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UNIVERSITY OF APPLIED SCIENCES

Final Report

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Submit date:	18/12/2018	
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1. Abstract

This is the final report of Digital System Design class. In this course, we study about the mechanism of electronics components (analog and digital) and how they can be connected to a microcontroller. We also know the design process of electronic systems and hence, we can develop and build a small microcontroller-based system.

In more detail, we will manufacture a temperature measurement system which can be used to measure temperature at distance of 100 meters. The product will be used in small summer cottage or middle size summer cottage. The designed device is consumer product and it can be used for other small buildings monitoring as well. The processor we used is Arduino UNO.

There are 3 members in our team:

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Instructor: Jani Ahvonen, teacher of Vamk. Email: jani.ahvonen@vamk.fi

All the documents and instructions were given by mr. Jani Ahvonen.

2. Pre-Design

a. Block diagram

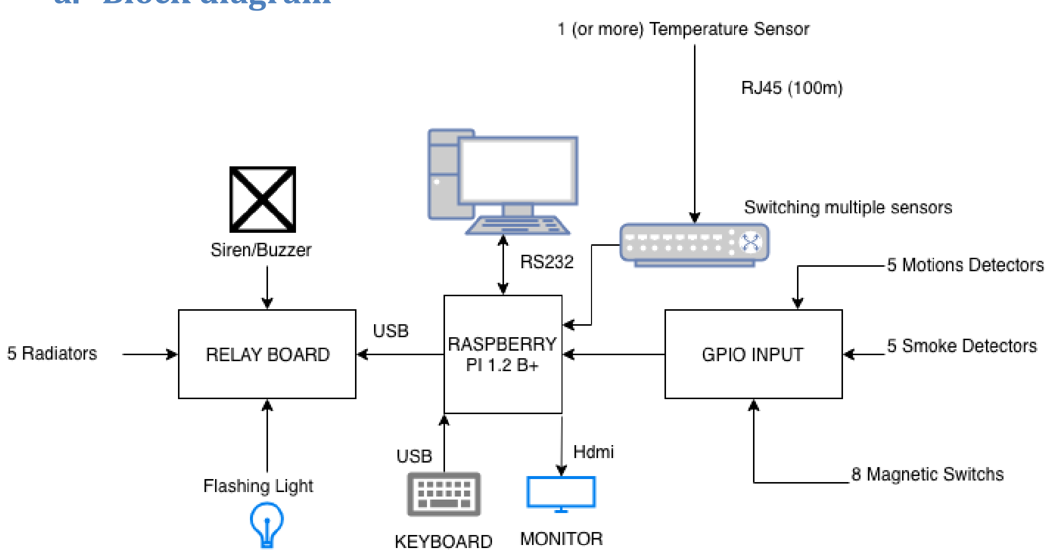

Figure 1: Block diagram

b. Product cost

For the finished device, it may cost out customer roughly 40 euros. We would take profit of 25%, which is 10 euros.

There are 3 PCBs that need to be made, which takes as little as 5 euros for 10 pieces in China or even cheaper if we produce a larger number. So for one device, we would calculate the cost for PCB to be 2 euros with shipping.

The components also get cheaper the more we buy, but we keep an estimated price of buying in small quantities of roughly…. per piece (information from Pads Logic).

The cost also has to include development cost. If estimating the time taken to finish the design and assembly, it will cost about 1 hour for each product, which is roughly 15 euros based on engineer's salary.

The finished device cannot contain just pcbs and wires, so a proper cover and product design must be applied. We estimate the cost for this part to be roughly 10 euros each.

In overall, each product may cost somewhere around 30 euros.

c. Communication method

Table 1: Comparison between five communication methods

	Distance (meters)	Signal loss	Cost
Current Loop	10 000	Lossless with respect to the transmission media (wire), and the interconnections (connectors), signal accuracy is not affected by voltage drop. Current loop fails when there is a lead break or open device.	Simple systems with the lowest cost per meter
RS232	15	Unbalanced transmission, cannot operated in long distance	RS232 is a low-cost interface but requires separate transceiver chips which will add cost to the system in long distance
RS485	1200	Balanced transmission line and immune to noise	Requires a complex system to operate RS485 interfaces and costly
CAN BUS	1000	Error detection supported but speed greatly reduced in longer distance	Costly due to a variety of features it support, and is usually used in field area with large

			number of devices needed to be connected to each other
MOD BUS	1200	It has similar characteristic with RS485, signal accuracy reduced because of voltage drop	MOD Bus is also a field bus that support multiple of slave devices and provide many features that are suitable for complex system, and also costly

According to the requirement specification given, our transmitter system needs to transfer the temperature information at least 100 meters; There is not any expensive components used but the communication is expected to tolerate electromagnetic interference. Due to this requirement, we came to conclusion that using current loop was the most suitable option for the project that we would built in the next step.

3. Analog Signal Processing

a. Design

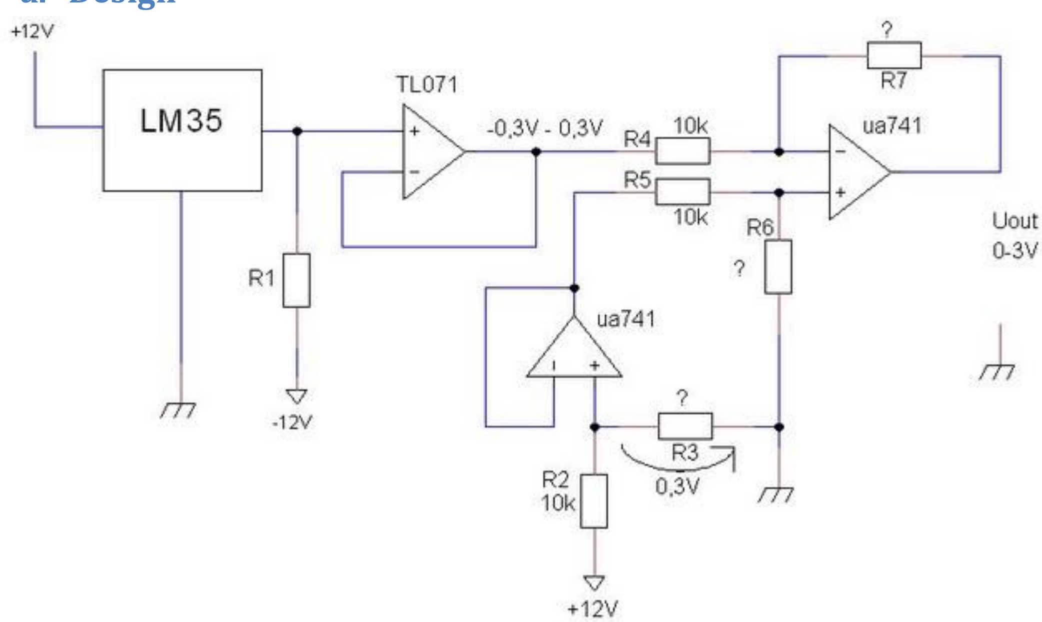

Figure 2: analog signal processing circuit

Figure 2 shows the circuit design of the analog signal processing circuit that was given to us. This circuit includes a temperature sensor circuit using LM35 temperature sensor, two buffer circuits using UA741 and TL071, a differential circuit using UA741. UA741 is an operational amplifier used for general purposes and TL071 is a low-noise JFET-Input operational amplifier used to deal with the low voltage input signal that only changes slightly but continuously through time.

In Figure 2, there are four values missing and they are marked with question marks. Those are R_1, R_2, R_6 and R_7 resisters. The calculation of these values is shown below.

According to LM35 datasheet from Texas Instrument:

$$R_1 = \frac{-V_S}{50\ \mu A} \tag{1}$$

$$R_1 = \frac{12}{50\ \mu A} = 240000\ \Omega$$

Using voltage divider, R_3 can be calculated by:

$$\frac{U_2}{R_2} = \frac{U_3}{R_3} \tag{2}$$

$$R_3 = \frac{U_3 R_2}{U_2}$$

$$R_3 = \frac{0.3 \times 10k}{12 - 0.3} = 256.41\ \Omega$$

In the differential amplifier circuit, amplification can be adjusted by replacing resistors with different size. However, the resistors must be equal in pairs. In our circuit, this means: $R_6 = R_7$ and $R_4 = R_5$.

$$U_{OUT} = -\frac{R_7}{R_4}(U_4 - U_5) \tag{3}$$

Given that when LM35 output voltage is at -0.3V, V_{OUT} reaches 3V and:

$$U_5 = U_3 = 0.3\ V \tag{4}$$

$$R_6 = R_7 = -\frac{U_{OUT} \times R_4}{(U_4 - U_3)}$$

$$R_6 = R_7 = \frac{3 \times 10k}{(0.3 + 0.3)} = 50\ 000\ \Omega$$

b. Simulation

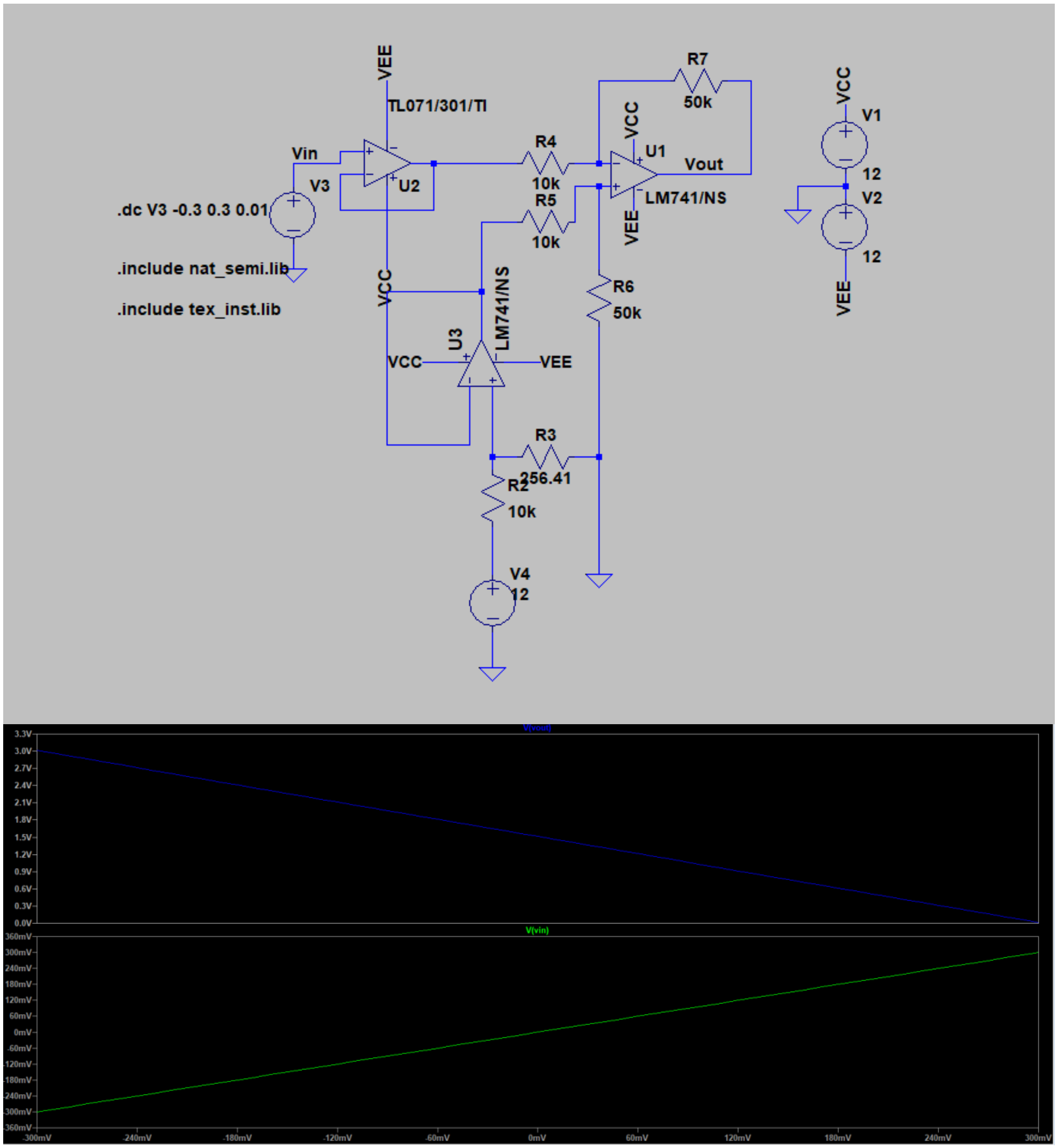

Figure 3: LTspice simulation

Using LTspice, we simulated the analog signal processing circuit with calculated values of resistors R3, R6 and R7. R1 was not included in this simulation because we had already simulated the input signal by replacing LM35 and R1 with a power source whose voltage increase linearly from -0.3V to 0.3V. In this simulation, the produced output voltage decreased linearly from 3V to 0V, which is the expected result of the circuit.

c. Circuit testing

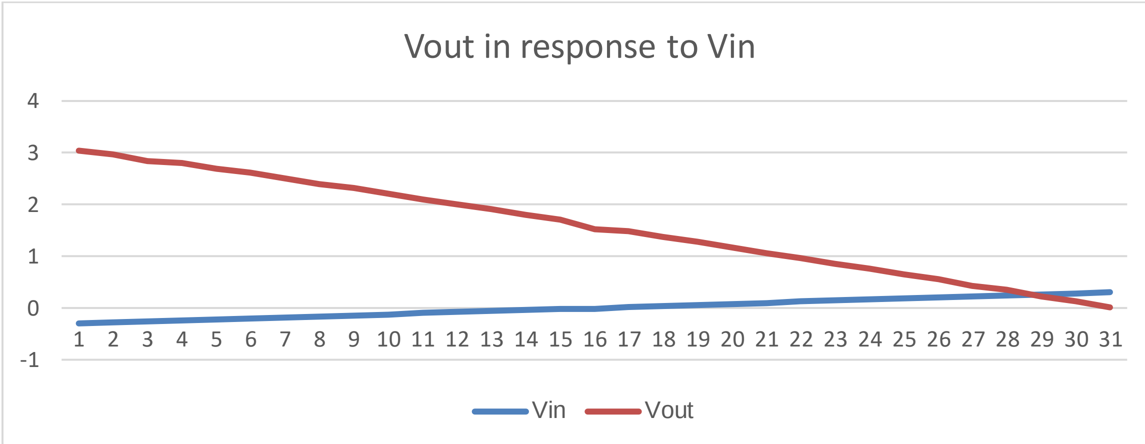

Figure 4: The change of Vout when Vin is adjusted

In the laboratory, we measured the change of Vout by removing LM35 sensor and R1 and adjusting the input voltage from -0.3V to 0.3V using 0.02V steps. The result of the measurement is shown in Figure 4. Compare to the result collected from the simulation in figure 3, the one obtained by bread board is basically the same; when Vin is about -0.3V, Vout is at approximately 3V; Vout then decreases linearly in response to the rise of Vin and stops at 0.012V when Vin reaches 0.306V.

Finally, the whole system, including LM35 temperature sensor and R1, was tested using cold spray. The results collected before and after cold spray was used on LM35 is shown in table 2. In general, the differences between the result using cold spray and adjusting Vin was not much; the tolerance was under 0.15V in Vout.

Table 2: Cold spray used on LM35

	Vin	Vout
Before	-0.29	2.9
After	-0.08	1.887

4. Communication

1. Task1

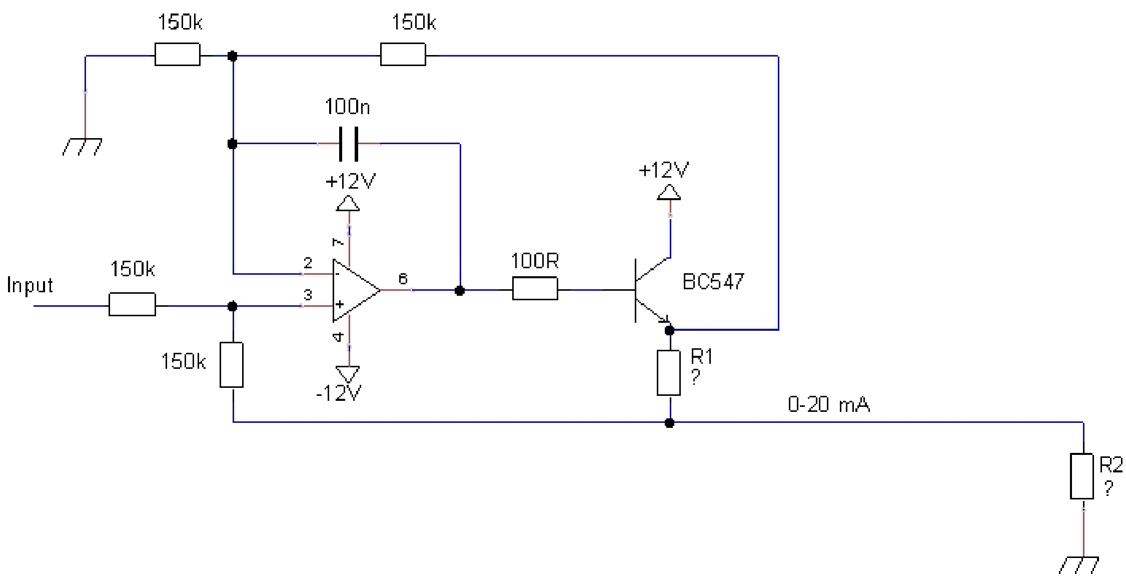

Figure 5 Transmitter

Calculate component values for transmitter and simulate the circuit by using LTspice:

- According to the material for this circuit, we have the equation

$$I_{out} = \frac{V_{input}}{R_1}$$

  This equation indicates that the output load current is a function only of the voltage V_{input} and the resistor R1
- As we mentioned in the previous chapter, the input voltage of the communication is the output of Analog signal processing circuit, which is from 0 to 3V
  If $V_{input} = 0$, $I_{out} = 0$; if $V_{input} = 3$, then

$$I_{out} = 20\ mA = \frac{V_{input}}{R_1} = \frac{3V}{R_1}$$

$$R1 = \frac{3V}{20\ mA} = 150\Omega$$

- According to the instruction, "When current 20 mA flows in circuit the resistor R2 must have 5V over it", so

$$R_2 = \frac{5V}{20mA} = 250\Omega$$

Simulate the circuit by using LTspice:

- What is BC547?
  A BC547 transistor is a negative-positive-negative (NPN) transistor that is used for many purposes. Together with other electronic components, such as resistors, coils, and capacitors, it can be used as the active component for switches and amplifiers.
- What is uA741?
  uA741 is a general-purpose operational amplifier (OpAmp) featuring offset-voltage null capability. OpAmp is a circuit that performs the mathematical operation of Integration, that is we can cause the output to respond to changes in the input voltage over time. Hence, its main purpose is to amplify a weak signal. 741 is used in two ways: inverting amplifier (if the input signal is from leg 2) and non-inverting amplifier (if the input signal is from leg3)
- We use LTspice to simulate the circuit, and use a linear DC power supply sweep from 0 to 3V as input signal, and this is the result

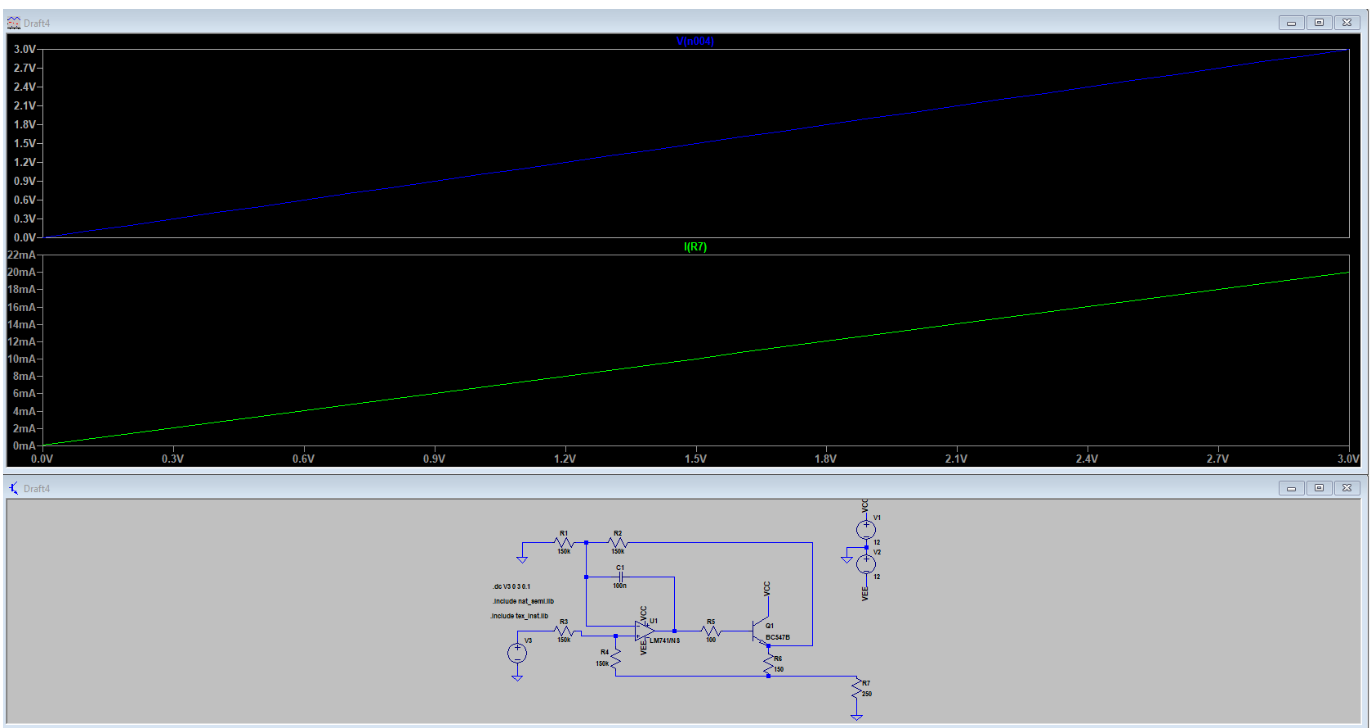

Figure 6 The blue waveform is input signal from 0 to 3V, and the green waveform is the output current from 0 to 20 mA

2. Task 2

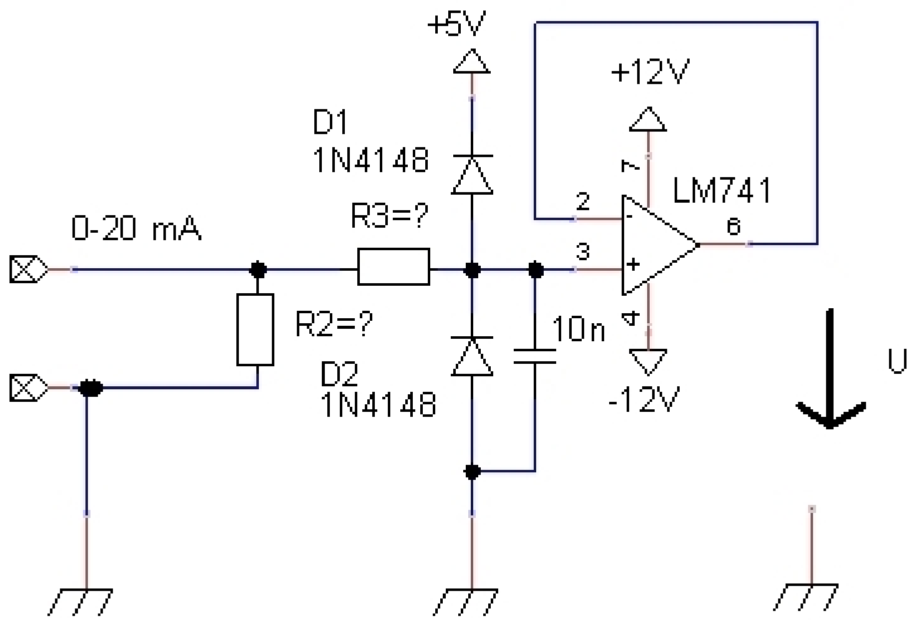

Figure 7 Receiver

- The previous transmitter resistor R2 is the same resistor as input resistor in this receiver circuit, hence R2 = 250 Ω
- If input signal contains 8kV ESD discharge voltage, we want that current during this ESD event is 0.8A through D1 or D2

$$0.8A = \frac{8kV}{R3}$$

$$R3 = \frac{8kV}{0.8A} = 10k$$

- What is the low pass filter cut-off frequency when you calculate it from R3 and 10nF connection?

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi 10k \times 10nF} = 1591.55\ Hz$$

- We use LTspice to simulate the circuit, and use a linear DC current sweep from 0 to 20mA as input signal, and this is the result

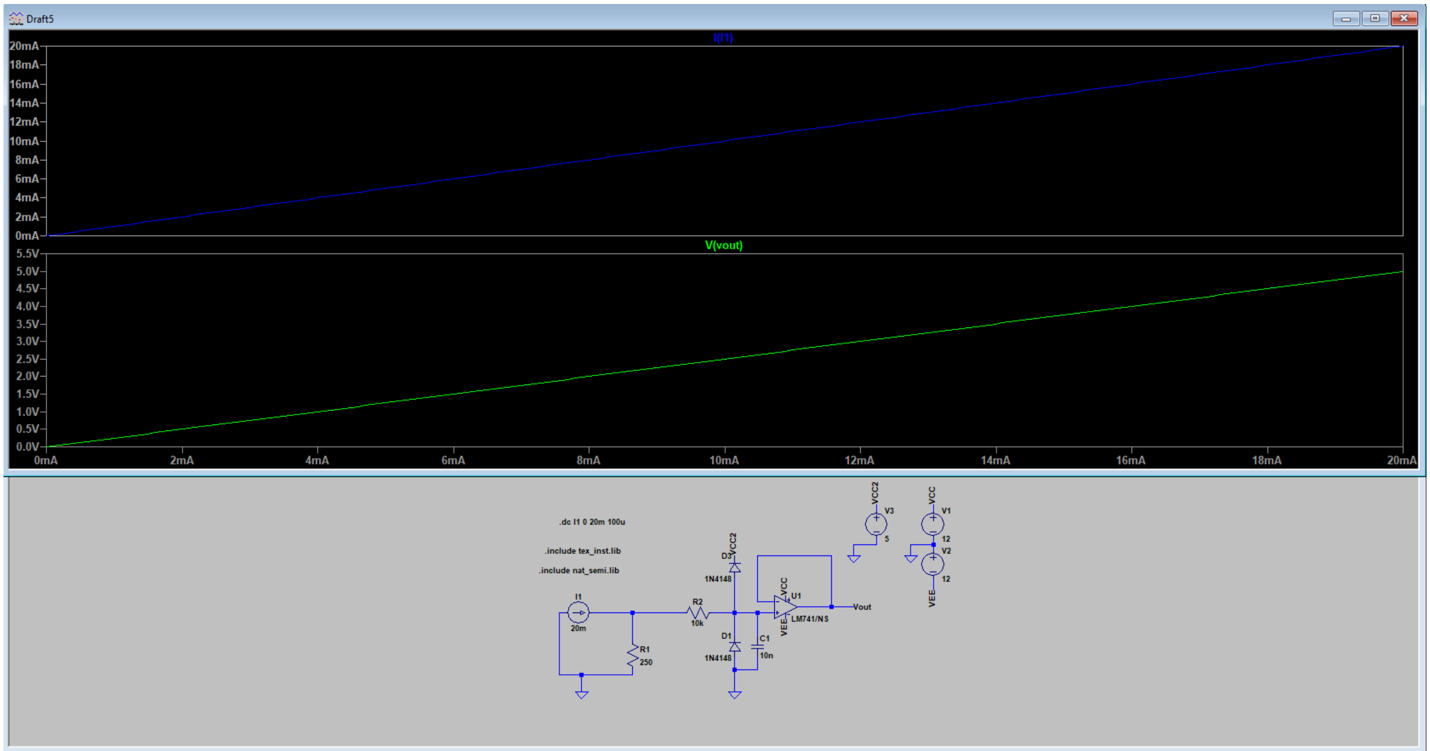

Figure 8 The blue waveform is input signal from 0 to 20mA, and the green waveform is the output voltage from 0 to 5V

3. Task 3

We start to test the whole system in bread board. Replace LM35 by DC-power supply and adjust -0.3V to +0.3V using 0.02V steps

	Vin	Vout
-0,3	-0,298	5,040
-0,28	-0,279	4,861
-0,26	-0,259	4,692
-0,24	-0,238	4,521
-0,22	-0,219	4,359
-0,2	-0,202	4,184
-0,18	-0,179	4,018
-0,16	-0,158	3,852
-0,14	-0,142	3,685
-0,12	-0,121	3,514
-0,1	-0,099	3,345
-0,08	-0,081	3,177
-0,06	-0,062	3,012
-0,04	-0,042	2,844
-0,02	-0,024	2,678
0	-0,013	2,509
0,02	0,019	2,335
0,04	0,042	2,177
0,06	0,06	2,004
0,08	0,08	1,833
0,1	0,102	1,666
0,12	0,122	1,477
0,14	0,142	1,335
0,16	0,16	1,162
0,18	0,182	0,994
0,2	0,201	0,829
0,22	0,224	0,653
0,24	0,241	0,476
0,26	0,264	0,322
0,28	0,281	0,155
0,3	0,306	0,008

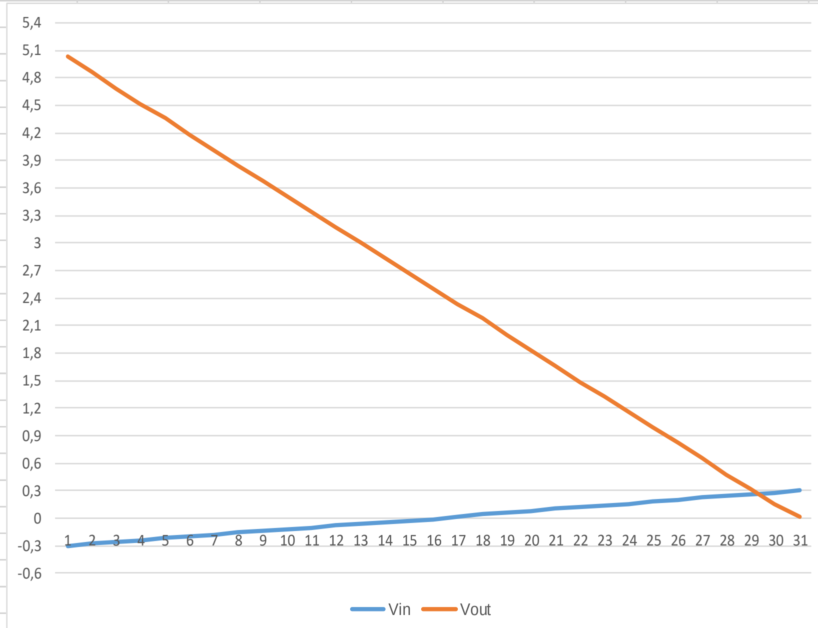

Figure 9 The change of Vout when Vin is adjusted

5. Analog to Digital conversion

1. Task 1

- What is the difference between MCP3002 and ADC0832 chips?
  MCP3002 is a 10 bit ADC combines high performance and low power consumption in a small package. It is ideal for embedded control applications.
  ADC0832 is a 8 bit successive approximation ADC with a serial I/O and configurable input multiplexers with up to 8 channels.

- We start design needed circuit for the ADC so that we can use it to measure temperature. Using LM431 as reference chip and MCP3002 as AD converter
- Calculate for LM431:

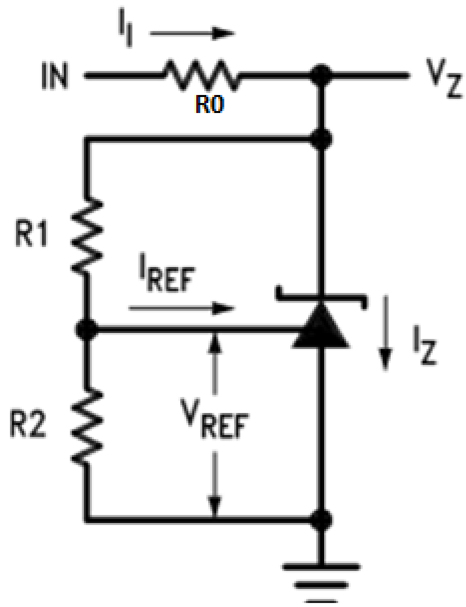

Figure 10 LM431 connection

We need V_Z=5V, we have R1=10k, I_I=10mA.
According to the datasheet, V_{REF}=2.5V

$$V_Z = V_{REF} \times \left(1 + \frac{R1}{R2}\right)$$

$$5V = 2.5V \times \left(1 + \frac{10k}{R2}\right)$$

$$\Rightarrow \quad R2 = 10k$$

And

$$R0 = \frac{V_{IN} - V_Z}{I_I} = \frac{12V - 5V}{10mA} = 700\Omega$$

- We proceed to set up the connection for MCP3002

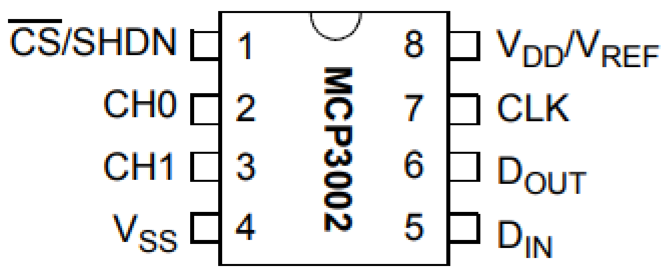

Figure 11 MCP3002 diagram

Port 8 V_{REF} of MCP3002 links to V_Z of LM741
Here is the header code given by the instructor:

```
pinMode(2, OUTPUT);
pinMode(3, OUTPUT);
pinMode(4, OUTPUT);
pinMode(5, INPUT);
pinMode(13, OUTPUT); //Arduino UNO pin 13 extra LED for ADC event

#define CS_HIGH digitalWrite(2, HIGH)
#define CS_LOW digitalWrite(2, LOW)

#define CLK_HIGH digitalWrite(3, HIGH)
#define CLK_LOW digitalWrite(3, LOW)

#define DIN_HIGH digitalWrite(4, HIGH)
#define DIN_LOW digitalWrite(4, LOW)

#define LED_ON digitalWrite(13, HIGH) //Arduino UNO pin 13 extra LED for ADC event
#define LED_OFF digitalWrite(13, LOW)
```

To be more detail:

- pin 2 of Arduino UNO must link with port 1 of LM3002 (CS)
- pin 3 of Arduino UNO must link with port 7 of LM3002 (CLK)
- pin 4 of Arduino UNO must link with port 5 of LM3002 (DIN)
- pin 5 of Arduino UNO must link with port 6 of LM3002 (DOUT)

- Test the whole circuit system on bread board:

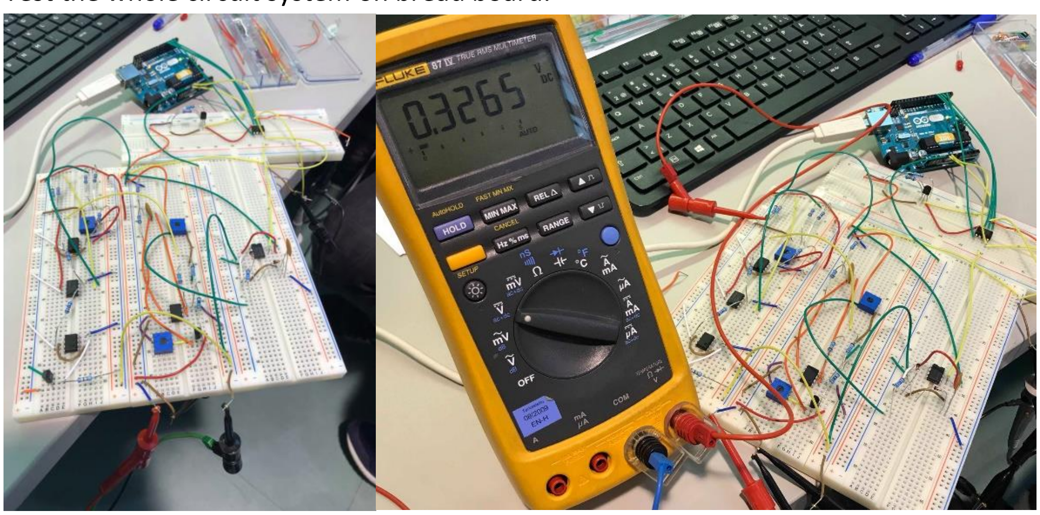

Figure 12 Testing on bread board

- We proceed to connect a 100m router between the transmitter and receiver. The entire system is efficient

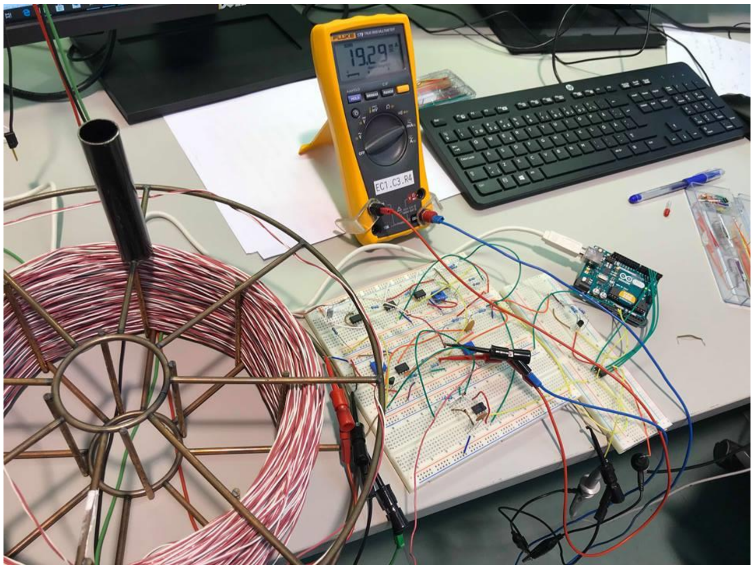

Figure 13 100m Connection Testing

2. Task 2

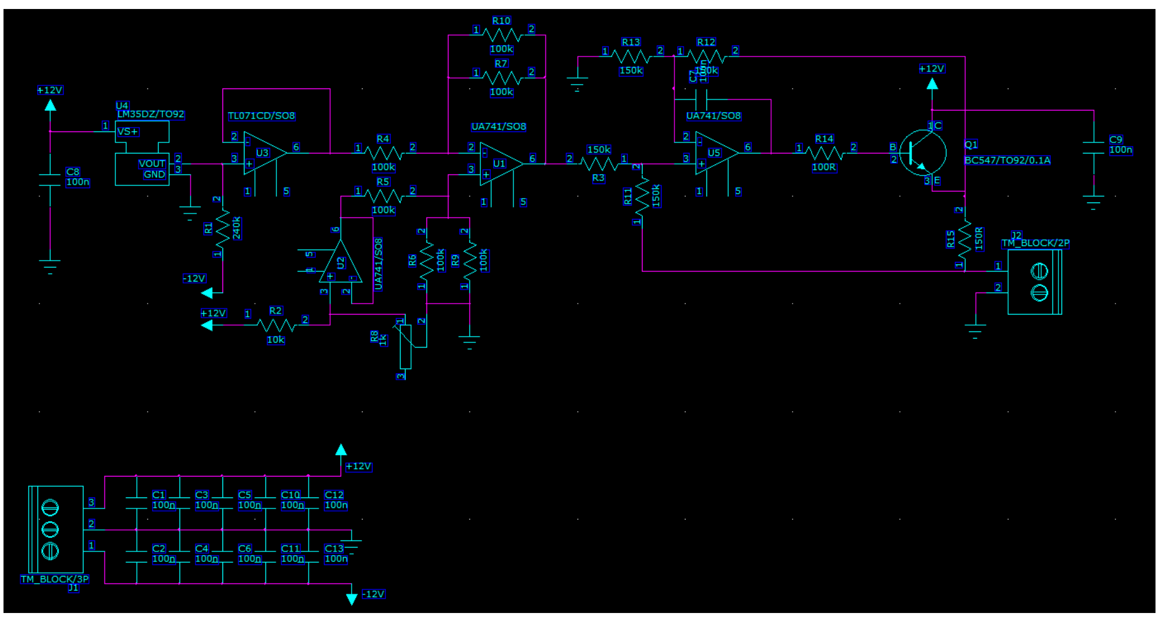

Figure 14 Transmitter pads circuit diagram

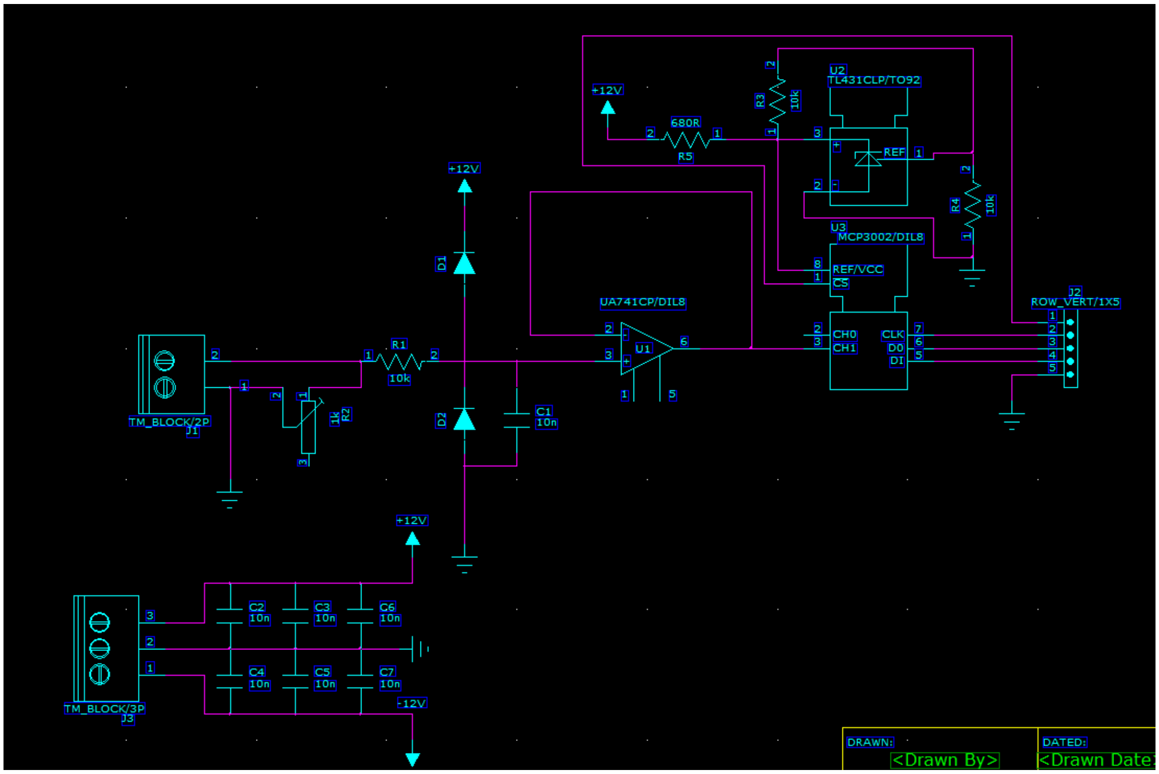

Figure 15 Receiver pads circuit diagram

6. Schematic Design

1. Task 1

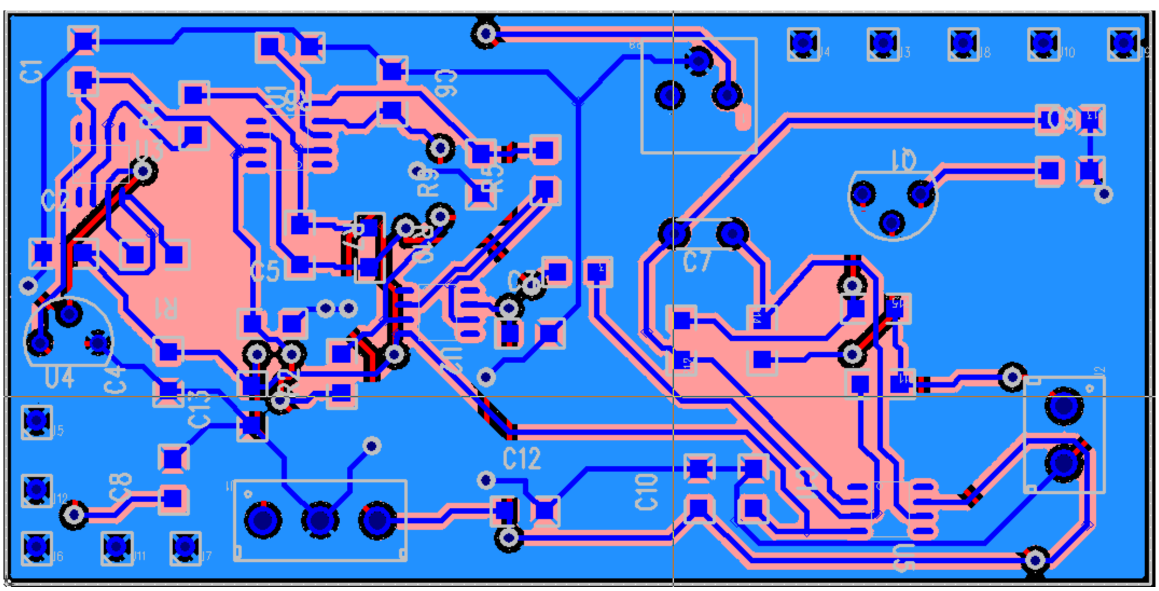

Figure 16 Topside copper pour

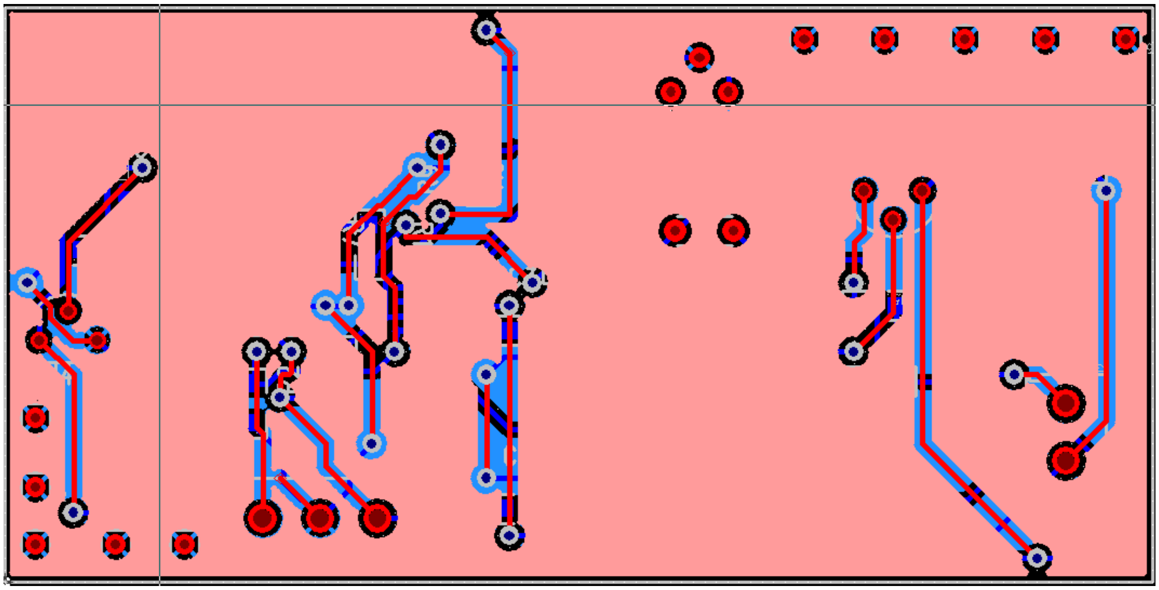

Figure 17 Botside copper pour

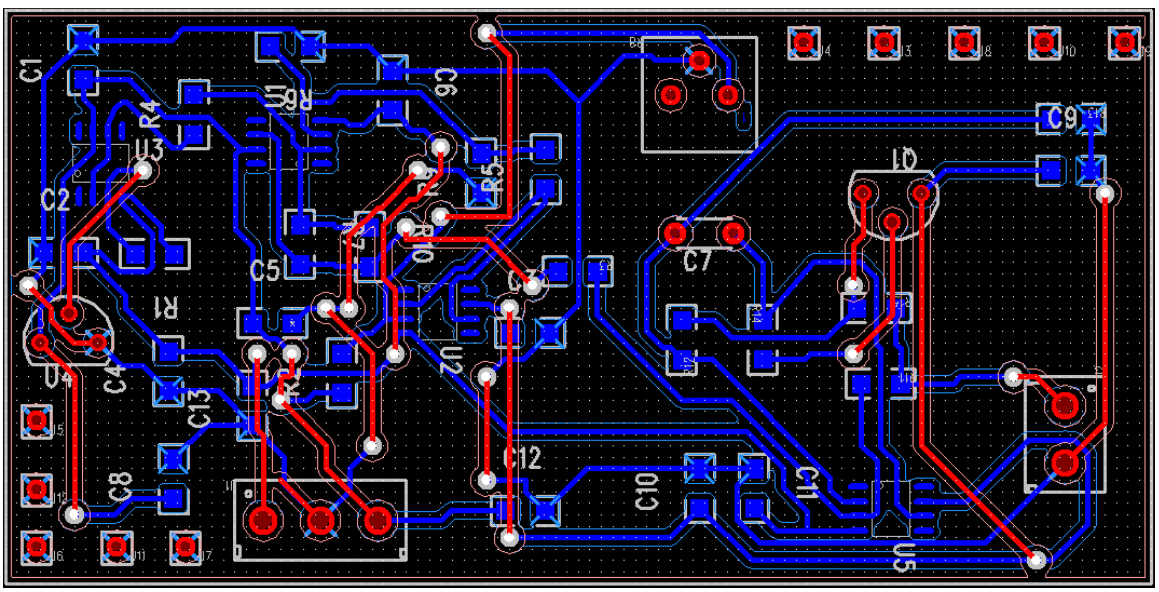

Figure 18 Without copper pour

2. Task 2

Bill Of Materials for transmitter.sch on Tue Dec 18 09:16:15 2018

Item	Qty	Reference	Part Name	Manufacturer	Description
1	6	R4-7R9-10	100K/5%/0.125W ,100k,+-5%	Multicomp	SMD resistor
2	12	C1-6C8-13	100NF/50V/CER, 100n,+-10%	Kemet	Multilayer ceramic SMD capacitor
3	1	C7	100NF/50V/CER, 100n,+-10%	Kemet	Ceramic disc capacitor
4	1	R14	100R/5%/0.125W ,100R,+-5%	Multicomp	SMD resistor
5	1	R2	10K/5%/0.125W, 10k,+-5%	Multicomp	SMD resistor
6	1	R1	10K/5%/0.125W, 240k,+-5%	Multicomp	SMD resistor
7	4	R3R11-13	150K/5%/0.125W ,150k,+-5%	Multicomp	SMD resistor
8	1	R15	150R/5%/0.125W ,150R,+-5%	Multicomp	SMD resistor
9	1	Q1	BC547/TO92/0.1 A, BC547/TO92/0.1 A	NATIONAL SEMICONDUCTOR	AMPLIFIER NPN SILICON TRANSISTOR
10	1	U4	LM35DZ/TO92, LM35DZ/TO92		Analog PRECISION TEMPERATURE SENSOR
11	1	U3	TL071CD/SO8, TL071CD/SO8		LOW NOISE, JFET INPUT, OPERATIONAL AMPLIFIER
12	1	J2	TM_BLOCK/2P, Socket, Power Terminal Block, 3 way		Socket, Power Terminal Block, 3 way
13	1	J1	TM_BLOCK/3P, Socket, Power Terminal Block, 2 way		Socket, Power Terminal Block, 2 way
14	1	R8	TRIMMER/1K,1k		Trimmer, 1k
15	3	U1-2U5	UA741/SO8, UA741/SO8		OPERATIONAL AMPLIFIER

Figure 19 Powerlogic part list of Transmitter

```
|------------------------------------------------------------------------------|
|Bill Of Materials for receiver2.sch on Tue Dec 18 09:22:43 2018               |
|------------------------------------------------------------------------------|
|Item|Qty |Reference|Part Name     |Manufacturer  |Description                 |
|----+----+---------+--------------+--------------+----------------------------|
|1   |3   |R1R3-4   |10K/5%/0.125W,|Multicomp     |SMD resistor                |
|    |    |         |10k,+-5%      |              |                            |
|2   |7   |C1-7     |10NF/50V/CER, |Kemet         |Multilayer ceramic SMD      |
|    |    |         |10n,+-10%     |              |capacitor                   |
|3   |2   |D1-2     |1N4148/0.2A,  |Philips       |High-speed diodes           |
|    |    |         |1N4148        |              |                            |
|4   |1   |R5       |680R/5%/0.125W|Multicomp     |SMD resistor                |
|    |    |         |,680R,+-5%    |              |                            |
|5   |1   |U3       |MCP3002/DIL8, |              |A/D-converter 12-bit,       |
|    |    |         |TLC0832IP/DIL8|              |internal reference 2-channel,|
|    |    |         |              |              |SPI-bus                     |
|6   |1   |J2       |ROW_VERT/1X5, |              |Plug, Vertical Row Header   |
|    |    |         |Plug, Vertical|              |                            |
|    |    |         |Row Header    |              |                            |
|7   |5   |J4-8     |SOCKET/1X1,   |              |Socket, IC                  |
|    |    |         |Socket, IC    |              |                            |
|8   |1   |U2       |TL431CLP/TO92,|              |Adjustable Micropower Voltage|
|    |    |         |TL431CLP/TO92 |              |Reference 1,24-5,30V        |
|9   |1   |J1       |TM_BLOCK/2P,  |              |Socket, Power Terminal Block,|
|    |    |         |Socket, Power |              |3 way                       |
|    |    |         |Terminal      |              |                            |
|    |    |         |Block, 3 way  |              |                            |
|10  |1   |J3       |TM_BLOCK/3P,  |              |Socket, Power Terminal Block,|
|    |    |         |Socket, Power |              |2 way                       |
|    |    |         |Terminal      |              |                            |
|    |    |         |Block, 2 way  |              |                            |
|11  |1   |R2       |TRIMMER/1K,1k |              |Trimmer, 1k                 |
|12  |1   |U1       |UA741CP/DIL8, |              |OPERATIONAL AMPLIFIER       |
|    |    |         |uA741CP/DIL8  |              |                            |
|------------------------------------------------------------------------------|
```

Figure 20 Powerlogic part list of Receiver

7. Printed Circuit Board Design

1. Explain following terms: EMC and EMI?

EMC: Electromagnetic Compatibility, the ability of a product to coexist in its intended electromagnetic environment without causing or suffering functional degradation or damage. It is also the name of a branch of electrical engineering which deals with unintentional generation, propagation and reception of electromagnetic energy.

EMI: Electromagnetic Interference, also called radio frequency interference (RFI) when in radio frequency spectrum, is a process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths (or both).

2. You need to make your PCB (embedded system) compliant with EMC. List the basic rules which your PCB should fulfill?

You need to make your PCB (embedded system) compliant with EMC. List the basic rules which your PCB should fulfill?

a. Designing ground planes:

Ground planes are copper areas covering a part of the PCB's total area, they may be on one layer or several layers. Ground plane helps to reduce emissions, crosstalk and noise so that good electrical characteristic and good heat dissipation may be achieved.

b. Other:

- Do not cross splits in ground planes
- Nets should not be routed too close to the edge of a ground plane
- Put filters on I/O lines near the connecter
- Isolate Analog and Digital circuit
- Decoupling is placed near IC power pins for reducing noise and crosstalk
- Use spatial decoupling to avoid lower-frequency power plane resonances
- Avoid 90^o angles for trace, vias, and other components because right angles cause radiation

3. Why we need decoupling capacitor for each chip?

Decoupling capacitor is used to reduce the change in power supply voltage caused by drawing higher currents from it. Power supply is usually slow in responding to this change, especially in high frequency process. Therefore, decoupling capacity provide a fast "charge storage" near the IC. When the IC or microcontroller switches outputs and need more currents, they first draw charge from the capacitors instead of the power supply. This method buys the power supply some time to adjust to the changing demands.

4. What is the inductance (nH/cm) for PCB-trace which w = 10 cm, wt = 1mm and h = 0.9 mm (hint: check curve in page 9)?

Approximately 4nh/cm

5. In circuit theory capacitor is pure (ideal) capacitor. Which components you need to model real world capacitor?

A capacitor is created out by two metal plates and a material called a dielectric. The dielectric can be any insulating materials: paper, glass, rubber, ceramic, plastic. The plates are a conductive material: aluminum, tantalum, silver, or other metals.

8. References

http://www.technologystudent.com/elec1/opamp1.htm

https://www.electronics-tutorials.ws/opamp/opamp_6.html

https://www.electronics-tutorials.ws/filter/filter_2.html

https://learn.sparkfun.com/tutorials/capacitors/capacitor-theory