

PCB design
ECE Specialization Areas Lab
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1 INTRODUCTION

In the lab, an insight of how an electronic device is actually designed was obtained. How the circuit is requested, specified, verified, PCB designed were studied by going through an example. The program LTspice, MATLAB were used to calculate and simulate the values of necessary components and to decide which components to use. Program KiCad was used to design the whole circuit. After deciding all the components and simulated, the PCB layout were set and designed.

2 REQUEST

Circuit which measures temperature and transmits the result as an I2C slave is required.

Temperature range: -10° to $+50^{\circ}$

Voltage supply: $5V \pm 10\%$, USB, RS232 port

Accuracy: $\pm(5\%rdg + 4dgt)$

Sample rate: 2Val/min

Stored history: Values last two hours

Environment: Resistance against condition inside normal office.

Other requirement such as weight, medium size, due date, costs needs to be considered.

3 SPECIFICATION

3.1 CIRCUIT DEFINITION

Circuit was divided into three functional blocks: Power, Analog, Digital

Power : Power supply of $+5V$ for analog and digital part

Analog : Sensor and Amplifier

Digital : Combined ADC and I2C

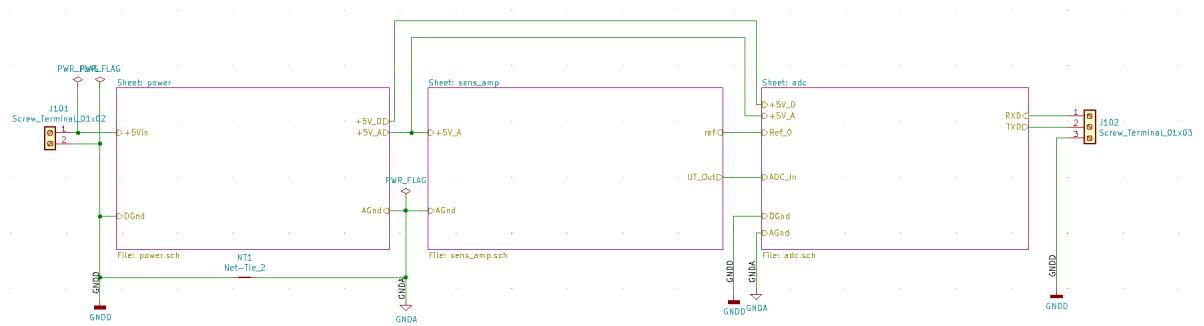


Figure 3.1: Circuit

3.2 DIGITAL PART

Digital part component : ADC, Timer, serial interface, memory

To contain all of the components, a micro controller is used. In the experiment, ATmega 328P was selected. ATmega328P includes 10 bit ADC. Which is enough to have one sample every 30 seconds(2Vals/min). However the error can be increased by 10 % but this is acceptable to reduce the cost.

The requested storage time says it has to store for two hours with sample rate of 2Val/min. With the calculation of $2\text{Val}/\text{min} \times 120\text{min} = 240 \text{ Vals}$ need to be stored. Each values has 2 Bytes therefore total of 480bytes are needed. ATmega 328P has internal memory of 2048byte RAM that gives enough RAM for the program to run and store data.

The used micro controller has a reference voltage of 1.1V that can be used in the analog part for accurate measurement. In addition, it contains timer and RS232 interface. All the information of the micro controller can be checked in the datasheet of ATmega 328P. The digital part circuit is shown in figure 3.2.

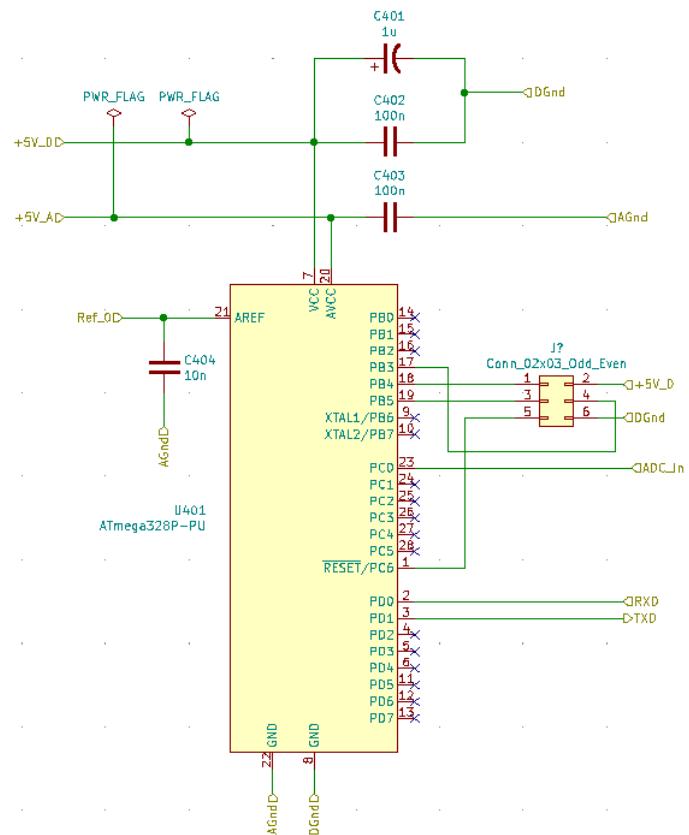


Figure 3.2: Digital part

3.3 ANALOG PART

Analog part components: Amplifiers, temperature sensor, reference voltage

The reference voltage comes from the micro controller from the digital part. This supply is too weak because the output is less than 1mA. Therefore a non inverting amplifier is used.

For the temperature sensor PT1000 is used in a Wheatstone bridge to sense the change in resistance. In addition, an instrumentation amplifier is used as a differential amplifier to amplify the output of the bridge circuit. The analog part circuit is shown in figure 3.3.

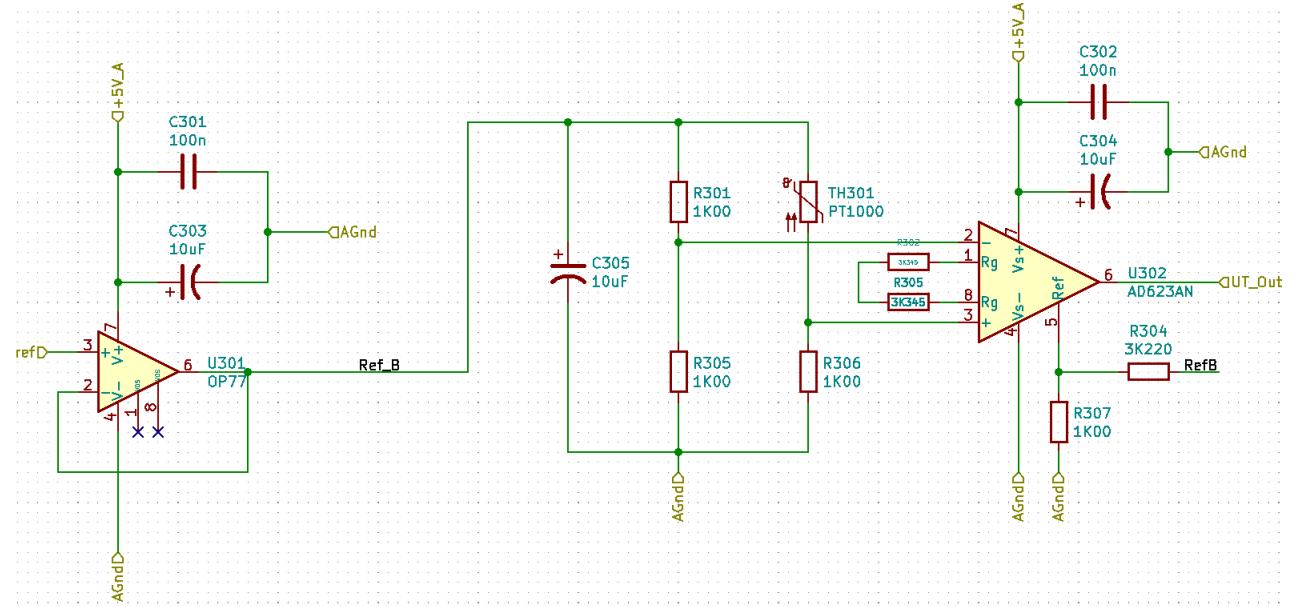


Figure 3.3: Analog part; Ref Vol Amp - Wheatstone PT1000 - Instrumentation Amp

3.4 POWER PART

In the power supply, 5V is requested as the supply voltage. To know the overall power usage, the overall usage of current needs to be known. The overall current is estimated as 13mA: micro controller needs up to 10mA, two amplifiers up to 1mA supply current, reference source about 2mA. The USB port can be used because it delivers up to 500mA and $5V \pm 10\%$. For the power, no converter or regulator is necessary because all the components can use to 5V. Also, the power supply is a RLC filter to reduce ripple from the source. The power circuit is shown in figure 3.4.

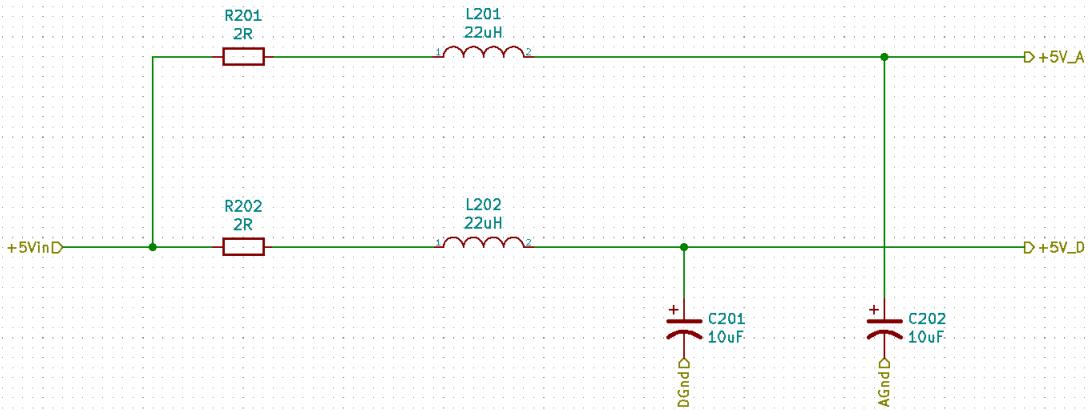


Figure 3.4: Power part

4 VERIFICATION

4.1 POWER PART

As explained before, the power part is a RLC filter. The filter has to work to suppress as much noise as possible in high frequency range. This is because ADC and differential amplifier in digital and analog part is sensitive to noise. LTspice is used here to figure out what type of capacitor and resistor is appropriate to suppress maximum amount of noise. The simulation circuit and result is shown in figure 4.1, 4.2.

Settings of LTspice simulation
frequency range: 10Hz - 1MHz

Inductor: Coilcraft DT3316P-223 with $L = 22\mu H$

Capacitor: C1- tantalum low ESR capacitor KEMET T521B106M016ATE100 with $C = 10\mu F$

C2 - Al type Nichicon UPR1C100MAH with $C = 10\mu F$

Resistors were verified: 0.1Ω , 1Ω , 2Ω

In the figure 4.2, it can be seen that C1(tantalum) capacitor, marked in green, has steeper slope. It shows that C1 is better to use since it suppresses more noise and faster in high frequency range. The difference in damping is because of the change in resistor. In case of C1, when the resistor is small (0.1Ω) it shows a high overshoot. As the resistor becomes higher to 2Ω , the overshoot disappears. Therefore, C1 capacitor - Tantalum low ESR capacitor should be used and resistor with resistance of 2Ω would be the proper selection of the component.

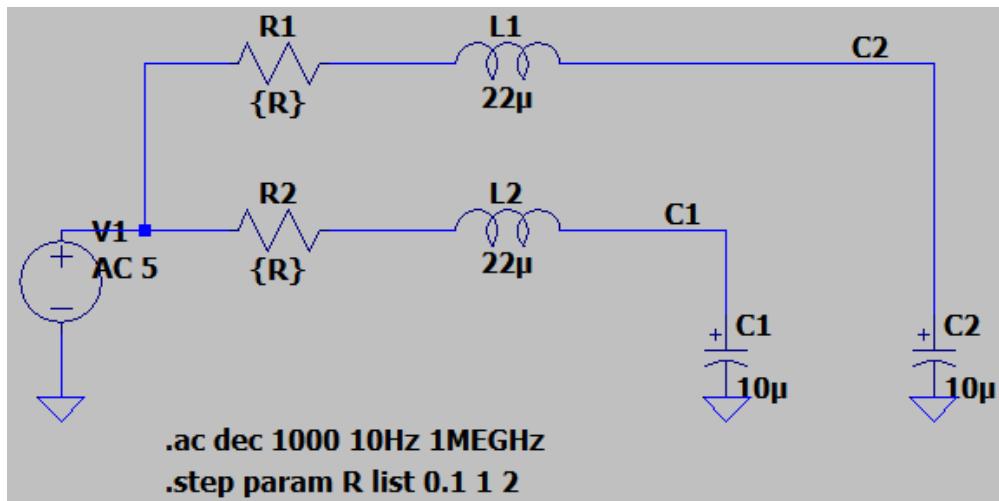


Figure 4.1: Power spice

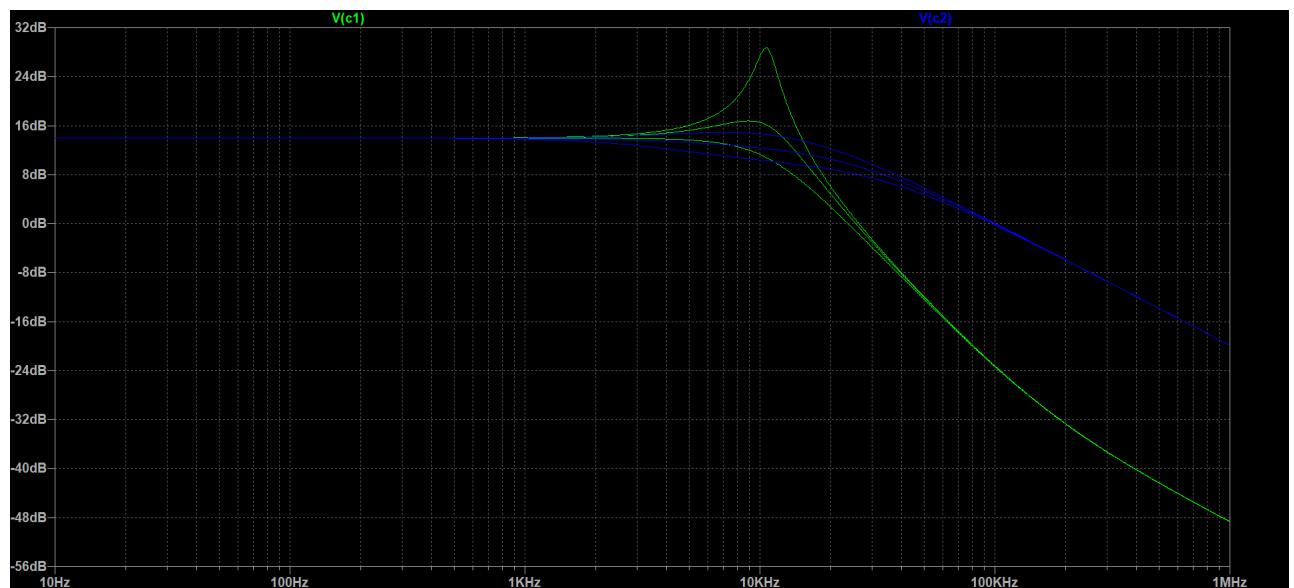


Figure 4.2: Power spice graph

4.2 ANALOG PART-INSTRUMENTATION AMPLIFIER

Task questions

1. *Describe the function of the circuit.*

As explained in part 2.2.3, the circuit is divided into three parts. First, the amplifier amplifies the reference voltage. Then Wheatstone bridge is used to detect the change in resistance and has the temperature sensor. Last, the instrumentation amplifier amplifies the output bridge circuit.

Describe the function of instrumentation amplifier, purpose of R302+303 and R304+307.
R302+303 is used to scale the voltage to the right range. and R304, R307 is used to shift the voltage to a proper level(gives an offset). This can be seen in the following simulation below.

2. Simulate Wheatstone bridge with differential amplifier.

Setup: $R_{302}+R_{303}=5000\Omega$, $R_{304}=5000\Omega$. Temperature: -10°C to 50°C , Amplifier: AD623

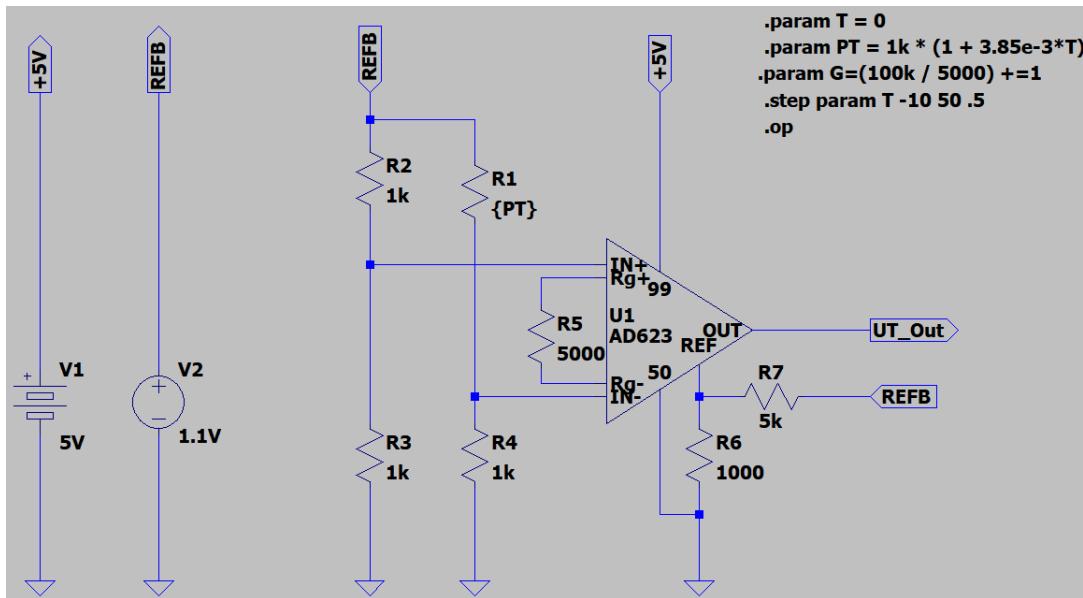


Figure 4.3: Wheatstone, Amplifier Spice

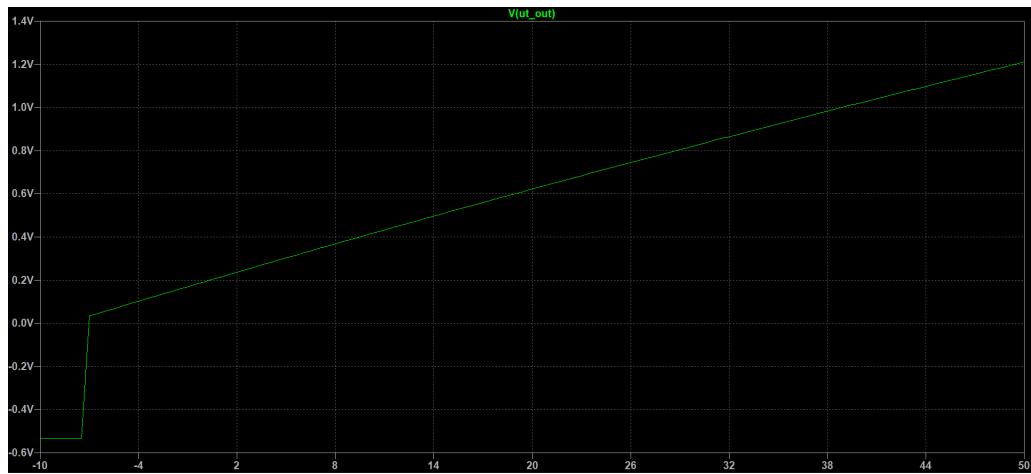


Figure 4.4: Amplifier Spice Graph

The simulation using LTspice is shown in figure 4.3, 4.4. As seen in figure 4.4, the result is a **rising function with a jump in the beginning where the temperature is negative**. This jump is caused when the input of the amplifier is negative. (When voltage difference between the positive input and the negative input of the amplifier is negative). The amplifier only works when it is uni polar. Hence it cannot amplify negative input signals. To fix this problem, an offset can be given by changing the ratio of R304 and R307. Also, R302+R303 is changed to provide proper scaling (gain) of the output.

3. *Calculate values of Resistors to get proper gain and offset.*

Temperature range: $-10^{\circ}C$ to $50^{\circ}C$ Output: 0V to 1.1V

```

1 clc; clear all; close all;
2
3 v_ref = 1.1; %reference voltage
4 r = 1000; %resistor value ref
5 a = 3.85e-3; %tep coefficient of PT1000
6 t_min = -15; %temperature min
7 t_max = 55; %temperature max
8 t_pts = -t_min + t_max + 1; %points
9 x = linspace(t_min, t_max, t_pts); %x axis , temperature
10 r_pts = r * (1 + a * x); % resistance of pt1000 over the
    temperatures
11
12
13 wheatV = ((r ./ (2 * r)) - (r ./ (r + r_pts))) * v_ref; %Wheatstone
    bridge volt
14
15 %plot(x, wheatV)
16
17 % scaling to 1.1 V
18 gain = v_ref / (wheatV(t_pts) - wheatV(1));
19 r_gain = 100e3 / (gain - 1); %Gain from resistor
20
21 % Used resistance and gain
22 r_gain2 = round(r_gain / 10) * 10;
23 gain2 = 100e3 / r_gain2 + 1;
24
25 v_off = - wheatV(1) * gain2; % offset
26 r_304 = (r * v_ref - r * v_off) / v_off; %R304
27 v_off2 = r * v_ref / (r + r_304); %Actual offset
28
29 fix_voltage = wheatV * gain2 + v_off; %offset added to have only
    positive values
30
31 plot(x, fix_voltage);

```

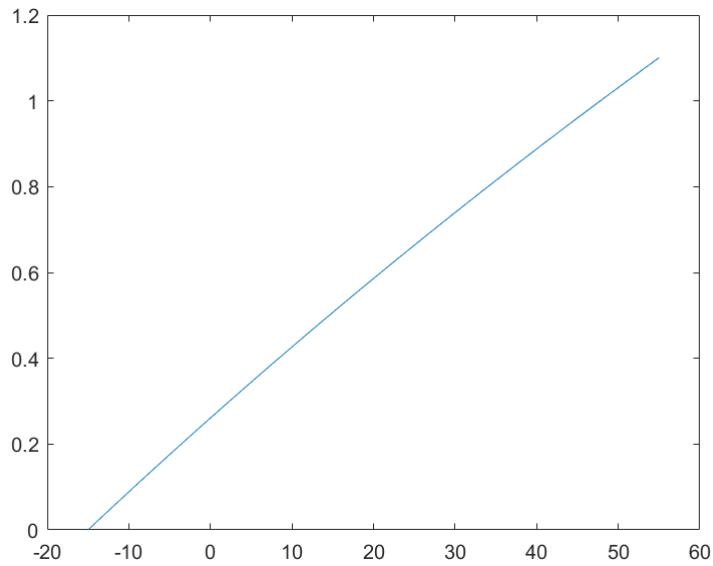


Figure 4.5: MATLAB graph

a	0.0039
fix_voltage	1x71 double
gain	15.9398
gain2	15.9477
r	1000
r_304	3.2178e+03
r_gain	6.6935e+03
r_gain2	6690
r_pts	1x71 double
t_max	55
t_min	-15
t_pts	71
v_off	0.2608
v_off2	0.2608
v_ref	1.1000
wheatV	1x71 double
x	1x71 double

Figure 4.6: MATLAB value results

As seen above, a MATLAB simulation is done to calculate the value of resistors to give proper gain and offset to get a better amplifying output. As shown in figure 4.5, now the output is a steady rising function that goes from 0V to 1.1V when the temperature is -10°C to 50°C .

In addition, shown in figure 4.6 the value of amplification and resistors were calculated.
Amplification: 16.

$$R_{304} = 3217.8\Omega \text{ (Later used } 3220\Omega)$$

$$R_{\text{gain}} = R_{302} + R_{303} = 6690\Omega \quad \text{Therefore, } R_{302}, R_{303} \text{ was set to } 3345\Omega$$

4. Verify using LTSpice with the calculated values

With the calculated values using MATLAB, R304 (R7) was set to 3220Ω and $R302+R303(R5)$ was set to 6690Ω . The simulation is shown in figure 4.7, 4.8. By the resulting graph in Figure 4.8, it can be seen that now it is a clear rising function from 0 to 1.1V in the temperature range of $-10^{\circ}C$ to $50^{\circ}C$.

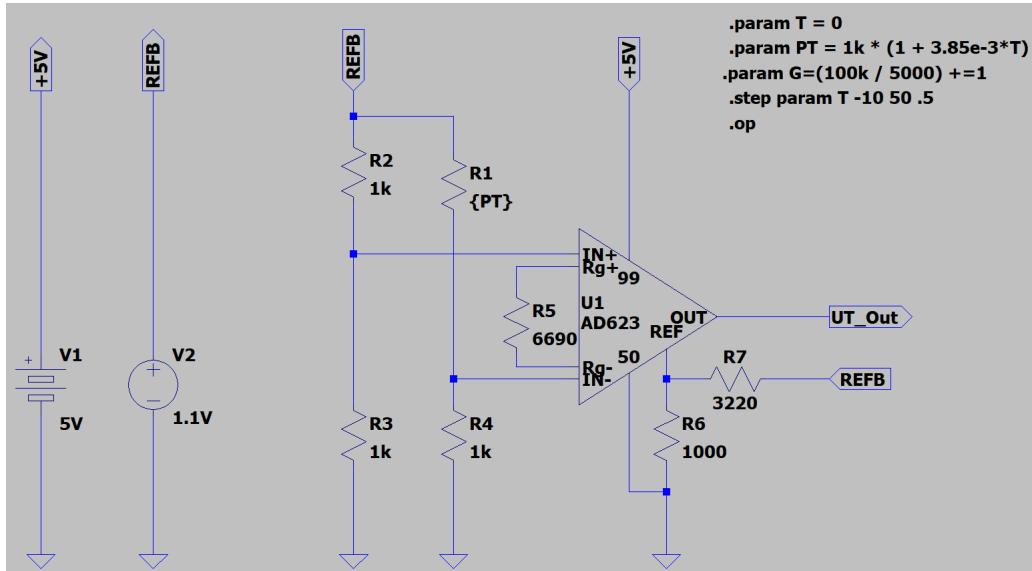


Figure 4.7: LTSpice verification

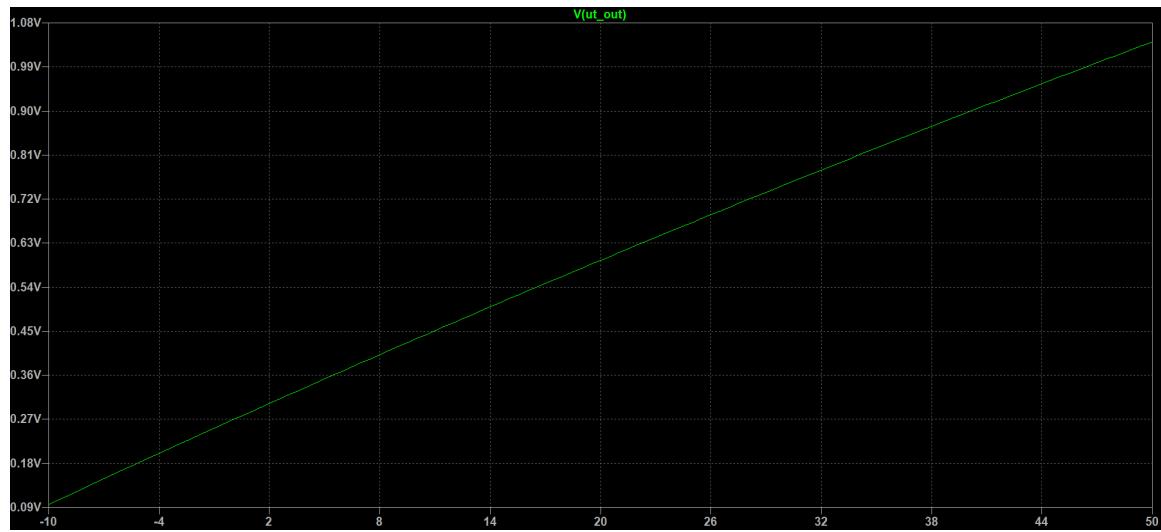


Figure 4.8: LTSpice verification graph

5 ERROR ESTIMATION

Bridge			
V_{Ref}	10%	100000ppm	cal
Resistors 0.1%	0.3%	3000ppm	fix
Bridge Nonlinearity	5%	50000ppm	cal
Error Inst. Amplifier			
V_{OS}	$100\mu V/70mV$	≈ 1500 ppm	cal
I_{OS}	$(1K\Omega \times 2nA)/70mV$	≈ 30 ppm	cal
Gain Error	0.35%	3500ppm	cal
Gain Nonlinearity	50ppm	50ppm	cal
Gain vs. Temp.	50ppm/ $^{\circ}C$	3500ppm	fix
CMR Error	105dB	≈ 50 ppm	cal
0.1Hz to 10Hz 1/f Noise	$1.5\mu V/70mV$	21.4ppm	fix

The table shows the error source of Wheatstone bridge and instrumentation amplifier. In the Wheatstone bridge, error regarding resistor can only be fixed by using better resistor and reference voltage error can be fixed by calibration. The output of wheatstone bridge is non linear. This is shown in figure5.1 comparing the result and the actual linear graph. More calibration and calculation is needed to reduce this non linearity.

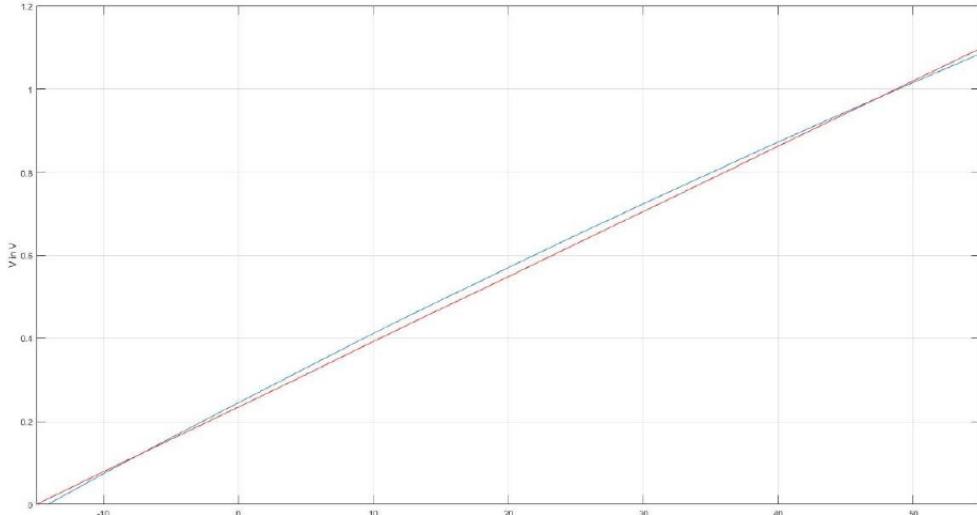


Figure 5.1: Linear error

In the instrumentation amplifier, gain, offset, linearity, CMR errors can be reduced by calibration. Also, selecting better resistors might improve errors too. Other errors such as gain non linearity and noise is hard to remove. These errors decrease the system resolution. In final, the total unadjusted error is estimated as 160000ppm while the resolution error is around 5000ppm.

In the analog part, the error can be reduced to 1% by calibration. The ADC adds 5 digits error. So around error of 0.350°C is included.

These errors can be reduced by using better components(Resistors, ADC, instrumentation amplifier, sensor..). Also, proper calibration will reduce error. After all the consideration, the right components should be selected. The components are all selected in KiCad and simulation was done to fix any errors in the circuit. The selected components are shown in figure5.2.

C201 -	10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
C202 -	10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
C301 -	100n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
C302 -	100n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
C303 -	10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
C304 -	10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
C305 -	10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
C401 -	1u : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
C402 -	100n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
C403 -	100n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
C404 -	10n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
J1 -	Conn_02x03_Odd_Even : Connector_PinHeader_2.54mm:PinHeader_2x03_P2.54mm_Vertical
J101 -	Screw_Terminal_01x02 : TerminalBlock_RND:TerminalBlock_RND_205-00001_1x02_P5.00mm_Horizontal
J102 -	Screw_Terminal_01x03 : TerminalBlock_RND:TerminalBlock_RND_205-00002_1x03_P5.00mm_Horizontal
L201 -	22uH : Inductor_SMD:L_1210_3225Metric
L202 -	22uH : Inductor_SMD:L_1210_3225Metric
NT1 -	Net-Tie_2 : NetTie:NetTie-2_SMD_Pad2.0mm
R201 -	2R : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R202 -	2R : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R301 -	1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R302 -	3K345 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R303 -	3K345 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R304 -	3K220 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R305 -	1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R306 -	1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
R307 -	1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
TH301 -	PT1000 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
U301 -	OP77 : Package_DIP:DIP-8_W7.62mm
U302 -	AD623AN : Package_DIP:DIP-8_W7.62mm
U401 -	ATmega328P-PU : Package_DIP:DIP-28_W7.62mm

Figure 5.2: footprint

6 PCB DESIGN

After all the components are decided, PCB design can be processed. While doing PCB design, it is important to simplify the circuit as much as possible. Complicated connection in the circuit will end in a bad circuit board. Therefore it is important to place the components in a way to shorten and simplify(unscramble) the connection in between. Also, the right trace should be selected. Wider and longer the trace will give less resistance, giving higher currents - with this trace, self heating has to be considered. Smaller traces are good to connect when going to a specific location on the board. Each traces can act as an inductor so it needs to be considered. It can disturb the circuit by giving mutual inductance. Also, loops in the circuit can act as a coil, giving inductance. To reduce this mutual inductance, loop areas should be kept as far as possible from each other. In addition, Two traces can act as a capacitor and store energy - giving stray capacitance. To remove this effect, a Faraday shield or Capacitive shield needs to be used.

The final PCB design is shown below.

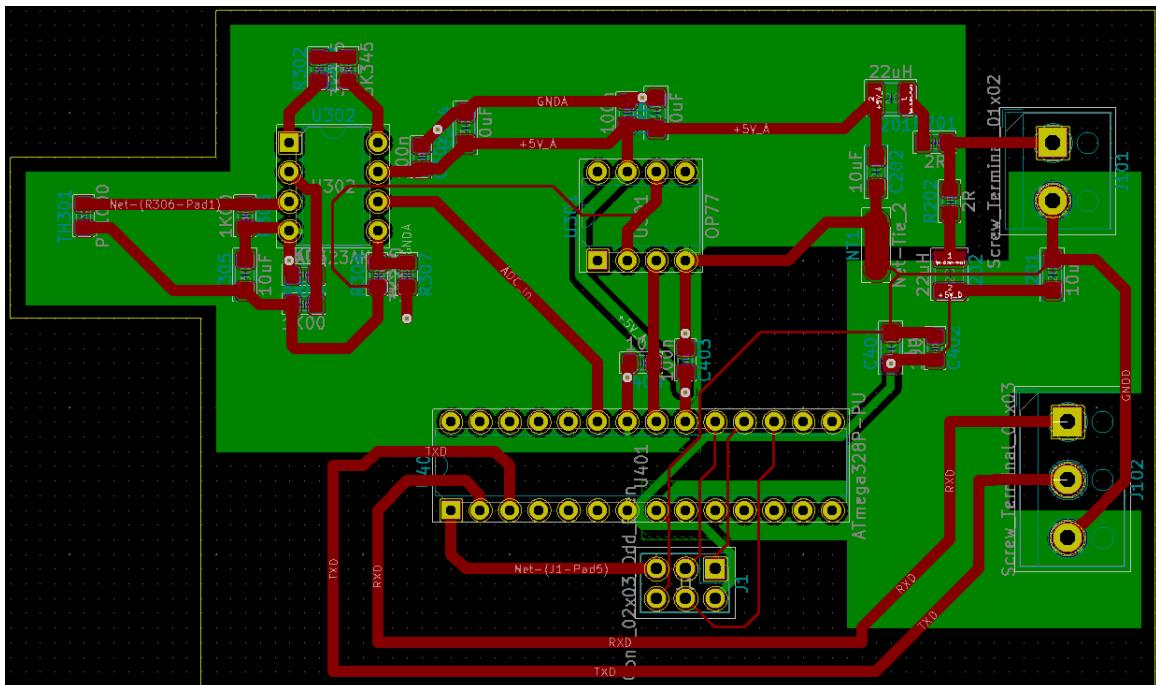


Figure 6.1: Complete PCB design

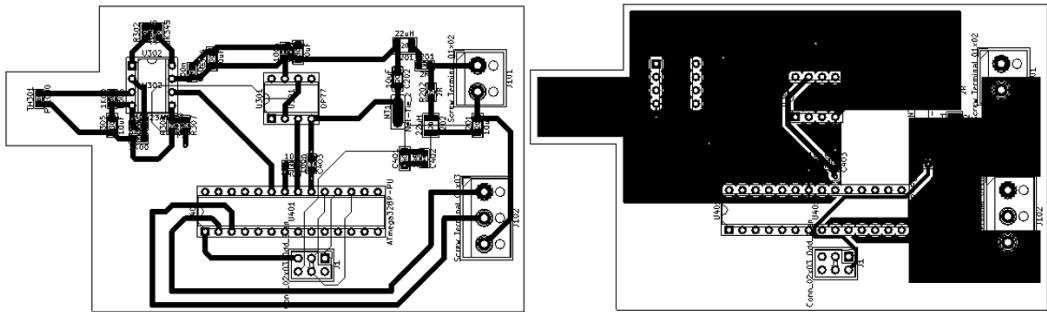


Figure 6.2: PCB upper and bottom layer

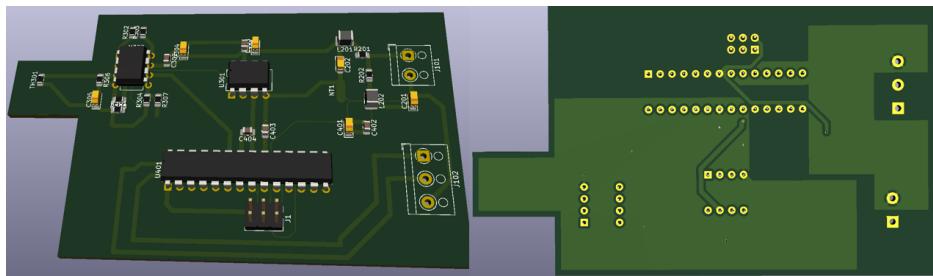
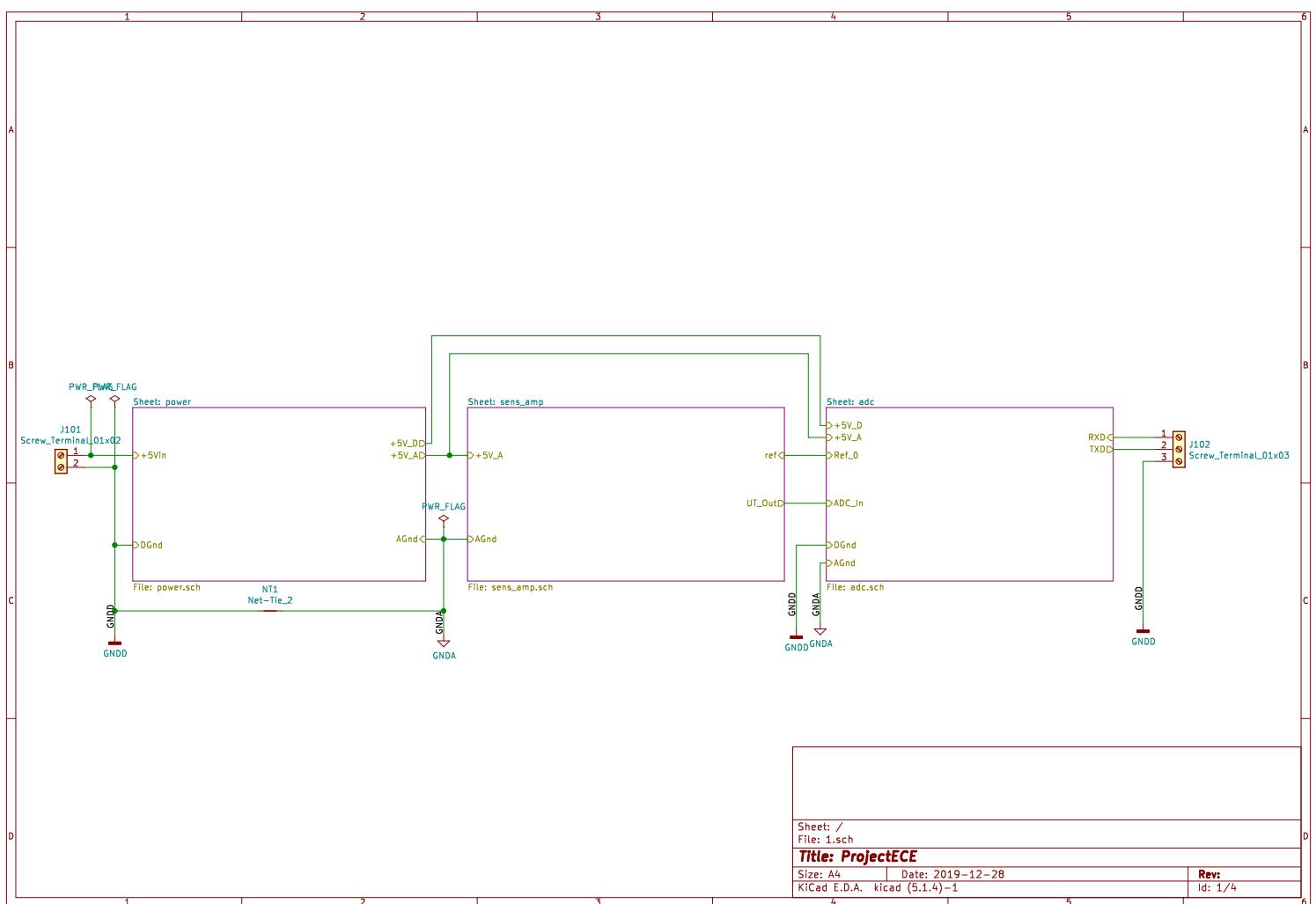


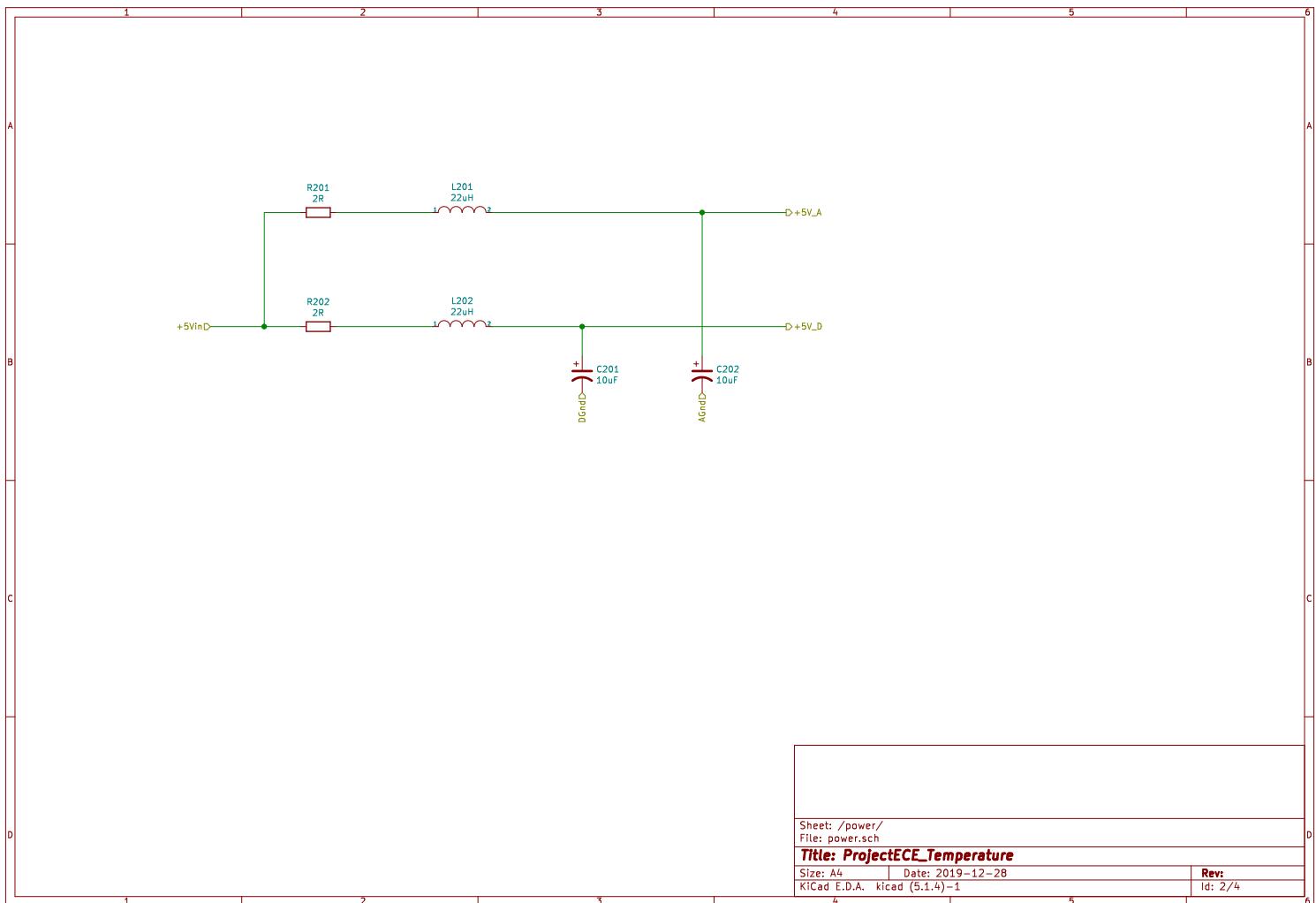
Figure 6.3: PCB 3D view

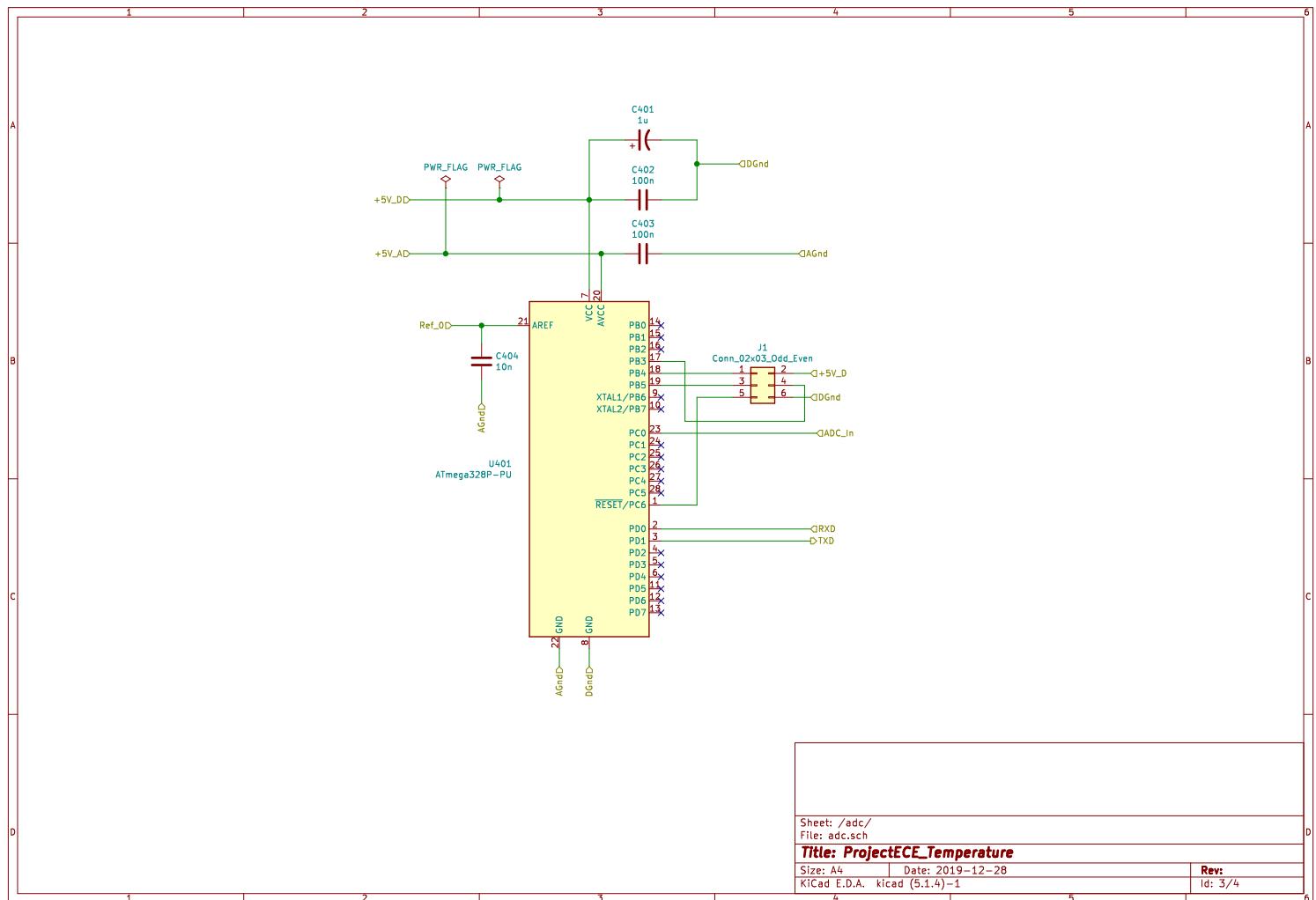
7 CONCLUSION

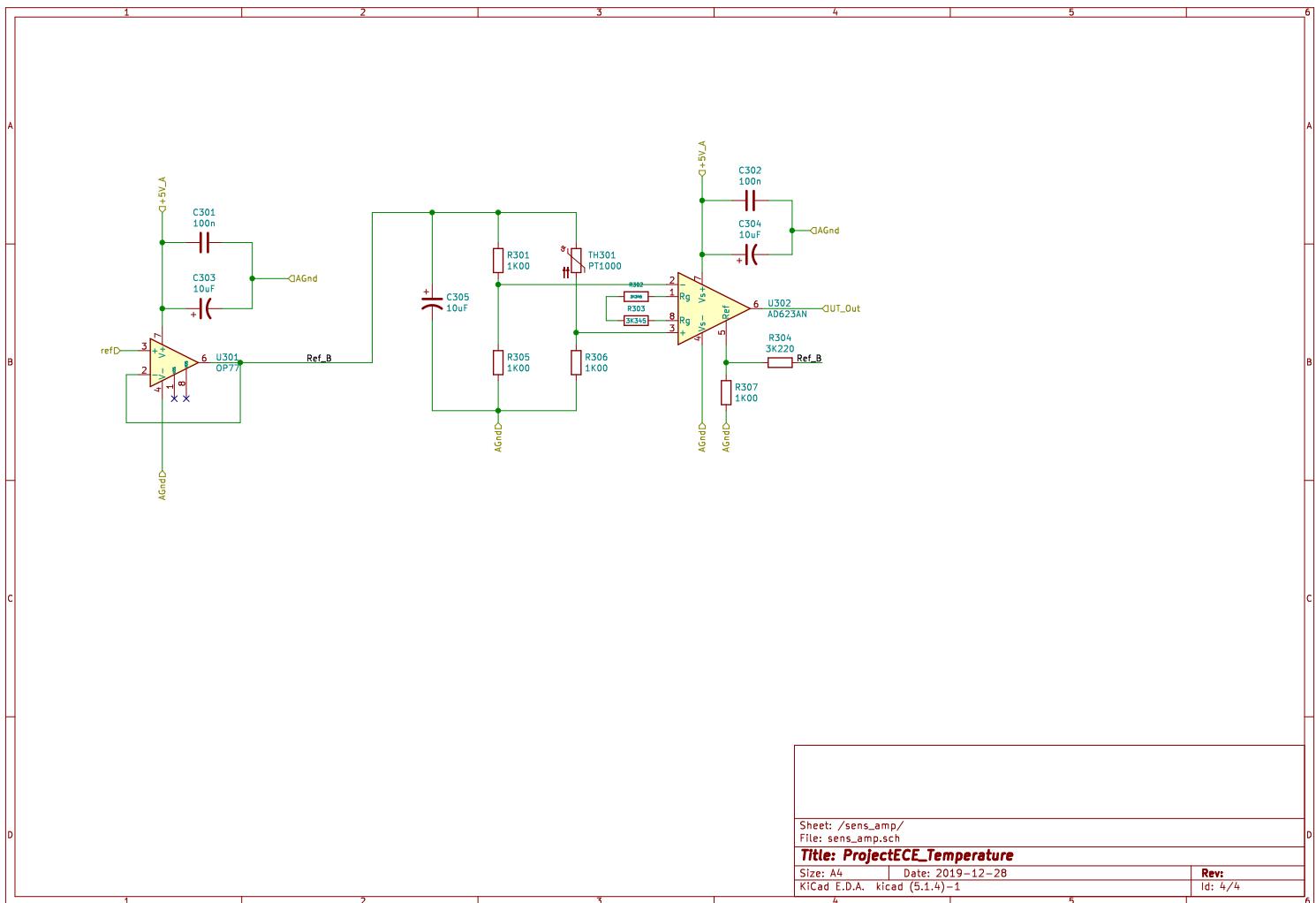
How the PCB design works were studied in the lab. Getting request, Specification, Simulation, Verification, estimating errors, designing circuit and PCB steps are all went through. Circuit that measures temperature and transmits the result are requested. According the given environment, the circuit was designed and simulated using MATLAB and LTspice to chose the right component. Than Kicad was used to design the circuit with the actual component. After selecting the right components and building the circuit, PCB design was done. The final circuit is shown in the section before. Some of the traces were too scrambled and messy. Also the components can be set in a better way to reduce disturbances. This can be improved by further experiences and studies.

Full schematic is included in the next pages.









8 REFERENCE

- [1] Inst. Uwe Pagel: 'ECE Specialization Areas Lab' (2019)
- [2] Walt Keser, Bridge Circuits, http://www.faculty.jacobs-university.de/upagel/03.0.specarealab/03.1.addlit/bridge_notes_0.pdf
- [3] Walter G.Jung, OP AMP APPLICATION,http://www.faculty.jacobs-university.de/upagel/03.0.specarealab/03.1.addlit/op_amp_analogdevices.pdf
- [4] Circuit components datasheet:AD623, OP77, Atmega328p, PT1000,available in <http://www.faculty.jacobs-university.de/upagel/03.0.specarealab/03.3.datasheet/index.html>