Jacobs University Bremen

CA11-300303
ECE Specialization Areas Lab

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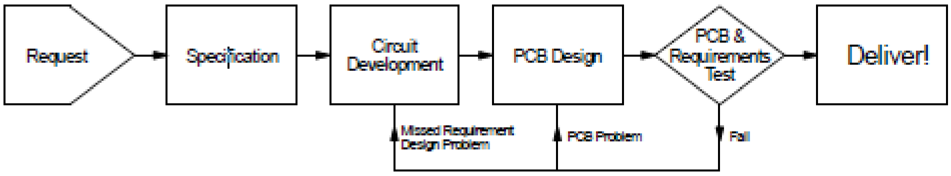
Objectives:

The few main objectives of this lab were:

- An insight into the design flow of an electronic device.
- Taking care of different steps and several aspects when implementing a circuit idea into a real device.
- Demonstrate the above two points by an example.

The prerequisite required for this experiment is EDA software 'KiCad'. 'KiCad' is a 'A Cross Platform and Open Source Electronics Design Automation Suite'. That means it is a software tool for the creation of electronic schematic diagrams and PCBs artwork.

Below is a general diagram of the general design flow:



1. The design starts with an idea or a request from a customer for a product.

2. A product specification has to be developed. This is the base for the circuit

design and has to be as detailed and accurate as possible!

3. Circuit development based on the product specification.

   - Define, develop, and simulate the circuit(s).

   - Specify the needed components.

4. Circuit design.

   - Finalize schematics, fix mechanical setup, and PCB layout

5. Final test of the device. Changes or redesign if required.

Request & Circuit development:

We received a request to develop a circuit which measured temperature and transmits the result as an I2C slave. Temperature range should be from -10C to +50C. Use a 5V ±10% supply. If possible a USB or RS232 port.

The further specifications were as follows which were part of specification sheet.

- Accuracy of the whole system - ± (5%rdg + 4dgt)
- Sample rate, stored history - 2V al/min, Values of last two hours
- Information about the environment. Resistance against environmental conditions - inside, normal office
- Mechanical requirements like weight, and size - medium size
- ... and important a timeline and the maximum allowed costs!!
- +5V power supply

Specification:

We started off by dividing our circuit into three functional blocks: power block, Analogue block and digital block.

For Digital Block, we needed ADC, Timer, serial interface, memory for data. All of these components were part of single microcontroller E.g. an Atmega168P or Atmega88P processor used on the Arduino board. It was the optimal solution to use Arduino as it offers nearly any timing, includes an easy controllable 10 bit ADC with acceptable error, enough memory for data and TS232 interface.

For the Analogue Block we require Reference Voltage, Sensor, amplifier. In the circuit other components might also be used like: The reference voltage needs amplification because the output from the controller is to weak. Easy solution is to use a precision OP-Amp in non-inverting configuration as buffer. The next deice is, one or two PT1000 as temperature sensors inside a Wheatstone Bridge to detect the change in resistance. An instrumentation amplifier used as differential amplifier to amplify the output of the bridge circuit.

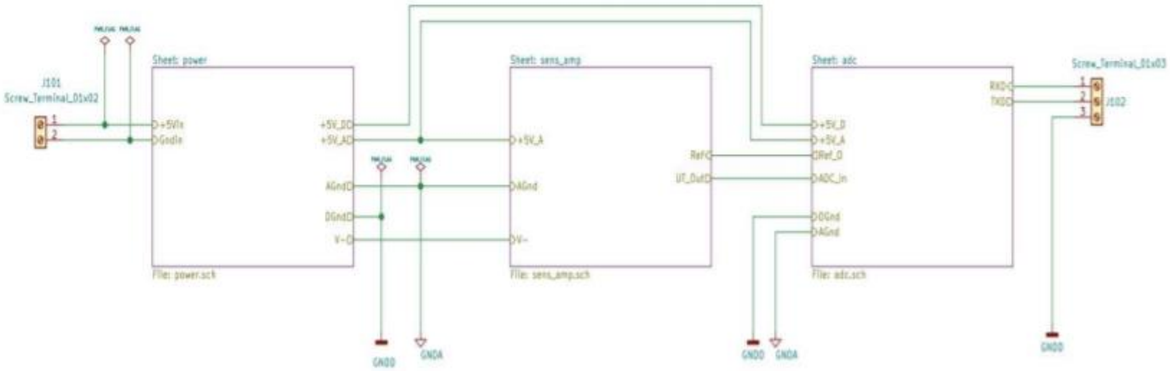
For Power Block, we required to have 5V supply voltage of the circuit. First, we had to determine the power requirements of all active components and the overall power consumption. For every functional block we have to estimate the current then we add up. The controller needs up to 10mA, the two amplifiers up to 1mA supply current, and the current for the reference source is about 1 to 2mA. To be safe, the external supply should deliver 5V ± 10% and $\approx 20mA$, so it is possible to use an USB port which is suitable for the design.

Afterwards, we designed a LC filter to reduce ripple from the power source as ADC and amplifier are sensitive to disturbance/noise. This was done in LT spice too to choose an optimal value of LC components according to requirements.

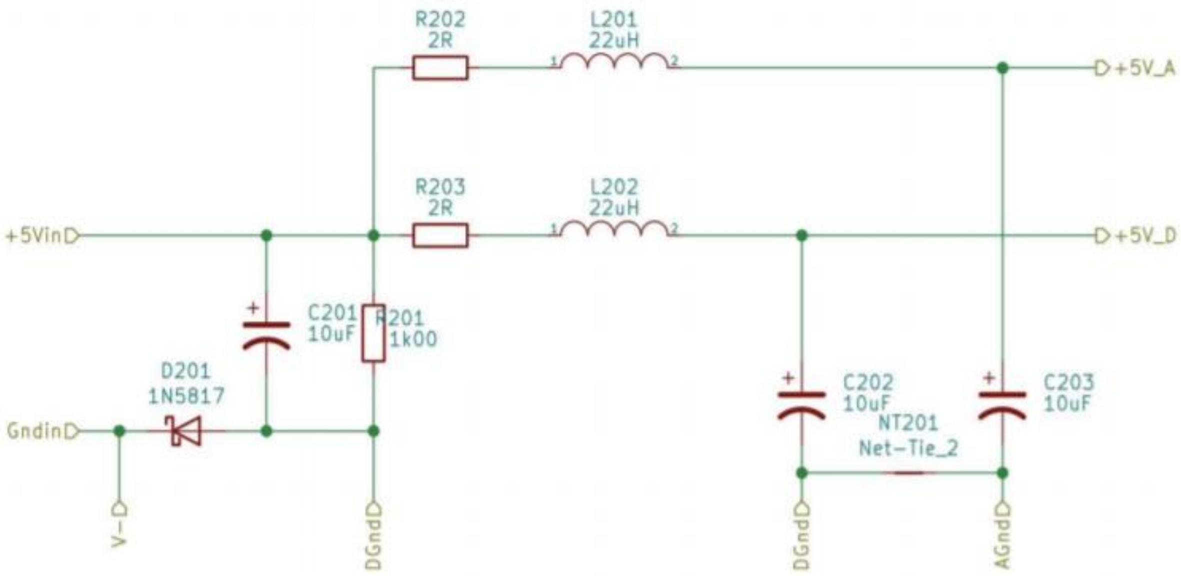
Report Task: Deliver a full set of circuit diagrams with your report.

KiCad Schematics:

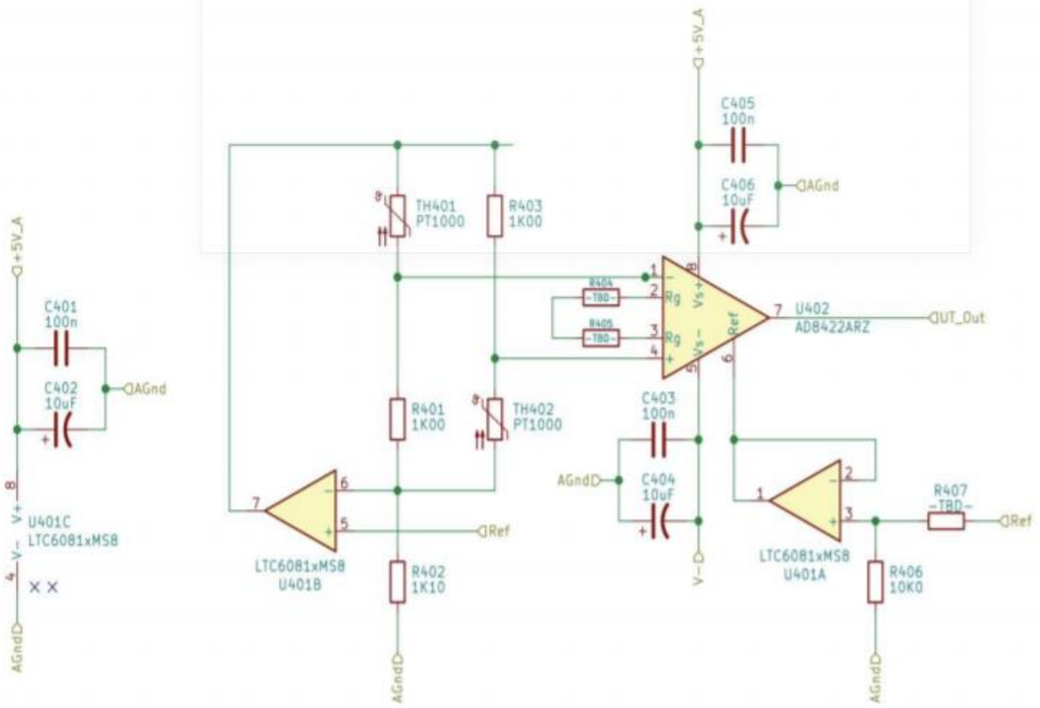
All the schematics were done in KiCad.



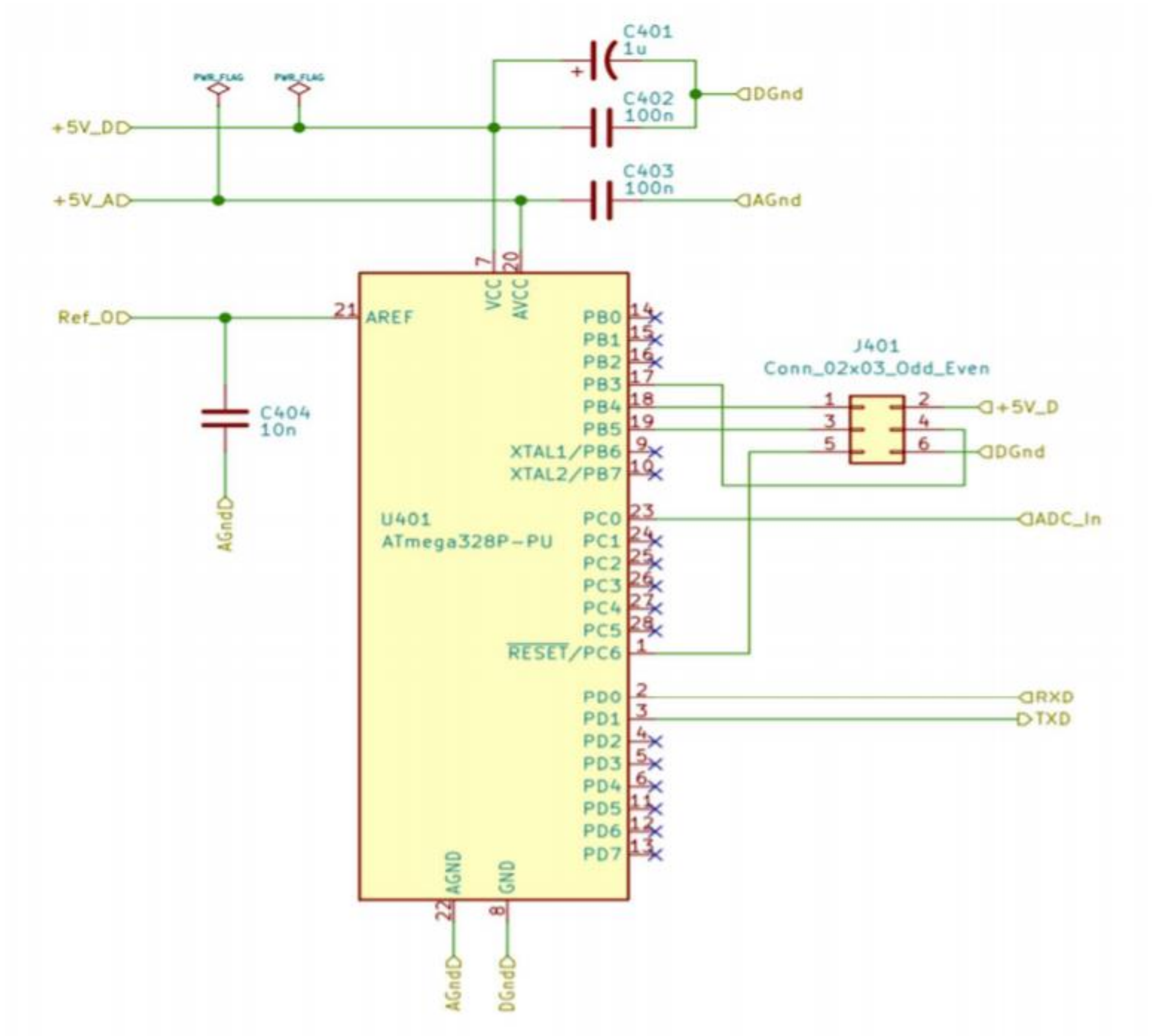
Top Drawing



Power Block



Sense Amp Block



ADC Block

The Engineering Part

Verification: Block Power

Report Task: Simulate the AC behavior of RLC filter in the range of 10Hz to 1Mhz using LTspice

- The detailed result is shown below:

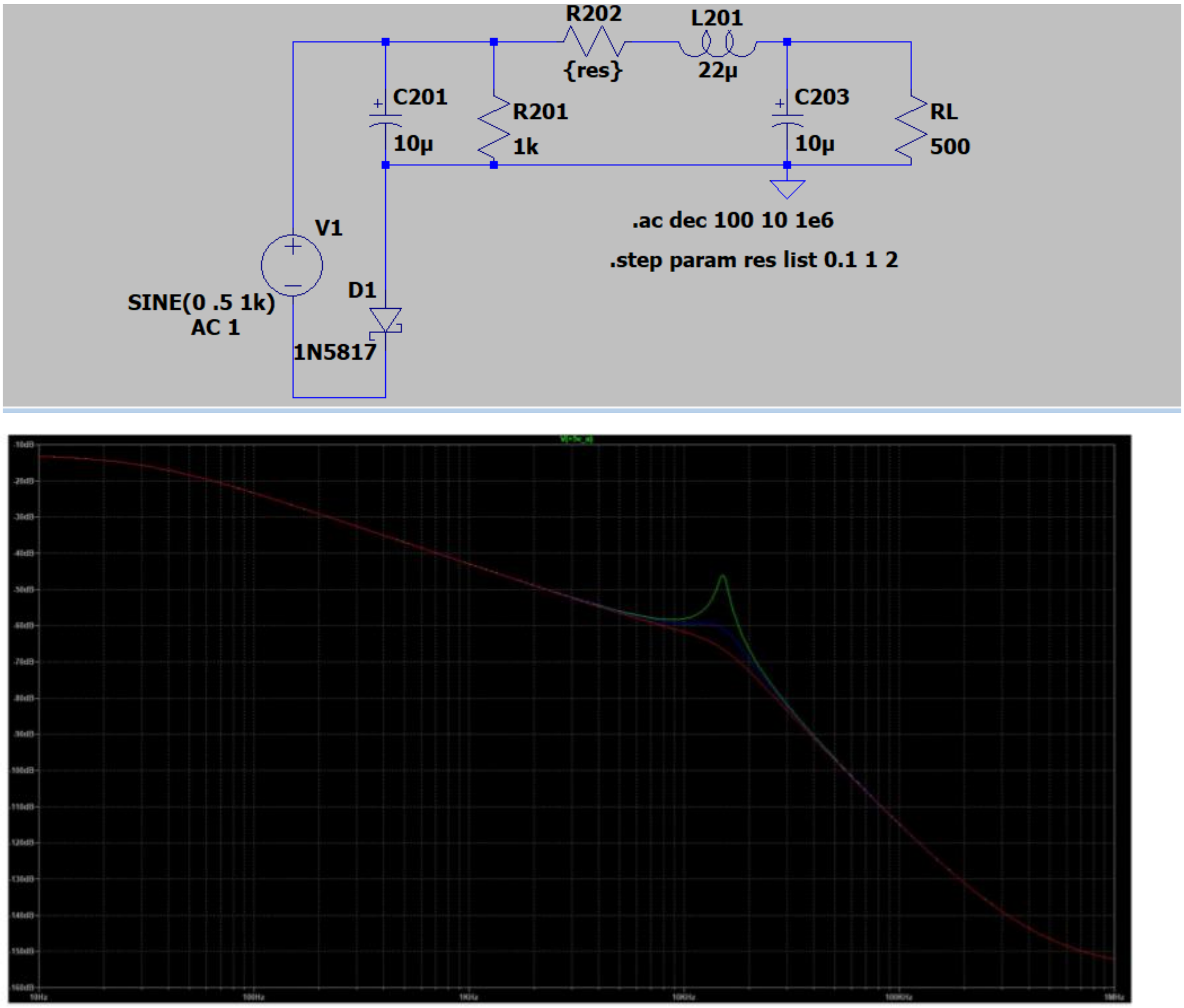


Figure 1:output with aluminium Capacator

Figure 2:Output with tantalum Capacator

According to its graph, Aluminum capacitors seem to perform better. The aluminum capacitor's overall resistance is much lower than a tantalum capacitor's. Aluminum overshoots over only a small range, whereas tantalum overshoots over a longer frequency range. Therefore, I would choose aluminum capacitor for the component.

Verification: Block Sens_Amp

Report Task: Determine the properties of the instrumentation amplifier:

1. What is the purpose of R404+405 and R406+407?

R404 + 405 is used to determine the overall gain of the instrumentation amplifier, and R406 + 407 is used to determine offset values for the output voltage.

2)Use LTSpice and simulate the given Wheatstone Bride without the other components. Carry out two simulations. For both cases simulate for a temperature range from −15 > +55◦C.:

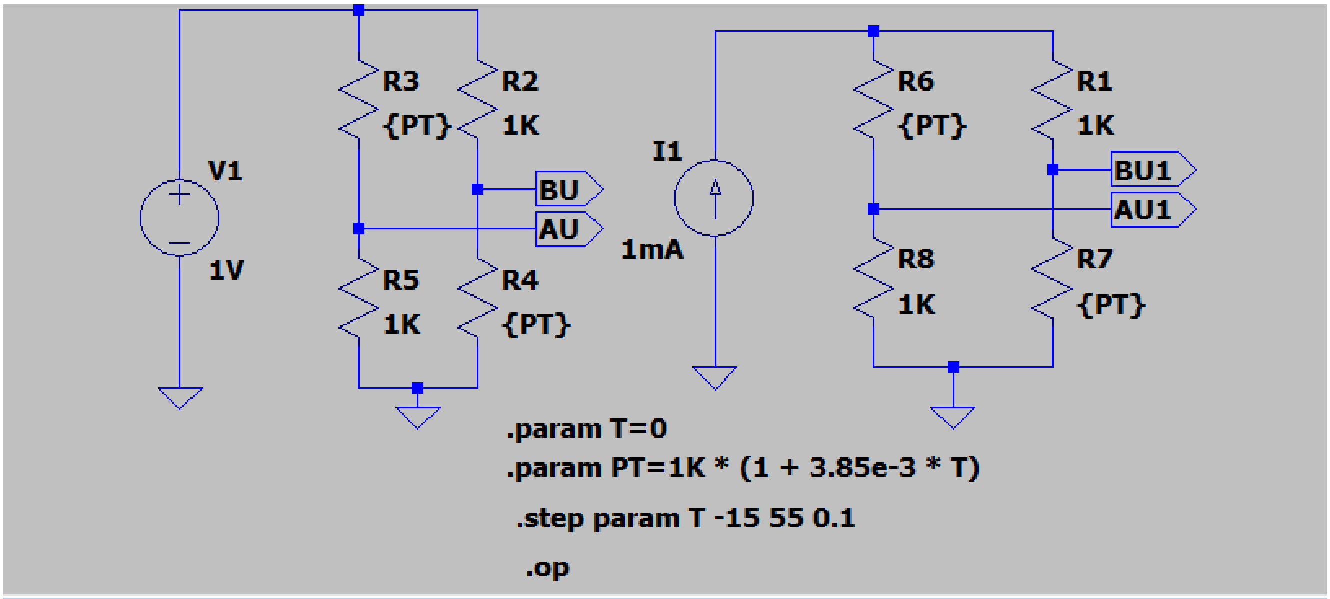


Figure 3:Voltage Difference level with both Voltage source and current source

Where,
V(aa,bb) → is the plot for the 1V reference source.
V(xx,yy) → is the plot for the 1mA reference source.

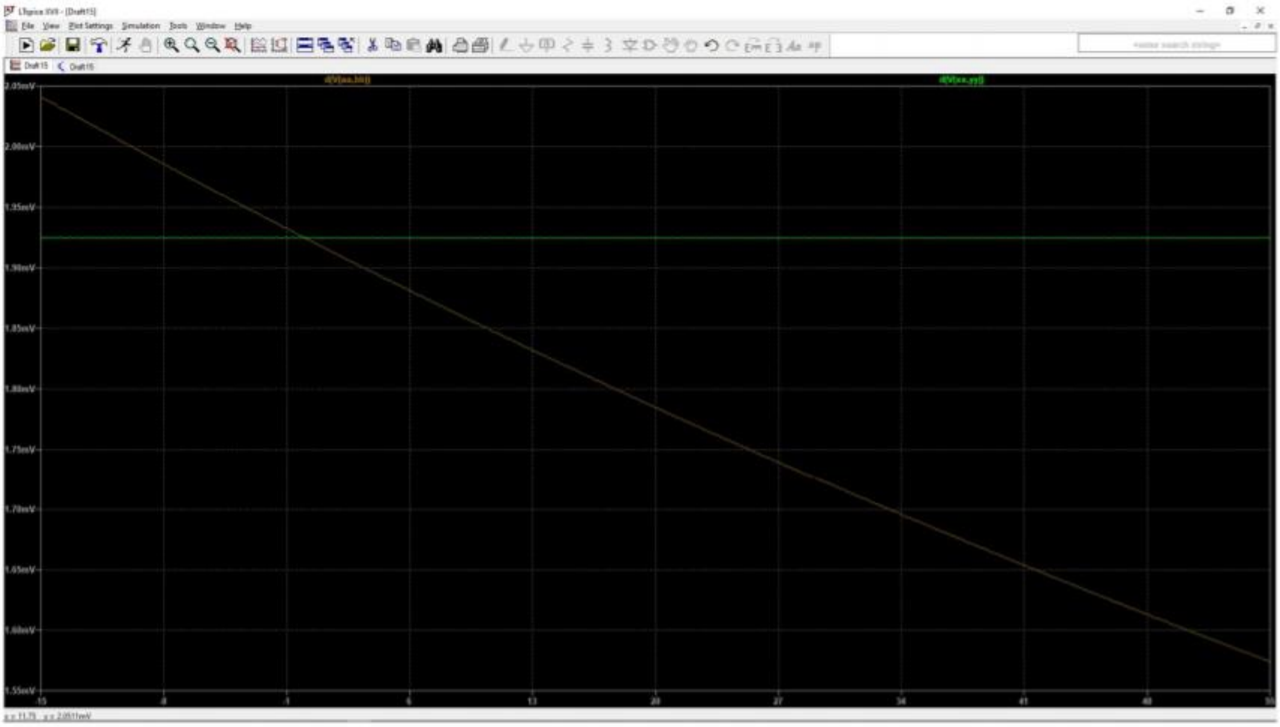


Figure 4:Simulation Plot for linearity check using d() function

Where,
d(V(aa,bb)) → is the derivative plot for the 1V reference source, linearity check.
d(V(xx,yy)) → is the derivative plot for the 1mA reference source, linearity check.

From the plots for voltage difference level it can be seen that the output difference voltage in case of voltage source is not linear, which is further clarified by the derivative plot, where in case of use of voltage source the derivative plot for it is linearly decreasing. While the output difference voltage calculated from using a current source seems to be linear which is supported by its corresponding derivative plot which is a constant.

3)Together with the findings from the previous simulation describe the function of the different parts of the circuit.

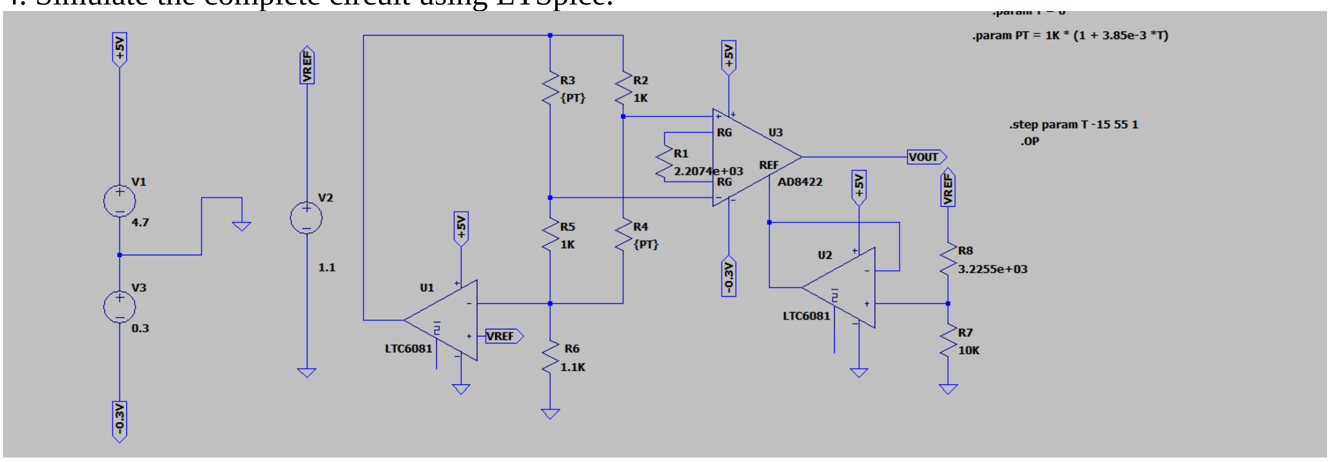
a) How is the Wheatstone bridge supplied? With constant voltage or constant current?

Two operational amplifiers are connected to the Wheatstone bridge in the Sens amp block, i.e. There are two lab manuals (U402 and U401B). Considered carefully, the op-amp U401B acts like a non-inverting amplifier. A reference voltage (Vref) is applied to the non-inverting input. Wheat stone bridge is in the feedback loop of the non-inverting amplifier. Hence, the Wheatstone bridge is supplied with constant current of amplitude (Vref/1k10), where 1k10 is the resistance R402. As given in the previous question the constant current source would be 1 mA.

b) How is the function of the instrumentation amplifier. How can the circuit work with a nearly unipolar power supply. Remember the Bridge delivers a negative / positive output signal over the temperature range.

Its purpose is to provide the output voltage in the range of 0V to 1.1V. A grounded supply will not produce a 0 V output voltage. A negative voltage is required for that. The amplifier amplifies the input supplied voltage and provides the output, so the voltage achieved is always positive. Therefore, the circuit can only be powered by a unipolar power supply.

4. Simulate the complete circuit using LTSpice.



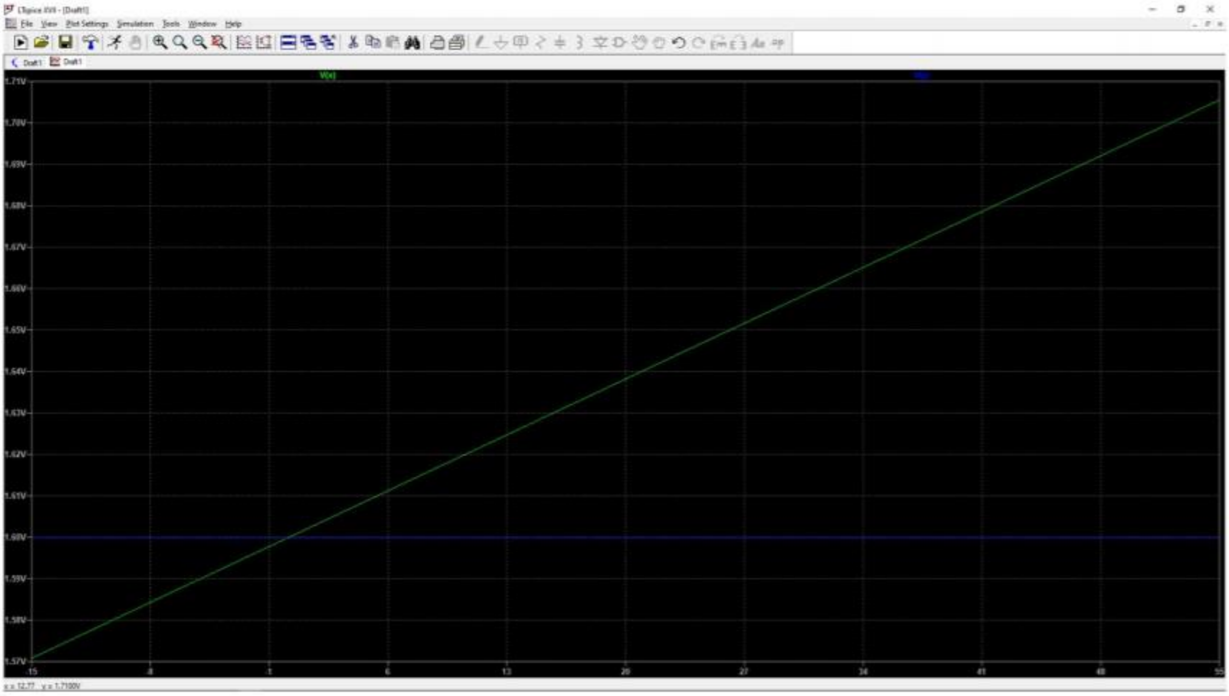


Figure : Simulation Plot for V(x) and V(y)

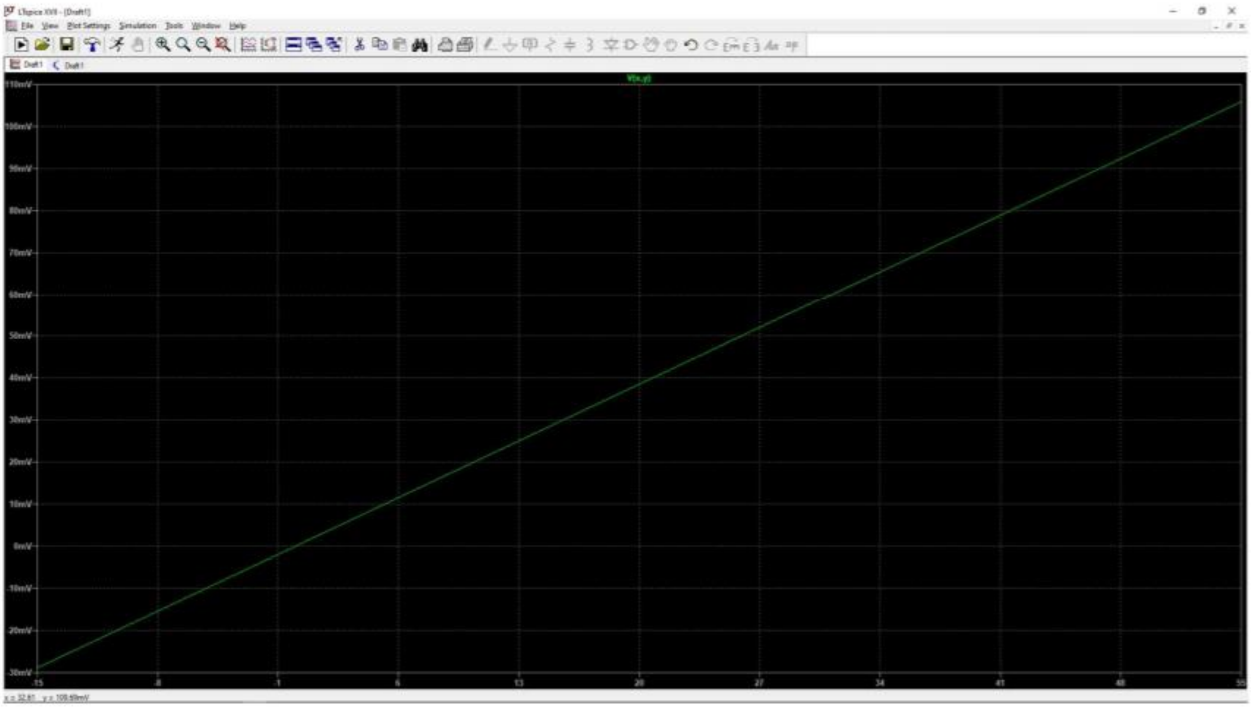


Figure : Simulation Plot for V(x,y), output voltage of the Wheatstone Bridge

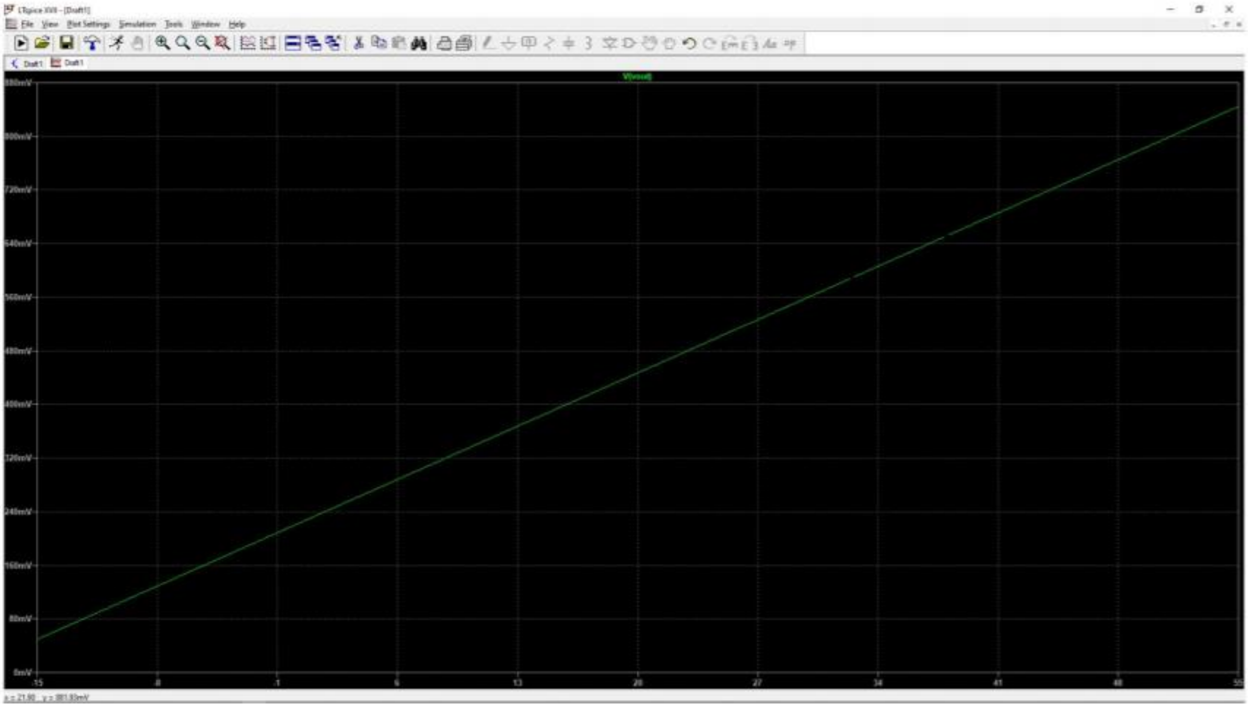


Figure : Simulation Plot for V_{out} , output of the differential amplifier

When visualizing the plot, it is evident that the output plot of the amplifier is indeed linear, but it is not within the specified range from 0 V to 1.1 V. In the given temperature range, it starts at 60 mV and ends at 860 mV. This output plot cannot clarify the nature output.

6. Matlab Codes:

```
% Paramters:
temp_min = -15 ; % Minimum Temperature in Degree Celcius
temp_max = 55 ; % Minimum Temperature in Degree Celcius
Alpha = 3.85 *10^-3; % Temperature Coefficient of Platinum Resistor from Data Sheet
V_Ref = 1.1; % Reference Voltage in Volts
R_Ref = 1100; % Reference Resistance with current I _Ref in ohms R_0 = 1000; % value of
resistance at 0 degrees
R407 = 36500;% These naming of the resistors are done for easiness as per the lab manual circuit
R408 = 165;
R404 = 2610;
R405 = 154;
R_gain = R404 + R405 ;
G = (100k / R_gain) + 1 ; R_div_h =
R407 + R408 ;

% Generating Points in between temperature range:

P = ((temp_max - temp_min) + 1) * 128 ; % no. of points to be selected under the range


% Resistance of Platinum Resistor over the temperature range:

T_P = linspace(temp_min, temp_max , P); % Generating linearly spaced P points between minimum and maximum given temperatures
R_PT = R_0 * (1 + Alpha * T_P); % list of linearly spaced resistance over the range

% offset voltage
V_offset_real = V_Ref * 10e3 /(R_div_h + 10e3) ;


% calculate the ideal linear output V_ad_lin =
linspace (0 ,1.1 ,P);

% Calculating Reference Current I_ref =
(V_Ref) / R_Ref ;


% Calculating bridge voltages over the range and maximum voltage difference V_bridge = I_ref/2 * (R_PT -
R_0);
V_delta = V_bridge(P)- V_bridge(1);

%Voltage amplifier
V_amp = (V_bridge * G) + V_offset_real ;
```

```
% Determining the gain and offset
Gain_Ideal = V_Ref / V_delta ; R_Gain_Used = 19.8e3
/(Gain_Ideal -1); V_offset_real_calc = (-V_bridge(1)) * G ;
I_off_div = V_offset_real_calc / 10e3 ;
R_U_VDiv = (V_Ref - V_offset_real_calc ) / I_off_div ;


% Print the results

fprintf ('a) The choosen resistors are:\nR404 = %4g Ohm\nR405 = %4g Ohm\nR407 = %4g Ohm\nR408
= %4g Ohm\n\n', R404, R405, R407, R408);
fprintf ('b) For the Bridge:\n Vmin = %9.6g V\n Vmax = %9.6g V\n V_diff = %8.6g V\n\n\n',V_bridge(1), V_bridge(P),
V_delta);
fprintf ('c) For the Calculated case: \nThe Gain Resistor (R_Gain) = %4g Ohm\nGain(G)=
%6.4f\n\n',R_Gain_Used,Gain_Ideal);
fprintf ('d) For the Selected Case:\nThe Gain Resistor (R_Gain) = %4g Ohm \nGain(G) =
%6.4f\n\n', R_gain , G);
fprintf ('e) Voltage Offset : %6.4gV with the upper resistance of : %4u ohm\n\n', V_offset_real_calc,R_div_h);
fprintf ('f) Offset voltage divider (The Resistors) : lower end = %6.2f ohm and higher end =
%6.2f ohm\n\n', 10e3, R_U_VDiv);


%Plot for the Bridge Voltage from temp_min to temp_max plot (T_P, V_bridge);
tit = sprintf ('Bridge voltage over range %+d to %+d degree',temp_min, temp_max); title (tit)
xlim([temp_min temp_max]); ylim([-
0.05 0.15]);
xlabel('TEMPERATURE / [deg C]'); ylabel('V /
[v]');

%Plot for Ideal Output and Amplifier Output for Comparison plot (T_P,V_ad_lin);
hold on;
plot (T_P, V_amp);
tit = sprintf ('Ideal Output and Amplifier Output over range %+d to %+d degree', temp_min
,temp_max);
title(tit);
xlim ([temp_min temp_max]); ylim ([0
1.2]);
xlabel('TEMPERATURE / [deg C]'); ylabel('V /
[v]');


%third figure with error
error = (V_ad_lin - V_amp) /V_ad_lin *100; plot (T_P, error);
```

Command Window

```
a) The choosen resistors are:
R404 = 2610 Ohm
R405 =  154 Ohm
R407 = 36500 Ohm
R408 =  165 Ohm

b) For the Bridge:
 Vmin = -0.028875 V
 Vmax =  0.105875 V
 V_diff =  0.13475 V


c) For the Calculated case:
The Gain Resistor (R_Gain) = 2764.1 Ohm
Gain(G)= 8.1633

d) For the Selected Case:
The Gain Resistor (R_Gain) = 2764 Ohm
Gain(G) = 8.1635

e) Voltage Offset : 0.2357V with the upper resistance of : 36665 ohm

f) Offset voltage divider (The Resistors) : lower end =  10000.00 ohm and higher end = 36665.15 ohm
```

From the calculations above, it can be analyzed that we need to adjust the resistance of our gain and offset resistors in order to achieve the desirable outcomes.

6) Verify the calculated values using the LTSpice simulation from before.

Based on the data obtained from the previous MATLAB calculations. During the previous LTSpice simulations, the gain resistor at the instrumentation amplifier and the offset resistor at the op-amp U401A were changed, and the results are shown below:

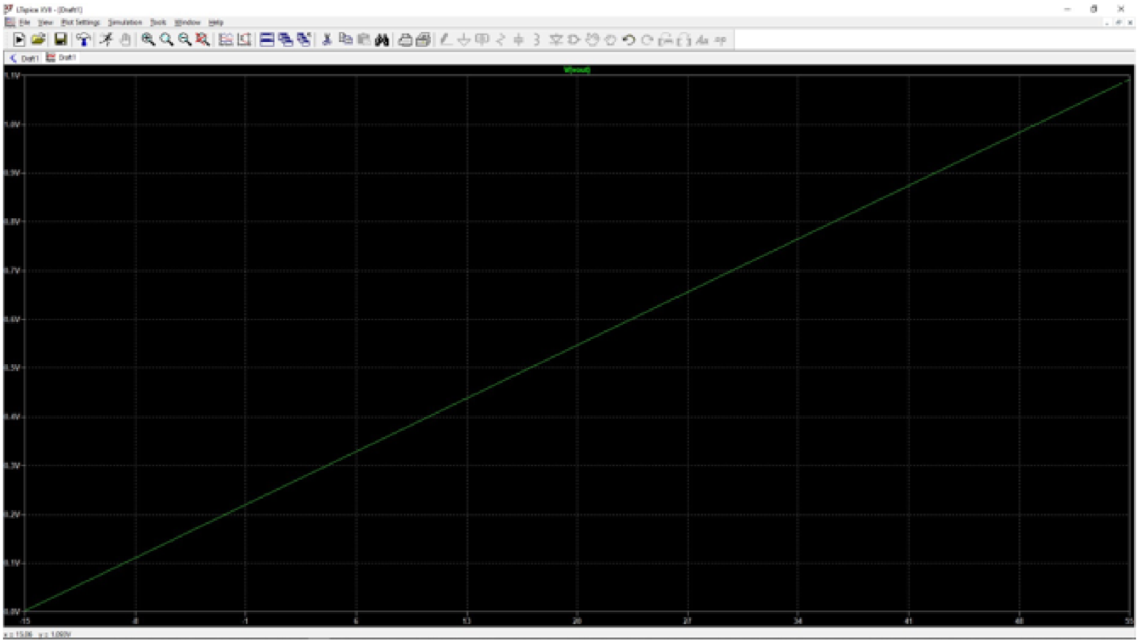


Figure: Updated Output plot of differential amplifier in the range of 0 - 1.1 v

Error Estimation:

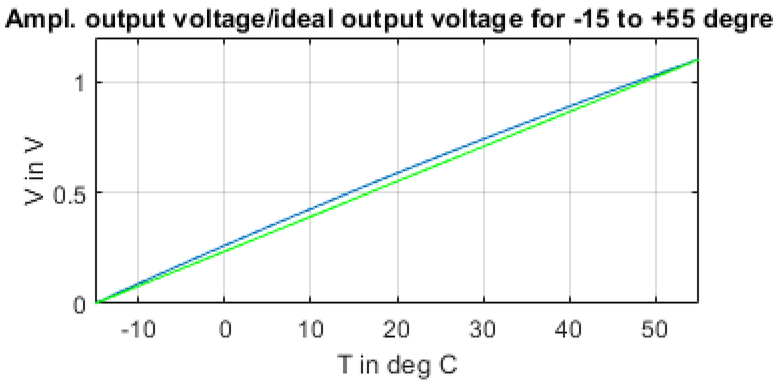
The circuit we have contains errors in the values of the components that are caused from the instrumentation amplifier and output of the wheat-stone. ADC contributes to more error.

Error of Wheatstone bridge

Bridge			
V_{Ref}	10%	$100000ppm$	cal
Resistors 0.1%	0.3%	$3000ppm$	fix
Bridge Nonlinearity	5%	$50000ppm$	cal

- The resistor error(tolerance) is fix unless we use resistors with better accuracy.
- The error of the reference can be removed by system calibration(cal).
- The output of a Wheatstone bridge with only one varying leg is not linear!

The way we are using wheat-stone bridge is not optimal. The error can be eradicated using different rules and development or the table or by deriving a function applied in MC to remove the non-linearity. The difference between ampl. output voltage (Wheat-stone) vs ideal ampl. Output voltage (Linear) is shown above with MATLAB script as well as stated here:



Error From instrumentation amplifier:

Error of instrumentation amplifier

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

- The linearity, gain, offset, and CMR errors can all be removed by a system calibration. Selected resistors may highly improve the error!!
- The remaining errors gain nonlinearity and 0.1Hz to 10Hz noise cannot be removed with calibration and ultimately limit the system resolution.

The uncalibrated error of the analog part is approximately 16% i.e.160000ppm. It is possible to reduce it to approximately 1% by calibrating the circuit either by selected components or in the MC program. Therefore, the accuracy of the analog part is inside the request.

The ADC adds about 5 digits error since it is not linear. Since the Resolution is 70°C/1024 = 68.4m°C this is an additional error of 5dig * 68.4m°C ≈ 350m°C. Anyhow, the result is acceptable.

How to improve the design?

_ Better resistors with 0.01% tolerance.
_ Use better circuit to read the wheat-stone bridge.
_ Better ADC (tolerance, resolution, linearity)
_ Better instrumentation amplifier
_ Use a sensor circuit without non-linearity!

Selection of Components:

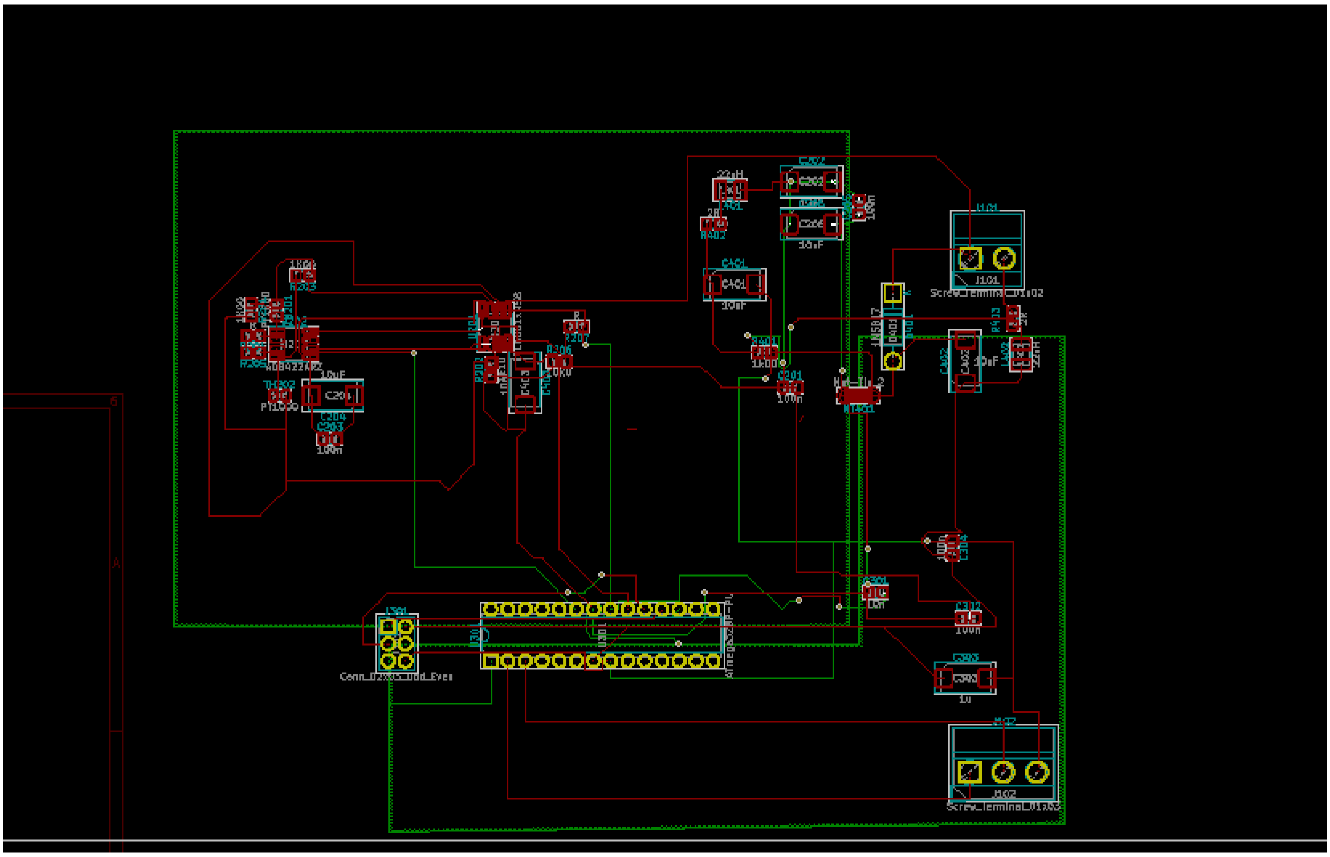
Symbol : Footprint Assignments

1	C201 -	100n :	Capacitor_SMD:C_0805_2012Metric_Pad1.18x1.45mm_HandSolder
2	C202 -	10uF :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
3	C203 -	100n :	Capacitor_SMD:C_0805_2012Metric_Pad1.18x1.45mm_HandSolder
4	C204 -	10uF :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
5	C205 -	100n :	Capacitor_SMD:C_0805_2012Metric_Pad1.18x1.45mm_HandSolder
6	C206 -	10uF :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
7	C301 -	10n :	Capacitor_SMD:C_0805_2012Metric_Pad1.18x1.45mm_HandSolder
8	C302 -	100n :	Capacitor_SMD:C_0805_2012Metric_Pad1.18x1.45mm_HandSolder
9	C303 -	1u :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
10	C304 -	100n :	Capacitor_SMD:C_0805_2012Metric_Pad1.18x1.45mm_HandSolder
11	C401 -	10uF :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
12	C402 -	10uF :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
13	C403 -	10uF :	Capacitor_Tantalum_SMD:CP_EIA-7343-20_Kemet-V_Pad2.25x2.55mm_HandSolder
14	D401 -	1N5817 :	Diode_THT:D_DO-41_SOD81_P10.16mm_Horizontal
15	J101 -	Screw_Terminal_01x02 :	TerminalBlock_MetzConnect:TerminalBlock_MetzConnect_Type011_RT05502HBWC_1
16	J102 -	Screw_Terminal_01x03 :	TerminalBlock_MetzConnect:TerminalBlock_MetzConnect_Type011_RT05503HBWC_1
17	J301 -	Conn_02x03_Odd_Even :	Connector_PinHeader_2.54mm:PinHeader_2x03_P2.54mm_Vertical
18	L401 -	22uH :	Inductor_SMD:L_1210_3225Metric_Pad1.42x2.65mm_HandSolder
19	L402 -	22uH :	Inductor_SMD:L_1210_3225Metric_Pad1.42x2.65mm_HandSolder
20	NT401 -	Net-Tie_2 :	NetTie:NetTie-2_SMD_Pad2.0mm
21	R201 -	1K00 :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
22	R202 -	1K10 :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
23	R203 -	1K00 :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
24	R204 -	R :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
25	R205 -	R :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
26	R206 -	10K0 :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
27	R207 -	R :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
28	R401 -	1k00 :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
29	R402 -	2R :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
30	R403 -	2R :	Resistor_SMD:R_0805_2012Metric_Pad1.20x1.40mm_HandSolder
31	TH201 -	PT1000 :	Resistor_SMD:R_0805_2012Metric

To fix the components for the PCB, we were given size and we needed to consider type and manufacturer of components.

PCB DESIGN:

For our schematic, we generate a Netlist and assign footprints as required. The Netlist is read by the PCB editor and we get our PCB design. Now we conduct routing after putting all the elements at their proper position. The KiCad Schematics are added in Report Task. Final layout is shown below without taking care of grounding scheme, line width:



Conclusion

Students gained a basic understanding of how an electronic device is designed in the PCB design lab. Ki Cad was used for the design of a PCB using various circuit design rules. It was subdivided into a power part, an analog part, and an electronic part. All blocks were designed separately with design rules applied in order to ensure no errors occurred. Primarily, the engineering part was done first, and then the placing and routing part was done during the second half of the lab session. We (the new comers) found the routing task challenging in the beginning and also quite interesting to do. In conclusion, this lab enabled us to gain a better understanding of how new devices and circuit boards are designed and printed in the technical industry in general.

References:

Uwe Pagel – Instructor

Lab Manual – Designed by Uwe Pagel

Matlab Resources from internet