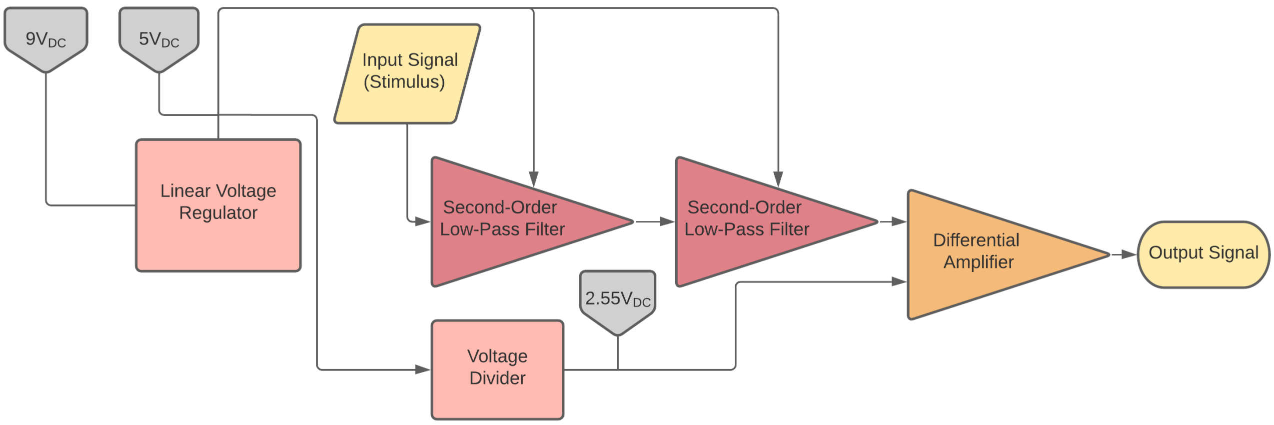

Figure 1.1: System Block Diagram

As part of the health monitoring system, which consists of an analogue temperature sensor and 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 received from a 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 **??**), as well as producing an output signal subject to very low noise (see Section **??**). Since the filtered signal still has a DC offset, the voltage divider connects to the differential amplifier in such a way as to simultaneously remove the input DC offset, and to add the virtual ground needed for the amplifier to produce an output signal with the correct DC offset. Finally, the differential amplifier increases the magnitude of the input signal to the degree needed at the input of a microcontroller ADC, which is to 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 **??**), 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-output of 9 V_{DC} and 5 V_{DC} [?]. 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. Resistor and capacitor configurations were determined according to the respective datasheets [?] [?].

2.2. Design

2.2.1. Linear Regulator

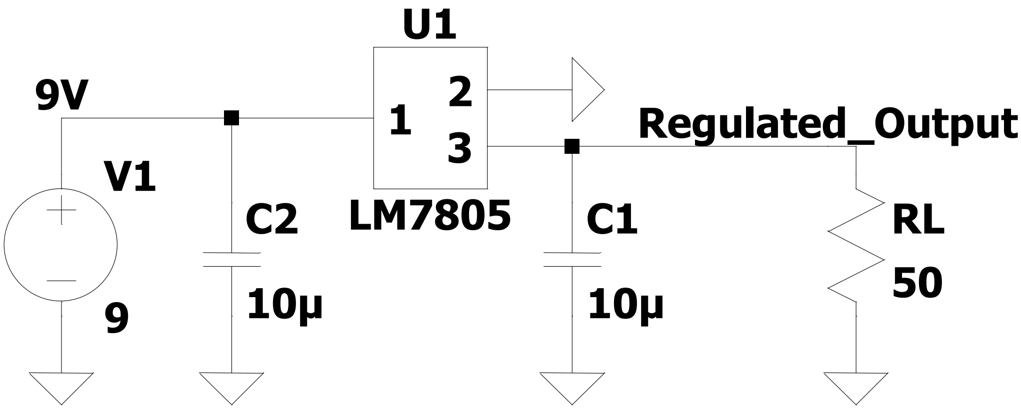

Figure 2.1: Linear Voltage Regulator

The LM7805 chip is shown in Figure 2.1, as well as the required peripheral circuit, which was obtained from the datasheet [?]. For testing purposes, a 50 Ω load was connected to the regulator, drawing 100 mA. Measurements are discussed in section 2.2.3.

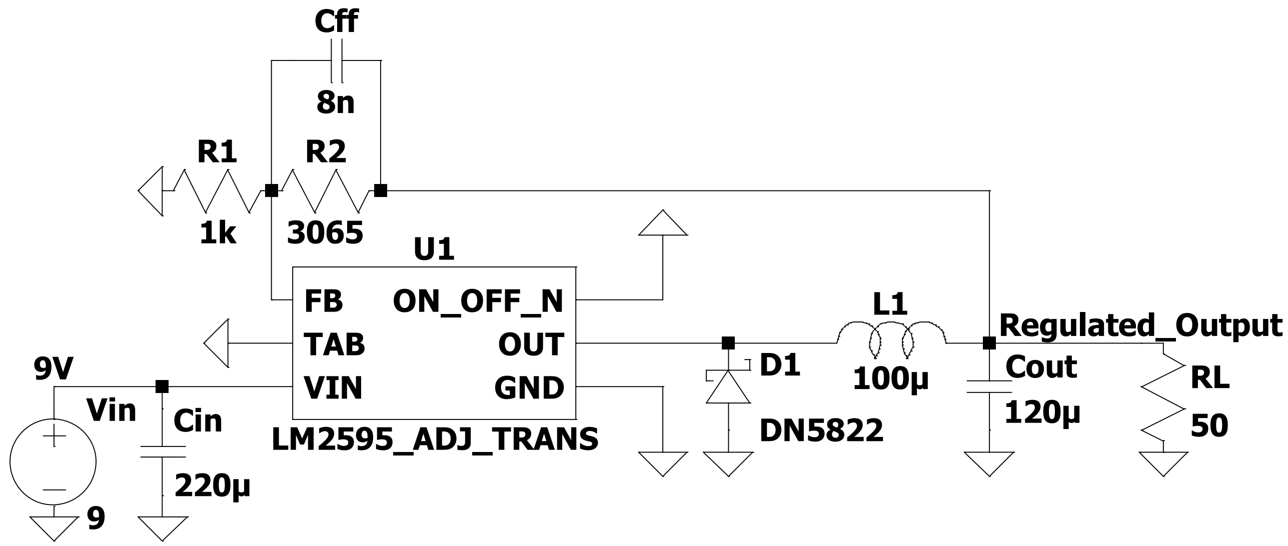

Figure 2.2: Switchmode Voltage Regulator

2.2.2. Switchmode Regulator

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

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

Selecting $\mathrm{R_1}$ as $1\,\mathrm{k\Omega}$, with $\mathrm{V_{out}}$ as $5\,\mathrm{V}$ gives $\mathrm{R_2}$ as $3065\,\Omega$. For testing purposes, a $50\,\Omega$ load was connected to the regulator, drawing $100\,\mathrm{mA}$. Measurements are discussed in section 2.2.3.

2.2.3. Voltage Regulator Comparison

The input and output power measurements are displayed in table 2.1.

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

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 $1.24\,\mathrm{ms}$, which is quite slow. Furthermore, the switchmode regulator creates noise levels of up to 950 $\mathrm{mV_{pp}}$ in the output, as can be seen in figure 2.3. This is a problem, as the large gain of the differential amplifier, which is fed by the voltage regulator, will result in the noise levels to increase in magnitude and become prevalent in the output. Considering all of the above, the linear regulator was selected for the design, despite being less efficient, as it provides an almost instantaneous settling time, coupled with negligible amounts of noise.

More vreg calcs, Voltage reg power calcs before sim?

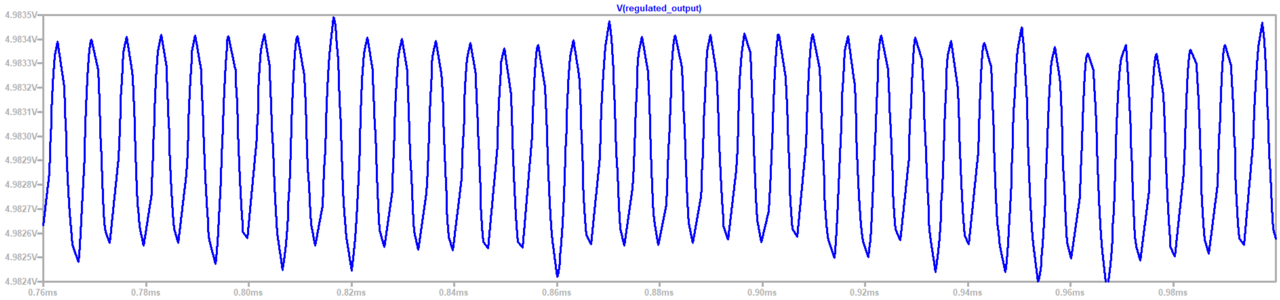

Figure 2.3: Switchmode Voltage Regulator Output

Table 2.2: Example of a simple table.

	2017	2018	Δ_{Abs}	Δ_{DiD}
A	9,868	10,399	+5	-11
B	10,191	10,590	+4	-12

2.3. Results

In this section, you want to demonstrate, by means of referring to simulation results, using the designed circuit, how your circuit behaves as you designed it in Section 2.2. Present and report on your simulated results in Figure ?? Be absolutely sure that the text and information in your report are readable.
You can use screengrabs or photos of the oscilloscope, or download the CSVs and plot them as PDFs using Matlab, Excel or similar. You can also use tables, example of which are presented in Tables 2.2 and 2.3.

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. This choice was made despite the fact that the switchmode regulator is approximately 40% more efficient than the linear regulator, influenced thereby that the total current drawn is still very low. 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.

Table 2.3: Example of another table.

Schools	Total energy used		Change	
	2017 [kWh]	2018 [kWh]	Δ_{Abs} [%]	Δ_{DiD} [%]
A	9,868	10,399	+5	-11
B	10,191	10,590	+4	-12

Chapter 3

Temperature sensor conditioning circuit

3.1. Intro

The signal obtained from the temperature sensor presents as DC, with a 35 mV, 50 Hz AC signal superimposed, which serves no purpose, but creates noise. The DC component increases linearly with respect to the temperature measured by the sensor. However, the sensor outputs a voltage of 440 mV at 0°C, which increases by 35 mV for every 1°C. These voltage levels are too small for a microcontroller ADC to take as input. Furthermore, as the sensor is only meant to measure human body temperature, 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 occupy as much of a 0 to 5 V range as possible, as this is the voltage range used by the ADC. To this end, a temperature sensor conditioning circuit is required to transform the given input into the desired output. This conditioning circuit consists 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 obtain an output signal with a minimal amount of noise. The offset removing subcircuit removes enough of the DC offset to ensure that the output signal is centered around 2.5 V, which is necessary to obtain the largest possible output swing as discussed previously. Finally, the amplifier increases the magnitude of the input signal in order to be suitable as input for an ADC.

3.2. Design

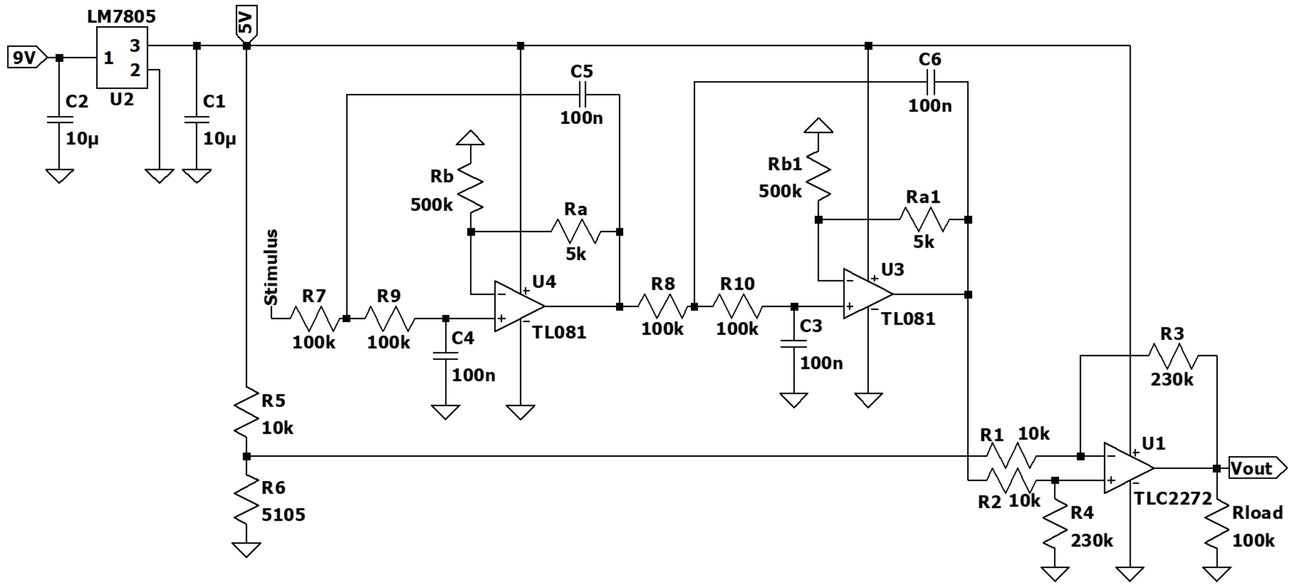

Figure 3.1: Temperature Sensor Circuit

The final design is shown upfront in figure 3.1 as to aid with the explanation of the design process. The voltage regulator is included in the figure to clarify the integration of the final circuit. 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. Since the output signal has to be centered around 2.5 V, a differential amplifier was decided upon, as the negative input can be used to adjust the offset present in the output. Given a zero-reference temperature sensor voltage (V_{zero}) of 440 mV, with an increase (V_{Δ}) of 35 mV for every 1°C. Therefore, temperature sensor voltage levels are calculated as follows:

$$V_{temp} = V_{zero} + V_{\Delta} \times \text{Temp}$$

Table 3.1: Temperatures and Corresponding Voltage Levels

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

According to table 3.1, the maximum input voltage swing equals $1.91 - 163 = 0.28$V, and has a DC offset of 1.77 V. Amplification is needed to reach an output voltage swing of 5 V. Therefore:

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

The TLC2272 op-amp was selected for the amplifier, as it can produce an output very close to its rails at 0 and 5 V. Now, R is selected as 10 kΩ, to prevent a large current from being drawn. This gives $R_{feedback} = 178.6\text{k}\Omega$, where R corresponds to R_1 and R_2, and $R_{feedback}$ to R_3 and R_4. 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 V. This means that 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 V (the lecturer mentions that this is an acceptable approach in Lecture Video 2). This approach also simplifies the design procedure, as it becomes unnecessary to calculate the virtual ground separately. The differential amplifier, however, has to be non-inverting. The calculation thus reduces to a simple differential amplifier gain formula [?]:

$$V_{out} = \frac{R_{feedback}}{R}\left(V_{in+} - V_{in-}\right)$$

Taking V_{out} as 2.5 V, V_{in+} as 1.77 V and the resistor values as calculated previously:

$$2.5 = \frac{178600}{10000}\left(1.77 - V_{in-}\right)$$
$$V_{in-} = 1.63 \text{ V}$$

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):

$$V_{in-} = 5\left(\frac{R_6}{R_6 \times R_5}\right)$$

Selecting R_5 as $10\,\mathrm{k\Omega}$ gives $R_6 = 4.84\,\mathrm{k\Omega}$.

The filter has to be designed next. Possible design choices included an active/passive first order low-pass filter, a simple RC filter, or a second order low-pass filter. Simulation of the aforementioned filters has shown the following: the RC filter is very simple, but does not meet the design requirements w.r.t. 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 $\mathrm{R_b} = 500\,\mathrm{k\Omega}$, a value of $5\,\mathrm{k\Omega}$ is suitable for $\mathrm{R_a}$, according to

$$A_v = 1 + \frac{R_A}{R_B}$$

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. In order to minimize noise, the cutoff frequency was selected at 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

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

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.

Under most circumstances, it is a good design practice to include a unity gain op-amp at the input of the op-amp responsible for the correct offset, as it acts as a voltage buffer, thereby clamping the voltage against fluctuations caused by the differential amplifier's other input. This design practice was considered, but ultimately decided against, as tests with and without the buffer provided outputs of equal quality (similar to the output shown in section 3.3. 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.

3.3. Results

The designed circuit produces a signal centered at 2.5 V with an output swing of 4.86 V, exceeding the required 3.5 V. The absolute maximum amount of noise measured is 25.6 mV, and the settling time is 65 ms, thereby meeting the requirements of 50 mV and 100 ms respectively. Total current draw is 12.83 mA, well below the required 15 mA. 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 3.2.

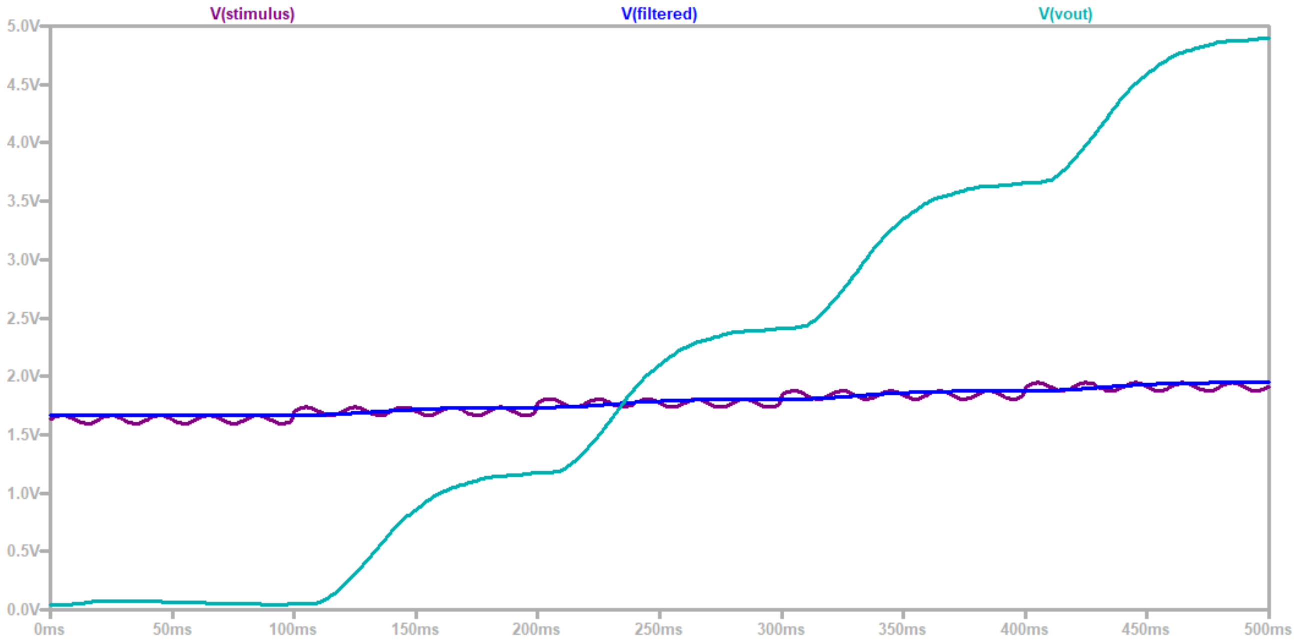

Figure 3.2: Temperature Sensor Conditioning Circuit Output

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.

Chapter 4

System and conclusion

4.1. System

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 design is modular, it should be easy to integrate with the rest of the health monitoring system, by feeding the output of the temperature sensor into the system designed in this report, and then connecting the output of this system to the microcontroller ADC. This requires relatively few connections. 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. However, the ADC still has to be calibrated to fit the amplified signal's range, which is now from A to B. Since the noise is low, the measurement error should be less than %, as the quantisation error is %. (E.g. what the calibration will look like and what the the measurement error will be given the range, quantisation error and noise).

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.

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

Stuff you want to include

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