Jacobs University Bremen

CA11-300303
ECE Specialization Areas Lab

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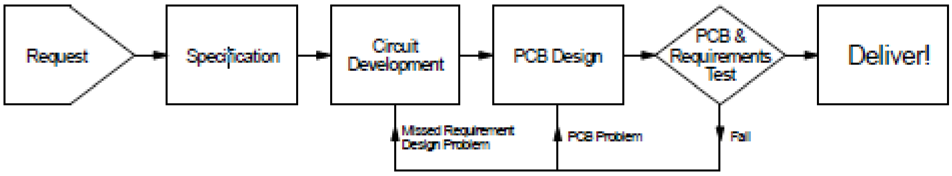
Objectives:

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 Analogue Block, we required Reference Voltage, Sensor, amplifiers. Since we want to measure accurate, we need an accurate reference voltage against we can compare. The MC includes a 1.1V reference voltage source we can use for the analog part (1.074mV/bit). But the reference voltage is too weak. Therefore, we used amplifier for the reference voltage that was a precision OP-Amp in non-inverting configuration. We used PT1000 as a temperature sensor inside a Wheatstone Bridge to detect the change in resistance. We also used an instrumentation amplifier (like an AD623) used as differential amplifier to amplify the output of the bridge circuit.

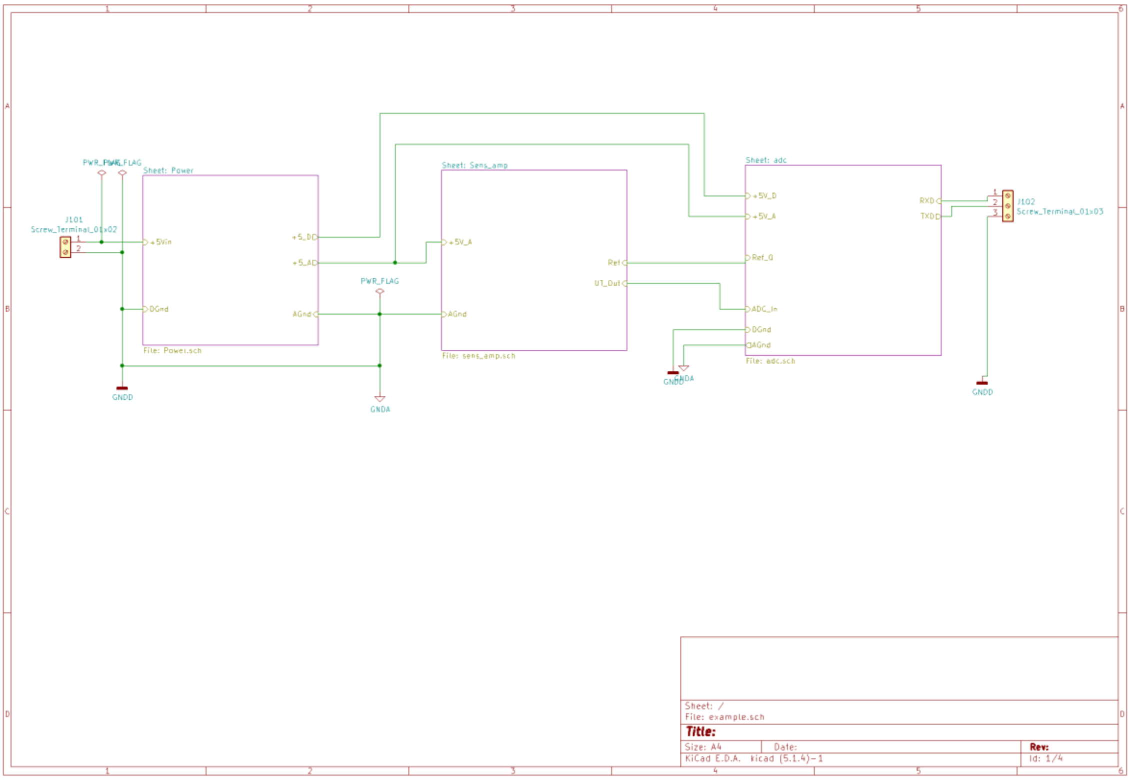
For Power Block, we required to have 5V supply voltage of the circuit. First, we had to determine the power requirements of all active components and the overall power consumption. For every functional block we have to estimate the current then we add up. The controller needs up to 10mA, the two amplifiers 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.

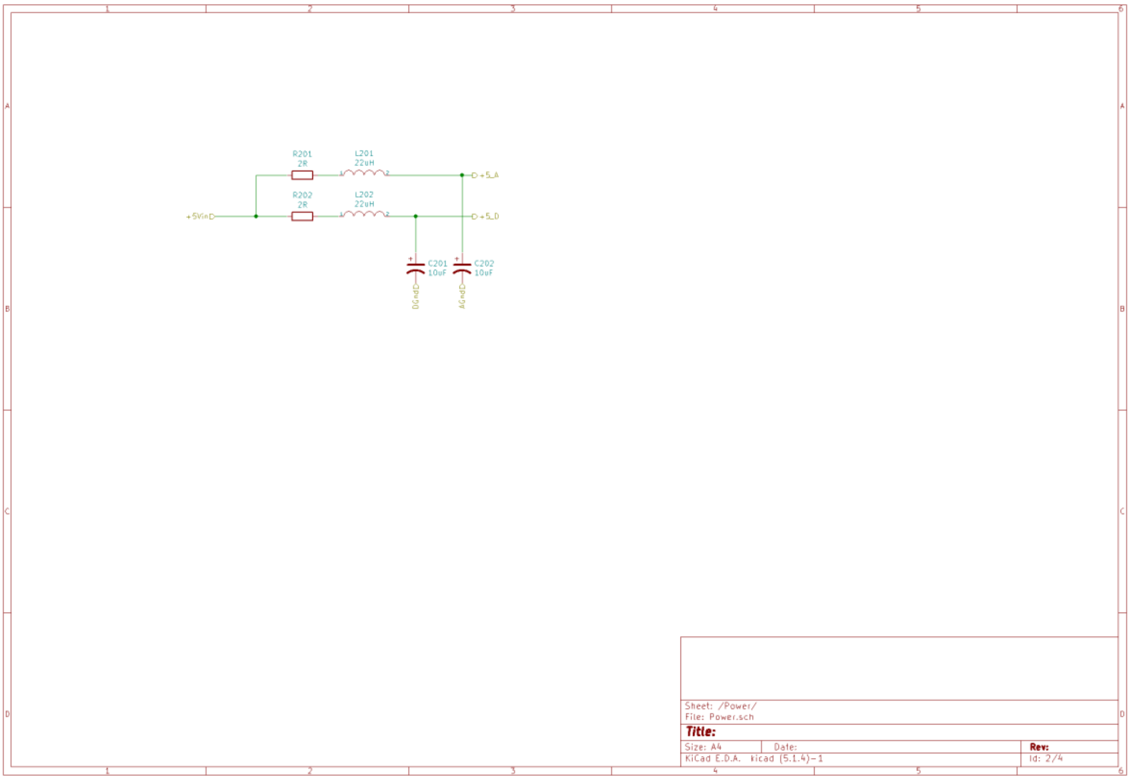
Report Task: Deliver a full set of circuit diagrams with your report.

KiCad Schematics:

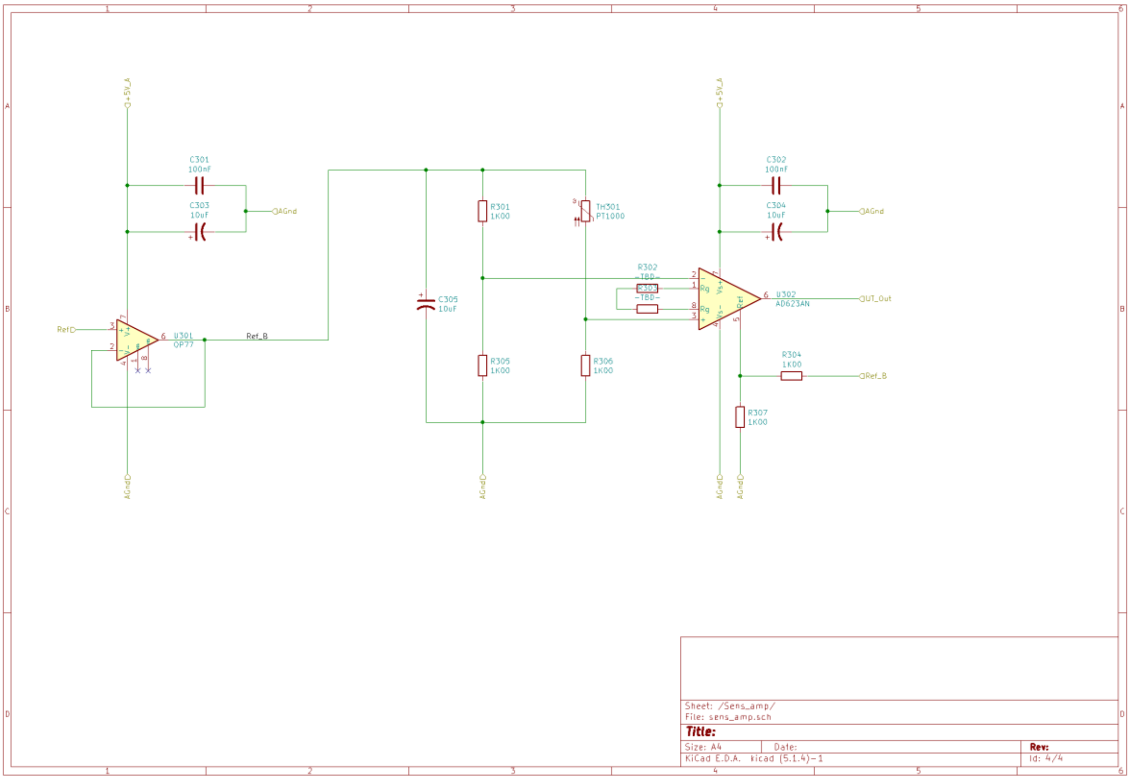
All the schematics were done in KiCad.



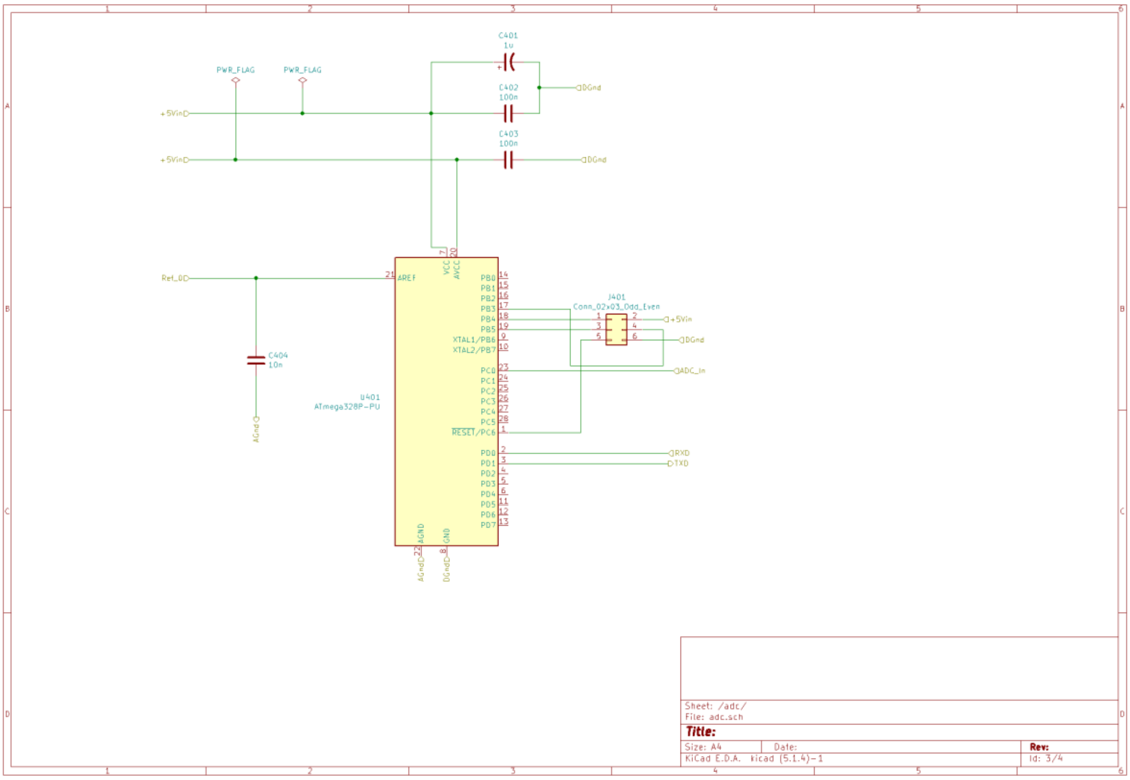
Top Drawing



Power Block



Sense Amp Block



ADC Block

The Engineering Part

Verification: Block Power

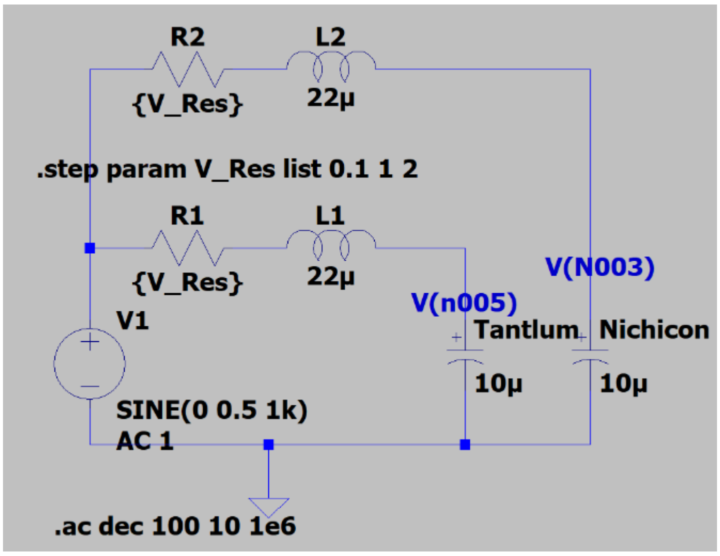
Report Task: Simulate the AC behavior of RLC filter in the range of 10Hz to 1Mhz using LTspice

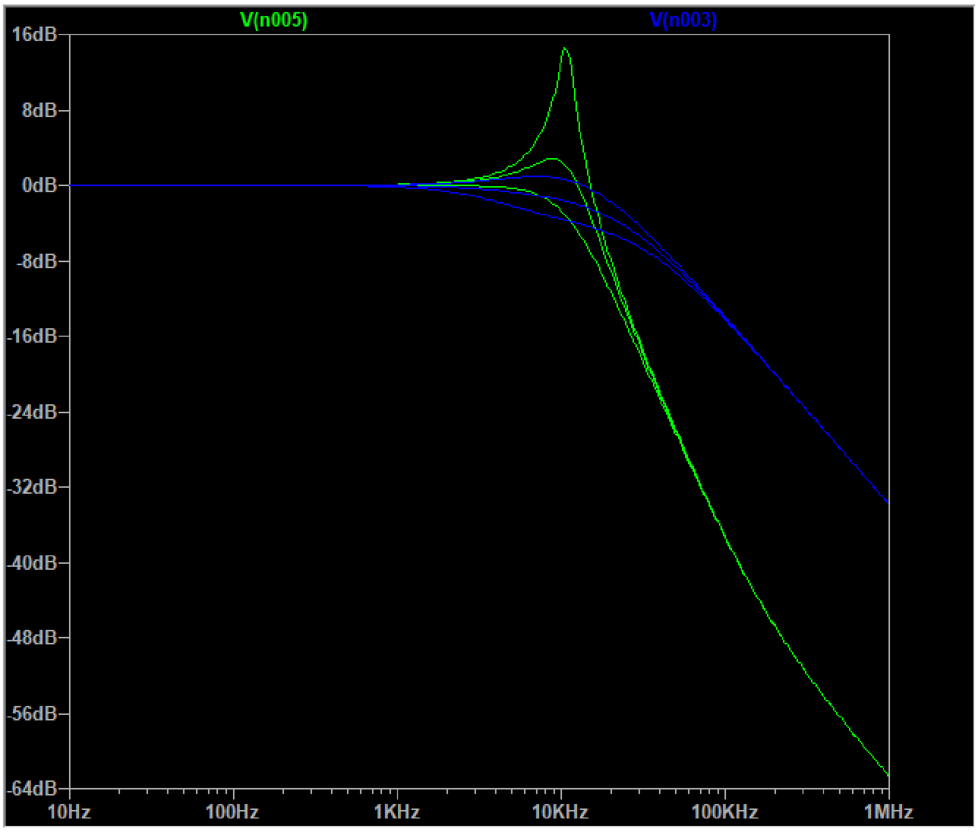
We simulated the power block using Low resistance coil with high enough current rate e.g. a Coilcraft DT3316P-223 with L = 22uH. We did simulation in LTspice with different values of R and different types of capacitors to observe different behaviors of power block. We ran our simulation with:

- a tantalum low ESR capacitor KEMET T521B106M016ATE100 with C = 10uF

- an Al type Nichicon UPR1C100MAH with C = 10uF

The detailed result is shown below:





V(n003) shows the characteristics of Nichicon capacitor and V(n005) shows characteristics of Tantalum capacitor. The tantalum capacitor has steeper response. Therefore, we choose tantalum capacitor. The cut-off frequency in the tantalum low ESR capacitor is higher than that of the Nichicon capacitor.

As the resistance is reduced, we see the change in damping, causing an overshoot in the Bode Plot.

Verification: Block Sens_Amp

Report Task: Determine the properties of the instrumentation amplifier:

1. Describe the function of the circuit. Especially the part with the instrumentation amplifier. What is the purpose of R302+303 and R304+307?

The function of this circuit is to measure the temperature and pass it on to ADC for processing. Instrumentation amplifier is used since the reference voltage from controller is very weak. It amplifies the output wheat-stone bridge voltage to range 0-1.1V. Our load is approximately $\frac{V_{Ref}}{1K\Omega+10K\Omega}$ that is bridge current and current to reference pin of the AD623. R302+303 allows to select any gain within the operating region of the device.

The output voltage at Pin 6 is measured with respect to the potential at Pin 5. The impedance of the reference pin is 100 kΩ; therefore, in applications requiring voltage conversion, a small resistor or set of resistors is added to not limit the increasing gain.

304 & 307 adds an offset to the input voltage of the amplifier so that we avoid negative input. Otherwise it is impossible to use a unipolar supply as amplifier only uses unipolar supply i.e. +5V.

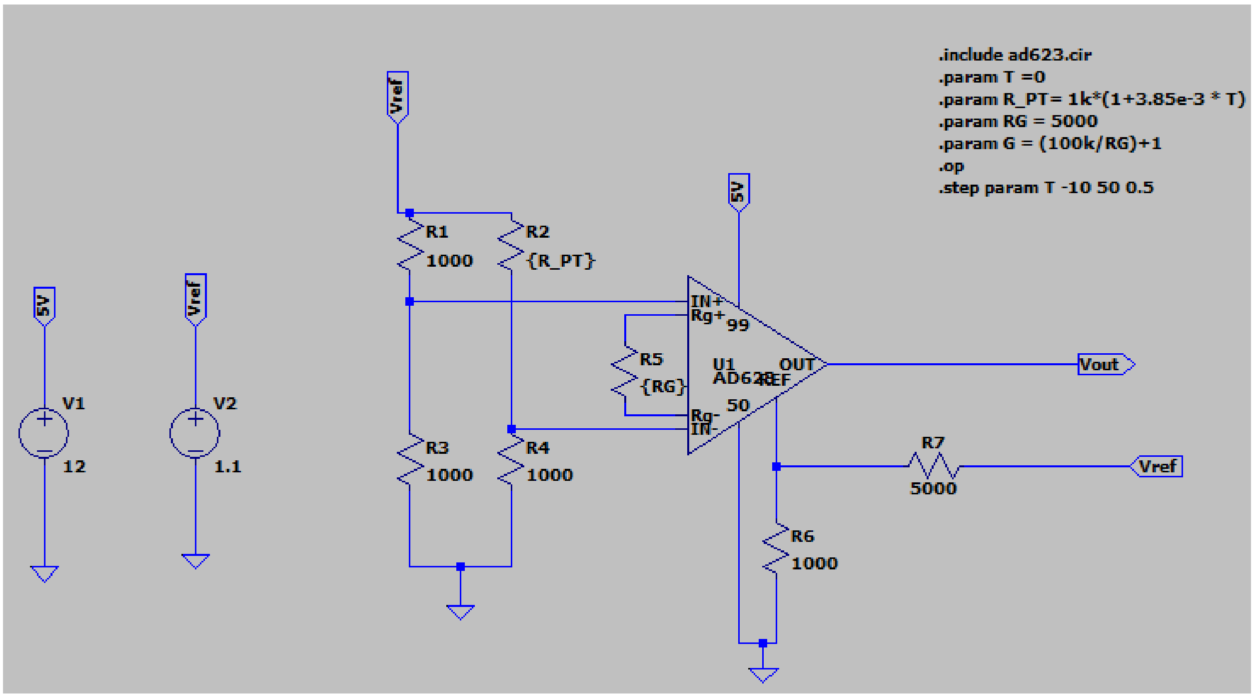
2.Simulate the Wheatstone bridge together with the differential amplifier using LTSpice.

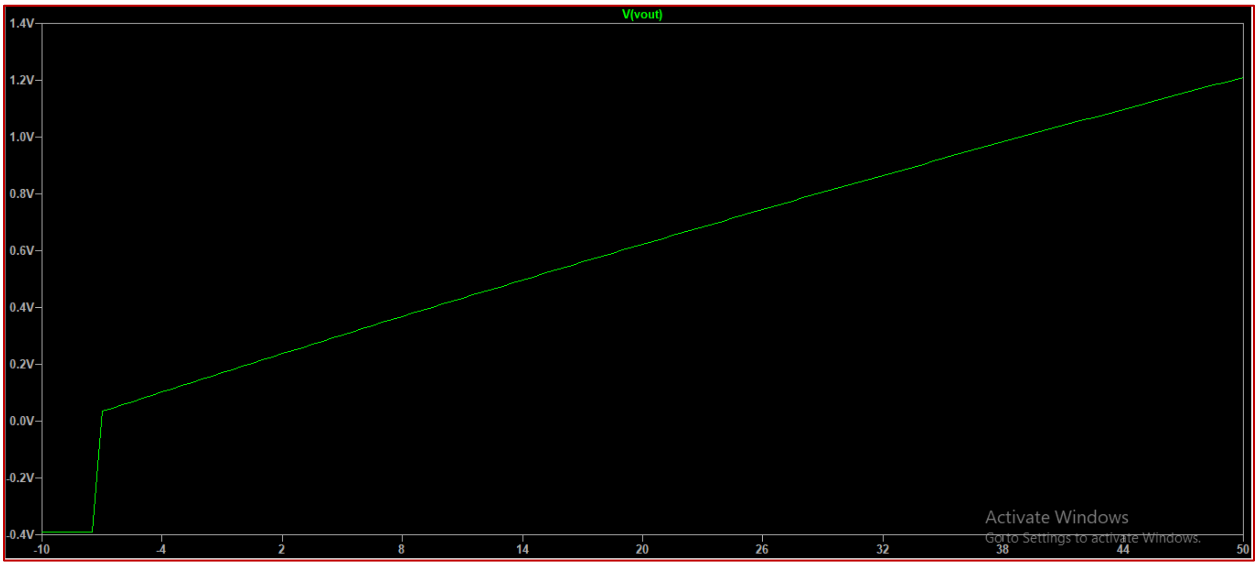
We followed the following and the schema and results are shown on next page:

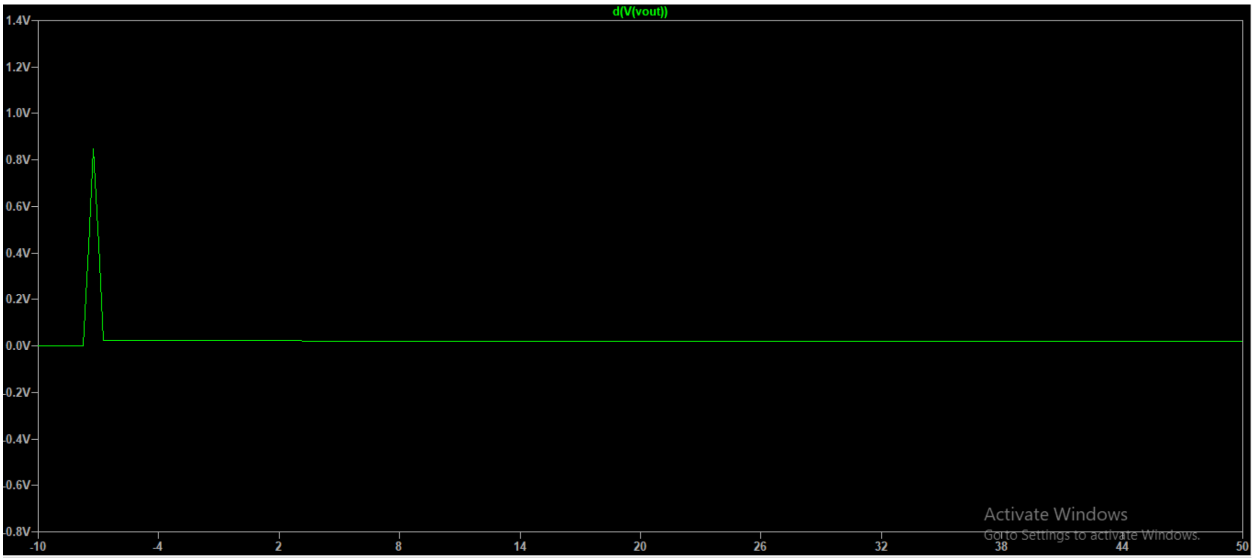
- Set the unknown resistors R302+R303 to 5000 and R304 also to 5000.

- Simulate for the requested temperature range -10 to +50 C.

- A Spice model for the AD623 is available on the Web site.


.include ad623.cir
.param T =0
.param R_PT= 1k*(1+3.85e-3 * T)
.param RG = 5000
.param G = (100k/RG)+1
.op
.step param T -10 50 0.5
Vref
R1
1000
R2
{R_PT}
R3
1000
R4
1000
R5
{RG}
R6
1000
R7
5000
5V
V1
12
Vref
V2
1.1
U1
AD623
IN+
Rg+
Rg-
IN-
OUT
REF
99
50
Vout
Vref


V(vout)
1.4V
1.2V
1.0V
0.8V
0.6V
0.4V
0.2V
0.0V
-0.2V
-0.4V
-10
-4
2
8
14
20
26
32
38
44
50
Activate Windows
Go to Settings to activate Windows.


d(V(vout))
1.4V
1.2V
1.0V
0.8V
0.6V
0.4V
0.2V
0.0V
-0.2V
-0.4V
-0.6V
-0.8V
-10
-4
2
8
14
20
26
32
38
44
50
Activate Windows
Go to Settings to activate Windows.

If we look at the Vout, it does not seem like a continuous rising linear function. It is because, the gradient decreases.

It is also amplifying in negative region although our voltage source is positive. Because of that we see the jump in the output voltage as shown on the red bordered picture above.

3. You should have seen that the output is not useful! The Wheatstone Bridge has a bipolar output but the instrumentation amplifier can only word unipolar because of the unipolar power supply.

The solution is to amplify the small _ input voltage and add an offset to the result. So −10 C to 50 C will become to 0V to 1:1V at the amplifier output. 0 is then the ADC value for -10_C. The amplifier is prepared to shift the zero point. Check the data sheet! First the gain is set by the resistors R302 and R303. The offset to add to the output is defined by the voltage divider R304 and R307.

```
clc; clear all;

V_ref = 1.1; %ADC reference voltage

r_0 = 1000; % 0 degree resistance for PT1000

alpha = 3.85e-03; %Temp coeff. of PT1000

temp_min = -15;

temp_max = 55;

r_div_l = 1000;

adc_bits = 10; %number of ADC bit



%length of vectors

pts = ((temp_max - temp_min) + 1)*16; % +1 to include all the values.



%PT1000

temp = linspace(temp_min, temp_max, pts); %Creating temperature range

R_PT = r_0 * (1 + alpha * temp); % Resistance of PT from PT formula
```

```
%Bridge voltage and max difference

V_bridge = V_ref * ((R_PT./(r_0 + R_PT)) - (r_0./(r_0 + r_0)));



%Finding the max voltage difference as we need to make the max val fit in

%adc range

V_delta = V_bridge(pts) - V_bridge(1);



%gain

G_th = V_ref / V_delta; %amplification required

r_gain_th = 100e3 / (G_th - 1);



%selecting resistors from std.series calculating resulting...

%gain

r_gain = 6690;

G = (100e3 / r_gain) + 1;



%find offset for amplifier

V_offset = (0 - V_bridge(1)) * G;



%offset volatge divider

i_off_div = V_offset / r_div_l;

r_div_h_calc = (V_ref - V_offset) / i_off_div;
```

```
%From slides, the value of offset we we use is below

r_div_h = 3200;

V_off = V_ref * r_div_l / (r_div_h + r_div_l);



%Output of op-amp

V_amp = (V_bridge * G) + V_off;

u_ad_lin = linspace(0, 1.1, pts); %ideal linear output



%printing results`

fprintf('Bridge Vmin@%2gDeg = %6.4gV \n', temp_min, V_bridge(1));

fprintf('-Vmax%2gDeg = %6.4gV -- Vdiff = %6.4gV \n', temp_max, V_bridge(pts),
V_delta);

fprintf('Amplification for ADC with ref %3.2gV is %g \n', V_ref, G);

fprintf('Selected gain resistor for AD623 is %6.2f results to G = %5.2f \n',
r_gain, G);

fprintf('Offset at the amplifier is %6.4gV \n', V_offset);

fprintf('Offset voltage divider - R_lo = %6.2f - R_hi = %6.2f \n',r_div_l,
r_div_h_calc);

fprintf('Selected R_hi = %4u results to offset voltage %6.4gV \n', r_div_h, V_off);

%plotting results

scrsz = get(0, 'ScreenSize');

width = scrsz(3)/3.5; height = scrsz(4)/4;

f = figure('Position', [10 scrsz(4)-80-scrsz(4)/4 width height]);

plot(temp, V_bridge); grid;

tit = sprintf('Bridge voltage over range %+d to %+d degree', temp_min, temp_max);

title(tit)
```

```
xlim([temp_min temp_max]);

xlabel('T in deg C'); ylabel('V in V');

f1= figure('Position', [10 scrsz(4)-2*80-2*scrsz(4)/4 width height]);plot(temp,
V_amp); hold on;

plot(temp, u_ad_lin, 'Color', [0 1 0]); grid;

tit = sprintf (['Ampl. output voltage/ideal output voltage for %+d to %+d degree'],
temp_min, temp_max);

title(tit)

xlim([temp_min temp_max]); ylim([0 1.2]);

xlabel('T in deg C'); ylabel('V in V');

err = (u_ad_lin(2:end) - V_amp(2:end)) ./u_ad_lin(2:end)*100;

f2= figure('Position', [10 scrsz(4)-3*80-3*scrsz(4)/4 width height]);

plot(temp(2:end), err); grid;

tit = sprintf('Error for %+d to %+d degree', temp_min, temp_max);

title(tit)

xlim([temp_min temp_max]); ylim([-15 5])

xlabel('T in deg C'); ylabel('V in V');
```

```
Bridge Vmin@-15Deg = -0.01635V

-Vmax55Deg = 0.05266V -- Vdiff = 0.06901V

Amplification for ADC with ref 1.1V is 15.9477

Selected gain resistor for AD623 is 6690.00 results to G = 15.95

Offset at the amplifier is 0.2608V

Offset voltage divider - R_lo = 1000.00 - R_hi = 3217.80

Selected R_hi = 3200 results to offset voltage 0.2619V
```

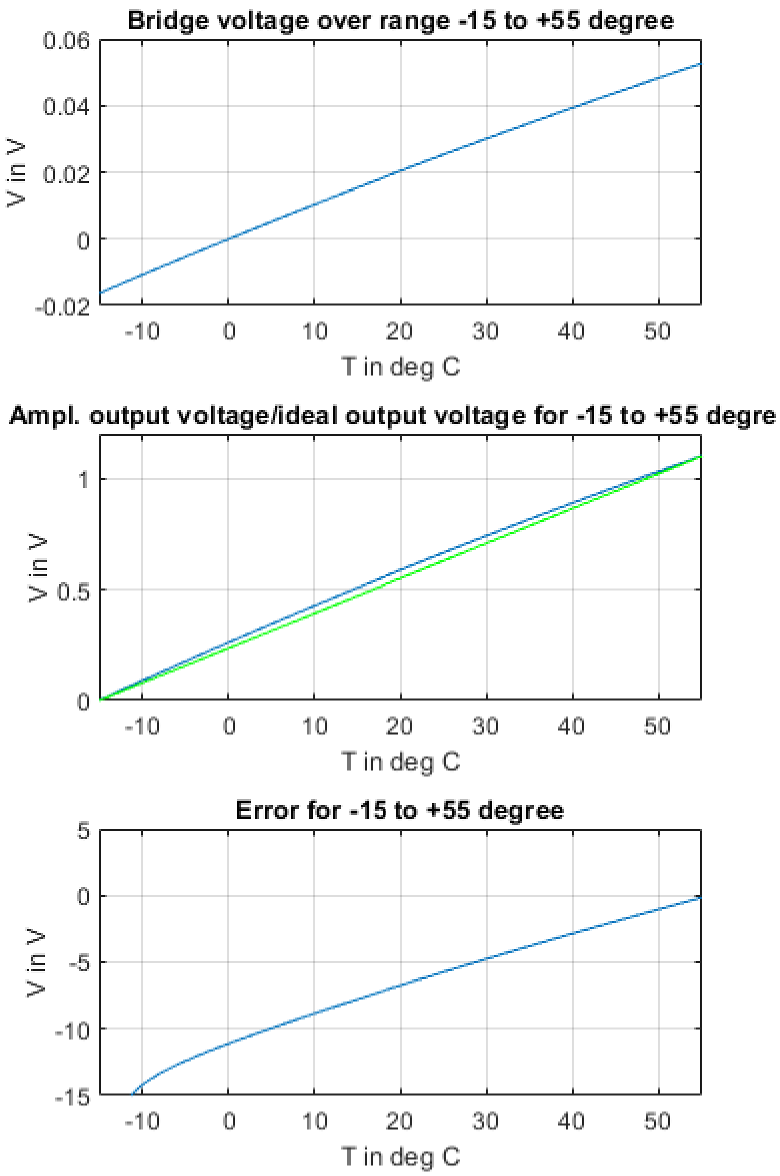


Figure 1

[Published with MATLAB® R2019b](#)

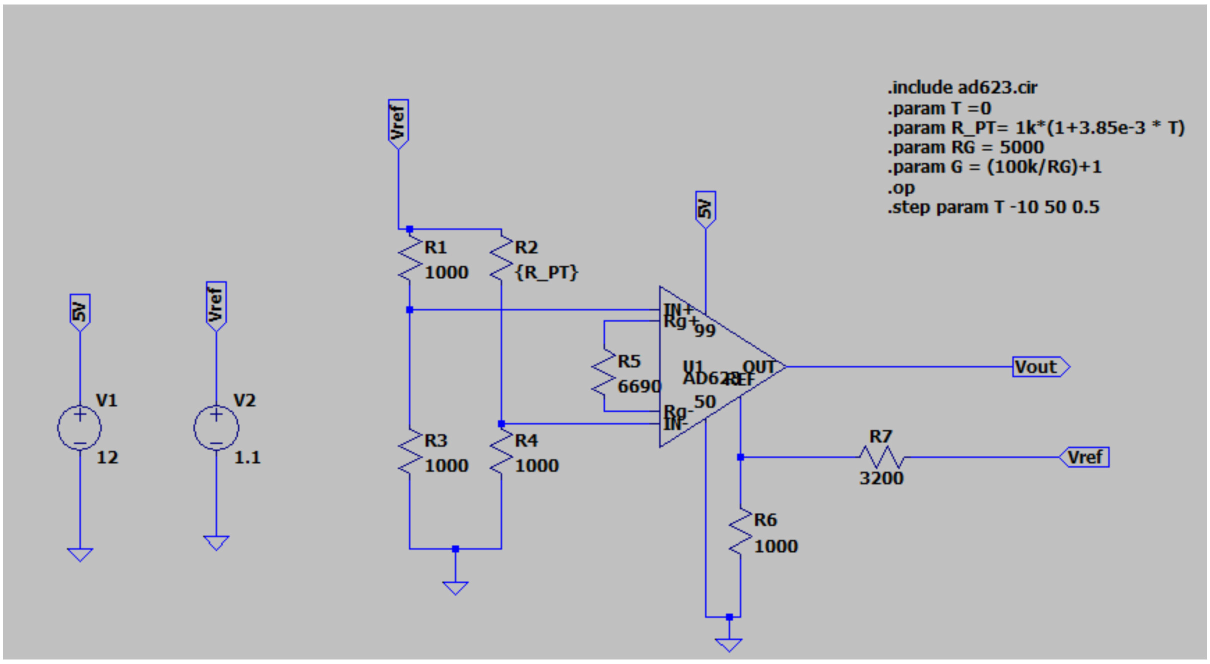
Name	Value
adc_bits	10
alpha	0.0039
err	*1x1135 double*
f	*1x1 Figure*
f1	*1x1 Figure*
f2	*1x1 Figure*
G	15.9477
G_th	15.9398
height	192
i_off_div	2.6080e-04
pts	1136
r_0	1000
r_div_h	3200
r_div_h_calc	3.2178e+03
r_div_l	1000
r_gain	6690
r_gain_th	6.6935e+03
R_PT	*1x1136 double*
scrsz	[1,1,1366,768]
temp	*1x1136 double*
temp_max	55
temp_min	-15
tit	'Error for -15 to +55 d...
u_ad_lin	*1x1136 double*
V_amp	*1x1136 double*
V_bridge	*1x1136 double*
V_delta	0.0690
V_off	0.2619
V_offset	0.2608
V_ref	1.1000
width	390.2857

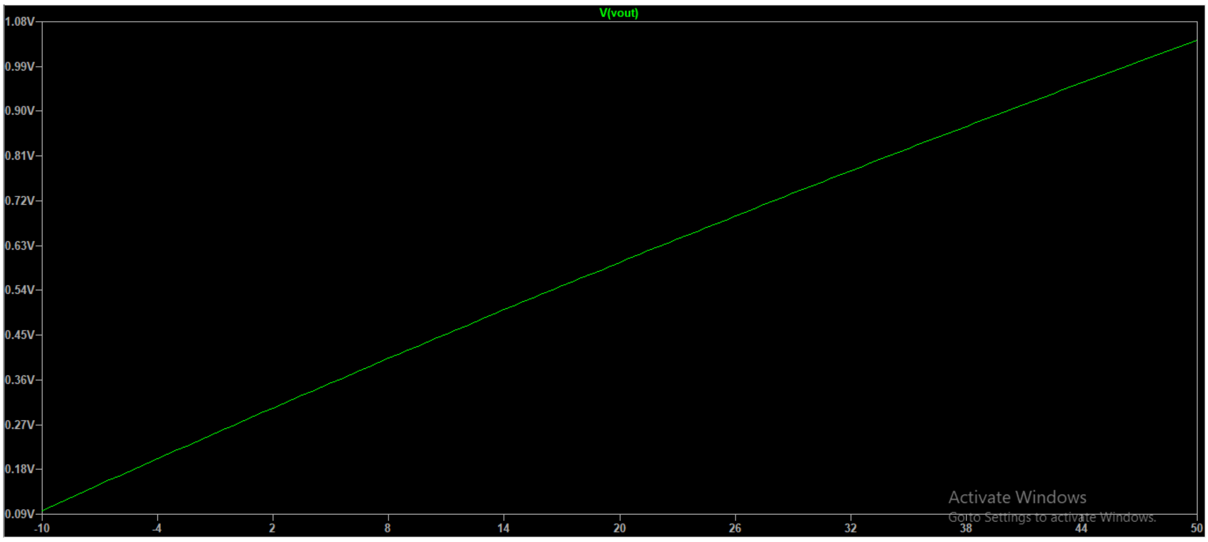
- *Calculate the output values and range of the Wheatstone bridge. Requested range is -10_ to +50_C. To have some margin around the maximum values calculate the bridge voltage for -15_ to +55_C. You need the min./max values to determine the absolute voltage range, and the offset. (remember reference voltage and max. input for the ADC is VRef = 1.1 V)*
- *calculate the amplification, offset, and resistor values. Calculate the amplification and find the gain resistor (see data sheet).*

From the results above we can see that the output gain is 15.947 and the range of wheat-stone bridge is defined as from -15 to +55 degrees Celsius. Selected R_hi = 3200 results to offset voltage 0.2619V. The value of R gain(RG) = 6690. If we see the graph for Bridge voltage over range -15 to +55 degree Celsius(Figure 1), it is almost linear increasing function now. R302 & R303 =6690(each 3345Ohm).

4. Verify the calculated values using the LTSpice simulation from before.

We simulate the circuit again with new values to verify our result.





Now amplification is done correctly, and the output seems more linear now. If we go from -15 Degree Celsius to +55Degree Celsius, our range becomes exactly in the range of ADC even if we have an error in the offset because we cannot set the error exact.

Error Estimation:

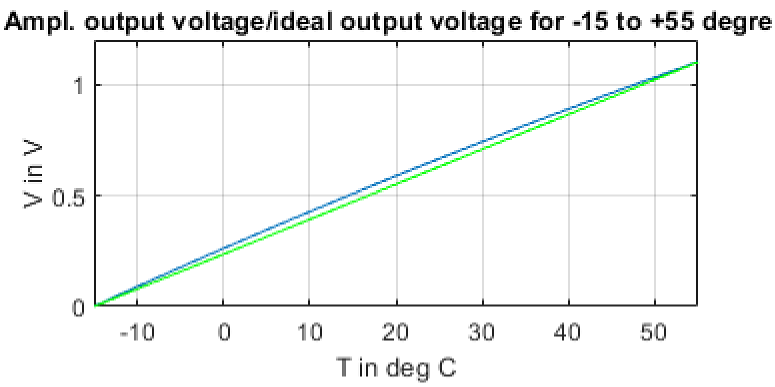
The circuit we have contains errors in the values of the components that are caused from the instrumentation amplifier and output of the wheat-stone. ADC contributes to more error.

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.	$50ppm/°C$	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℃/1024 = 68.4m℃ this is an additional error of 5dig * 68.4m℃ ≈ 350m℃. 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 -            10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
  2    C202 -            10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A
  3    C301 -           100nF : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
  4    C302 -           100nF : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
  5    C303 -            10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A_Pad1.58x1.35mm_HandSolder
  6    C304 -            10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A_Pad1.58x1.35mm_HandSolder
  7    C305 -            10uF : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A_Pad1.58x1.35mm_HandSolder
  8    C401 -              1u : Capacitor_Tantalum_SMD:CP_EIA-3216-18_Kemet-A_Pad1.58x1.35mm_HandSolder
  9    C402 -            100n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 10    C403 -            100n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 11    C404 -             10n : Capacitor_SMD:C_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 12    J101 - Screw_Terminal_01x02 : TerminalBlock_RND:TerminalBlock_RND_205-00045_1x02_P5.00mm_Horizontal
 13    J102 - Screw_Terminal_01x03 : TerminalBlock_RND:TerminalBlock_RND_205-00046_1x03_P5.00mm_Horizontal
 14    J401 - Conn_02x03_Odd_Even : Connector_PinHeader_2.54mm:PinHeader_2x03_P2.54mm_Vertical
 15    L201 -            22uH : Inductor_SMD:L_1210_3225Metric
 16    L202 -            22uH : Inductor_SMD:L_1210_3225Metric
 17    R201 -              2R : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 18    R202 -              2R : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 19    R301 -            1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 20    R302 -           -TBD- : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 21    R303 -           -TBD- : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 22    R304 -            1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 23    R305 -            1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 24    R306 -            1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 25    R307 -            1K00 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 26   TH301 -          PT1000 : Resistor_SMD:R_0805_2012Metric_Pad1.15x1.40mm_HandSolder
 27    U301 -            OP77 : Package_DIP:DIP-8_W7.62mm
 28    U302 -          AD623AN : Package_DIP:DIP-8_W7.62mm
 29    U401 -    ATmega328P-PU : Package_DIP:DIP-28_W7.62mm
```

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

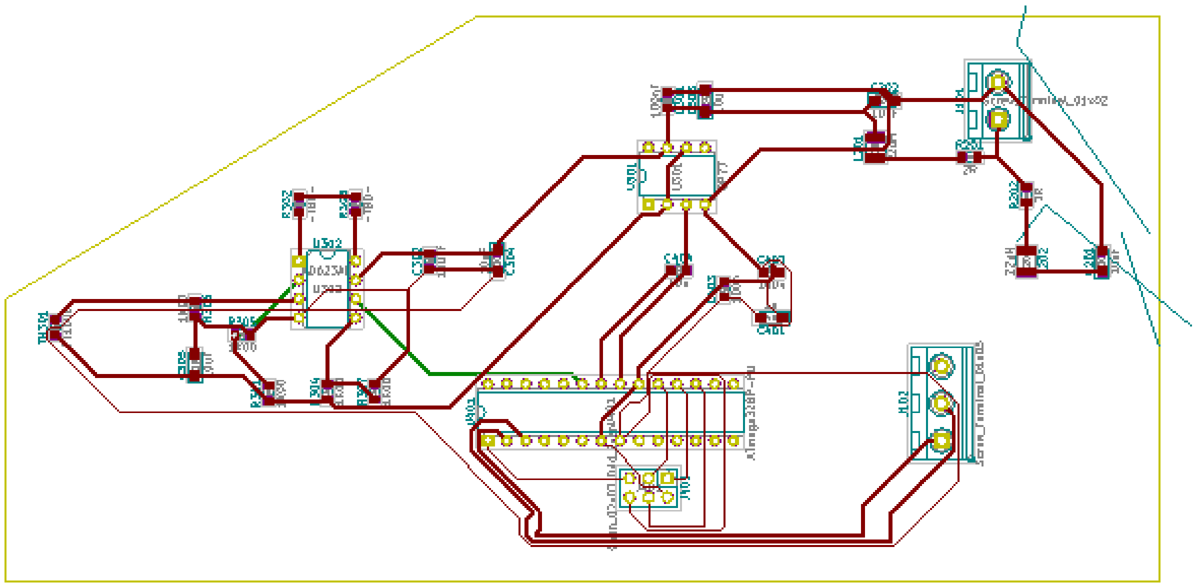
Since the ESR of tantalum capacitor is low, we selected the tantalum for the power block which was proven in the simulation before. For others, we chose ceramic capacitors as they filter the spikes.

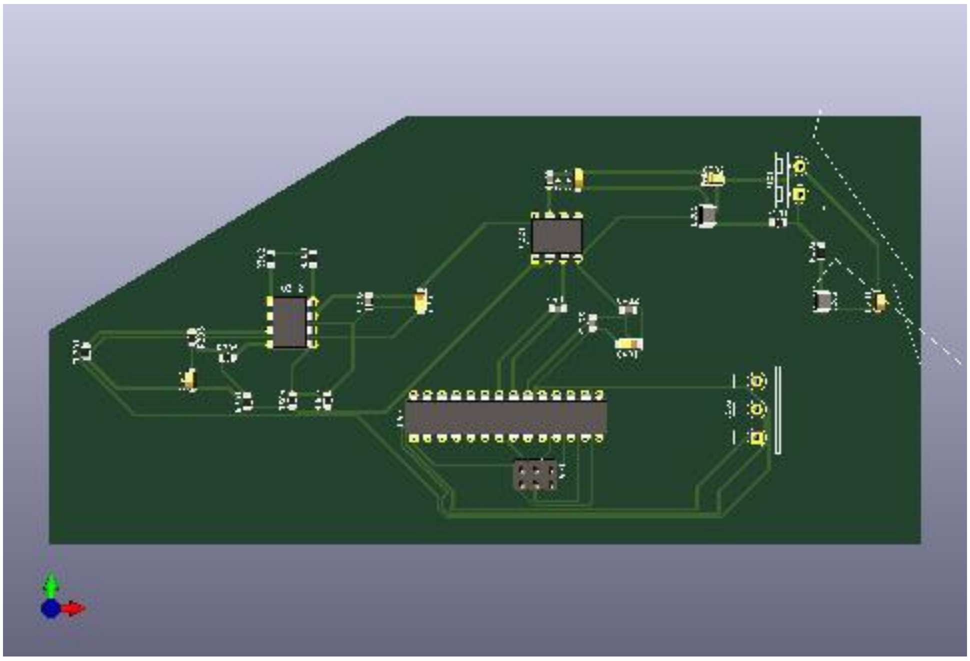
We chose Metal Film Vishhay Y16241K00000T9R Ultra High Precision Foil Wraparound resistor since we need precision in controlling offset of the amplifier at reference voltage. For all other precision is not very important. It also has good TC, wide range of values and good tolerance. The other resistors act as kind of pull down i.e. standard resistors.

We chose Murata LQH32MN470J23L, LQH32MN220J23L chip inductors since we have low resistive part due to non-magnetic core therefore it is independent of large currents carried through. Also, it has high quality factor-Q.

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

In conclusion we saw how we can go from the request from a customer to building an entire PCB. Once we have our PCB design, we then print that PCB and finally solder on the components that we need.

Some of the parts were simulated in Matlab and LTspice to get better idea of how things work in reality. We also had a look on errors and fixed accordingly for instance, unipolar supply problem fixed with offset. The errors could be minimized by improving the quality of components and by methodical implementation on MC. For every single component we had to make a choice. For most of them you can decide but you have to look what is the function. If it is important function related to the error, then the component choice becomes crucial.

At the end, we put the PCB in a case as and if needed which gives us the final product that we can give to our customer.

There were few limitations in our design. We only had analogue ground when we did design rule check. We connected digital and analogue ground together which was forbidden. It could be resolved using a SMD 0 Ohm resistor (simple way) or we look for a component.

References:

Uwe Pagel – Instructor

Lab Manual – Designed by Uwe Pagel

Matlab Resources from internet