VAASAN AMMATTIKORKEAKOULU
VASA YRKESHÖGSKOLA
UNIVERSITY OF APPLIED SCIENCES

Digital System Design

Laboratory Report

Minh Nguyen (1700681)

Tin Luu (1700674)

Lam Nguyen (1700685)

Contents

1 PRE-DESIGN

The following figure depicts a simple illustration of how to build up a circuit for temperature measurement.

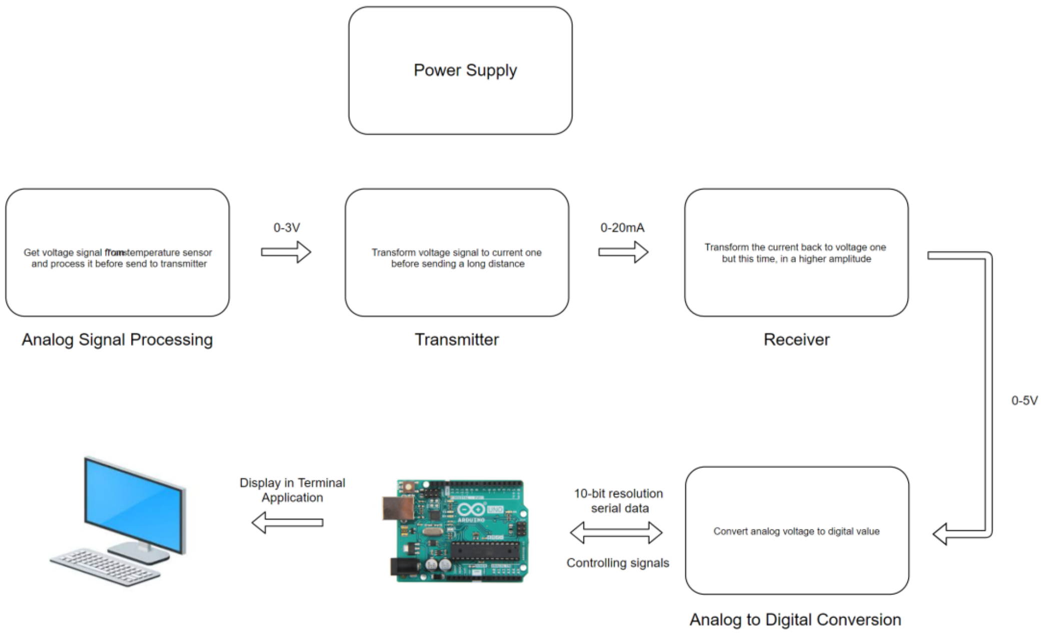


Figure 1. Block diagram for the circuit

In the Analog Signal Processing section, the electrical thermal sensor being used is LM35 along with operational amplifiers to amplify the output voltage value of the sensor.

The Analog to Digital Conversion section uses MCP3002 as the ADC.

Finally, the microcontroller which is used to both read the serial values from ADC and control it is Arduino UNO.

Preliminary Description:

- Function: the product has to monitor and manage property. The product is used in small or middle-size summer cottage. This product mostly serves household consumers. The product contains a temperature sensor which can measure at a distance of 100 meters. The restriction is that no wireless connection is possible.

- Temperature measurement: The system is able to measure the ambient temperature by 0.5-degree accuracy. The measurement range should be at least from -30 to 30 degree Celsius. The measured temperature is constantly informed in the device screen.
- Communication: The transmitter is able to reliable transfer data about temperature to at least 100-meter distance. The environment contains sensors which are equipped with a transmitter while the main unit contains intelligence and sensor inputs. The transmitter does not use expensive components. The communication can be used in environment which contains electromagnetic interference.

2 ANALOG SIGNAL PROCESSING

This chapter describes the part of the circuit where the analog input is processed prior to being transmitted in the communication section.

2.1 Circuit Diagram

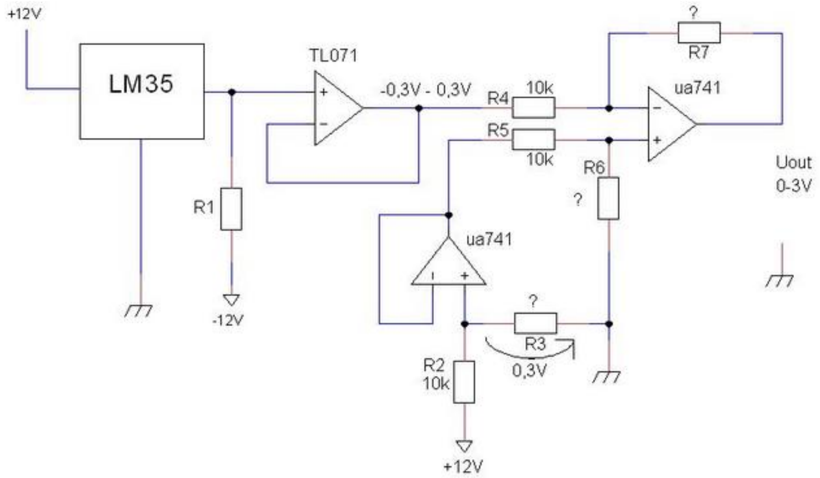


Figure 2. Analog Signal Processing circuit diagram

According to the circuit, there are still four resistors R1, R3, R6 and R7 that are missing their resistance values. Temperature sensor LM35 has its output voltage changed from -0.3V to 0.3V corresponding to the ambient temperature from -30 to 30 degrees Celsius. The output voltage value of the differential amplifier circuit is expected to reach 0 to 3V.

2.2 Resistance Calculation

The range of temperature: -30°C to 30°C implies that each degree is equivalent to a change of 10mV.

For R1: The input voltage for LM35 is +12V and according to the equation given in the datasheet, $R1 = \frac{12V}{50\mu A} = 240000\Omega = 240k\Omega$

For R7, we have the -0.3V to 0.3V connected with R4 in series with R7 and connected to U_{out}. We have the following formula

$$3V = \frac{R7}{R4} \times |-0.3V - 0.3V|$$

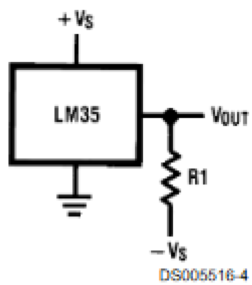


Figure 3. LM35 R1 calculation

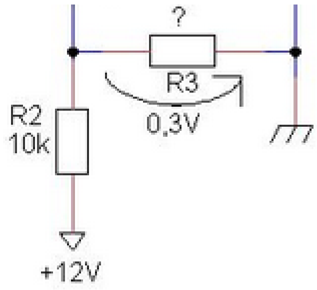


Figure 4. Calculation of R3

We have the value of R4 as 10kΩ. Thus, we can substitute it into the equation to find R7.

$$R7 = 10000 \times \frac{3V}{|-0.3V - 0.3V|} = 50000\Omega = 50\mathrm{k}\Omega$$

And we also have R6=R7=50kΩ.

For R3, its value can be obtained using the following formula of voltage divider.

$$0.3V = \frac{R3}{R2 + R3} \times 12V$$

Substitute the value of R2 as 10kΩ and solve the equation, we get the value of R3=256.4Ω

2.3 LTspice Schematic and Simulation

The following figure shows the LTspice schematic for Analog Signal Processing circuit.

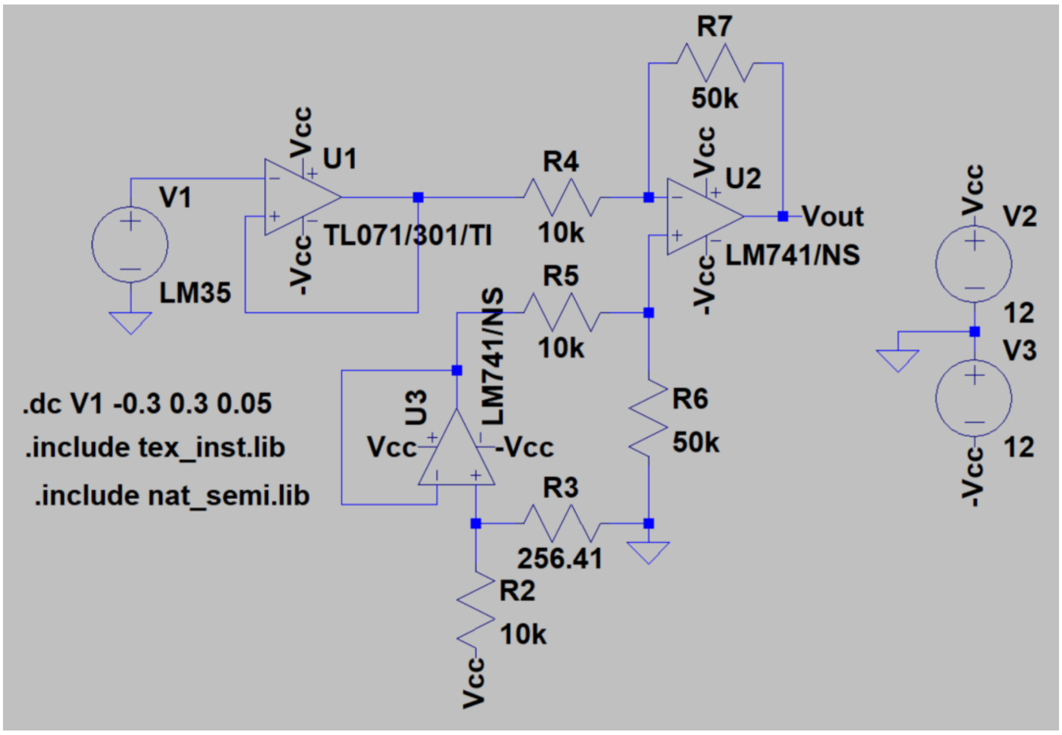


Figure 5. LTspice Schematic

Accompanying with the schematic is the result of simulation, which is illustrated in the following figure. In the figure, the green and blue lines denote the behavior of the input and output voltage signals respectively.

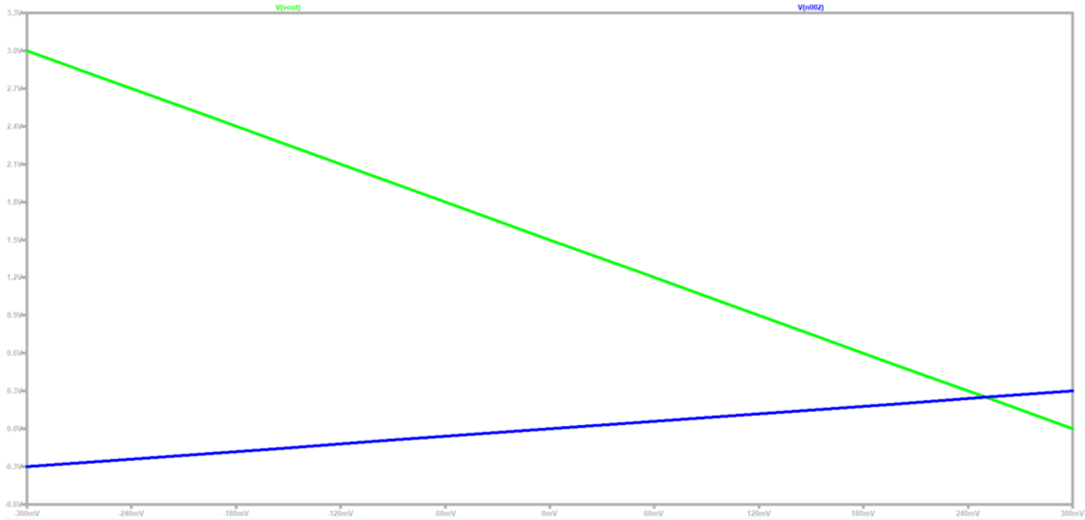


Figure 6. LTspice simulation result for Analog Signal Processing

2.4 Excel Calculation and Graph

The following table shows the values of all the resistors in the circuit calculated in excel application.

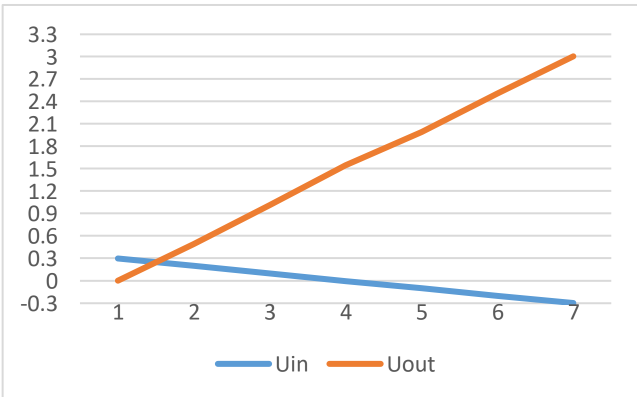
Table 1. Calculated resistor values in Excel

R1	240000		Vs	12
R2	10000		Uin	12
R3	256.41		Uout	0.3
R4	10000		U-	-0.3
R5	10000		U+	0.3
R6	50000		Uout	3
R7	50000			

The table and graph below demonstrate the relation between the input and output voltage.

Table 2. Input and Output Voltage Relation

Uin	Uout
0.299	0.002
0.202	0.49
0.099	1.013
-0.007	1.546
-0.096	1.993
-0.199	2.509
-0.297	3.005



3 COMMUNICATION

This section of the circuit aims at simulating the long distance transmission of the signal (not really long). It comprises of two main sub-circuits, a transmitter for sending and a receiver for receiving (and a potential isolator circuit).

3.1 Transmitter

3.1.1 Circuit Diagram and Calculation

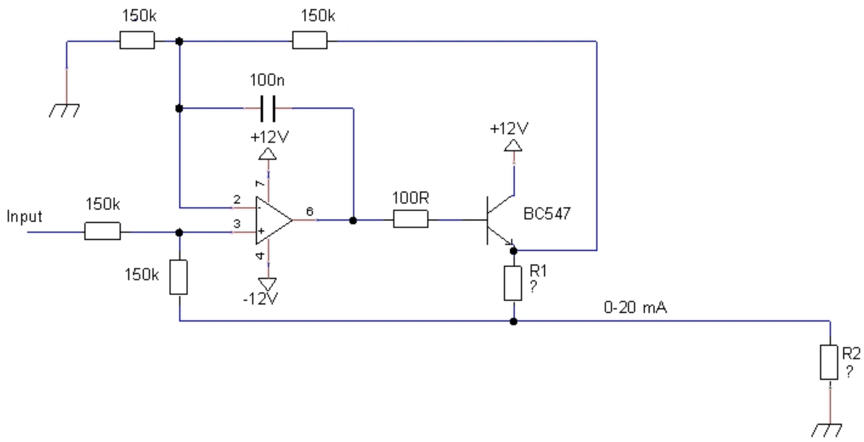


Figure 7. Transmitter Circuit Diagram

When the input voltage varies in the range of 0 to 3V, the current flowing through R1 is from 0 to 20mA correspondingly. In addition, when the current of 20mA flows in the circuit, the voltage over resistor R2 must be 5V.

Calculation of R1 and R2:

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

$$R2 = \frac{5V}{20mA} = 250\Omega$$

3.1.2 Signal Waveforms

The following figure depicts the behavior of the input voltage and the current flowing through resistor R1 in the transmitter circuit.

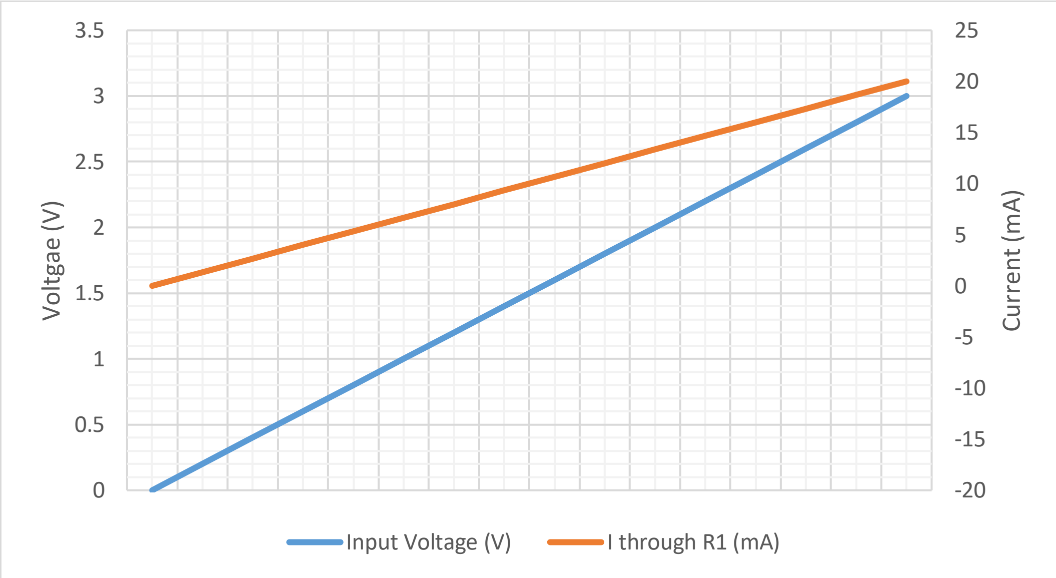


Figure 8. Transmitter Signal Waveforms

3.2 Receiver

3.2.1 Circuit Diagram and Calculation

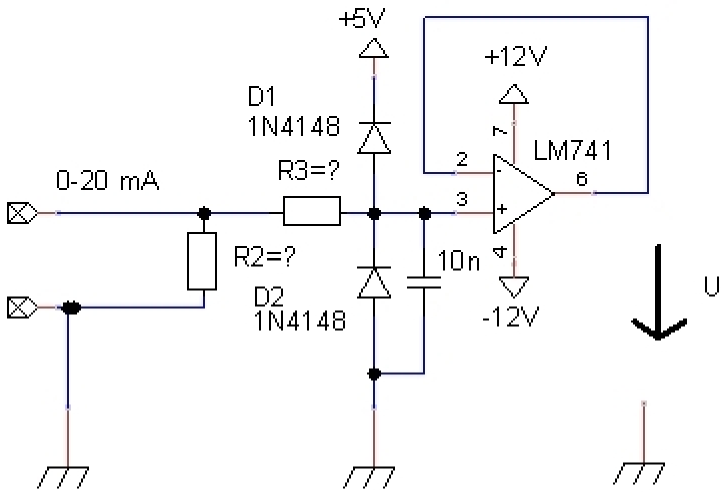


Figure 9. Receiver Circuit Diagram

The resistor R2 is the same R2 being used in the transmitter circuit, whose resistance value is 250Ω. For R3, if input signal contains 8kV ESD discharge voltage, the current value for D1 and D2 during this ESD event to be 0.8A.

Calculation of R3: $R3 = \frac{8kV}{0.8A} = 10000\Omega = 10\text{k}\Omega$

3.2.2 Signal Waveforms

The following figure demonstrates how the two signals, namely input current and output voltage of the receiver circuit, will change accordingly.

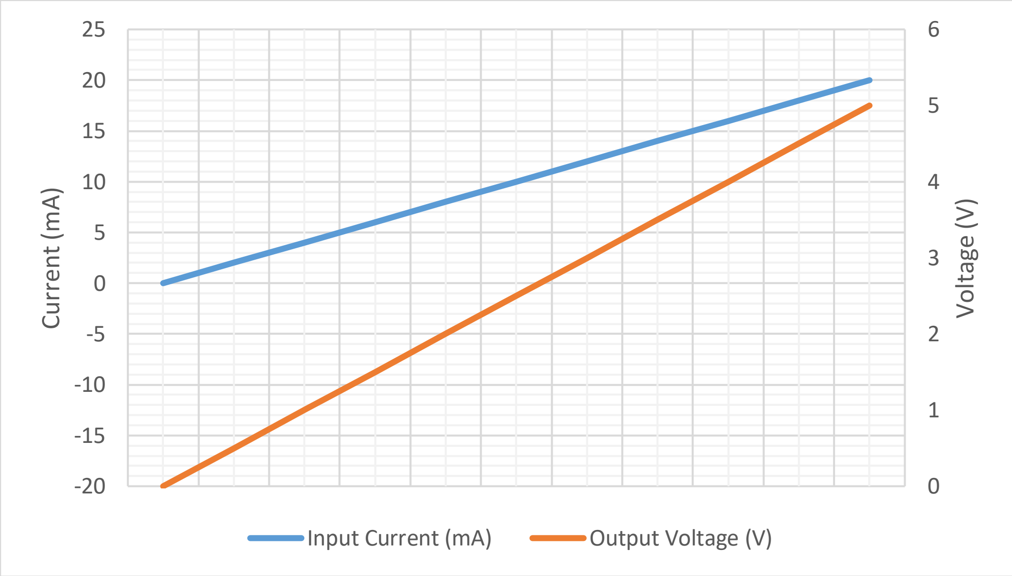


Figure 10. Receiver Signal Waveform

4 ANALOG TO DIGITAL CONVERSION

This section pays attention to converting the received analog signal into digital one which will later be sampled by the Arduino UNO for further calculation of the result.

4.1 MCP3002 vs ADC0832

Table 3. Comparison between MCP3002 and ADC0832

MCP3002	ADC0832
10-bit resolution	8-bit resolution
Dual channel	Input multiplexer with up to 8 channels
200ksamples/second	32μs/sample

In this circuit, MC3002 is used as the ADC chip. The following is the summary to the chip MC3002. MCP3002 10-bit Analog-to-Digital Converter (ADC) combines high performance and low power consumption in a small package, making it ideal for embedded control applications. The MCP3002 features a successive approximation register (SAR) architecture and an industry-standard SPI™ serial interface, allowing 10-bit ADC capability to be added to any PICmicro® microcontroller. The MCP3002 features 200k samples/second, 2 input channels, low power consumption (5nA typical standby, 520µA typical active), and is available in 8-pin PDIP, SOIC and TSSOP packages. Applications for the MCP3002 include data acquisition, instrumentation and measurement, multi-channel data loggers, industrial PCs, motor control, robotics, industrial automation, smart sensors, portable instrumentation and home medical appliances.

4.2 Circuit Diagram and Calculation

4.2.1 Reference Voltage Circuit

In order to maintain a consistent voltage for both the supply and reference voltage for MCP3002 (it uses the same pin for supply and reference voltage), a reference voltage circuit is employed which uses LM431 as the voltage regulator.

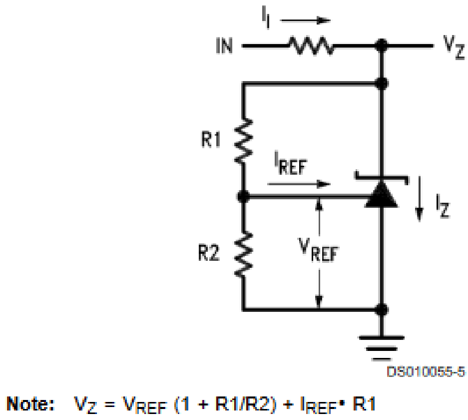


Figure 11. Reference Circuit for ADC conversion

According to the datasheet, we already have R1=10kΩ, I_{REF}=2μA, V_Z=5V and V_{REF}=2.495V. With these values, we can calculate the resistance of R2.

$$5V = 2.495 \times \left(1 + \frac{10k\Omega}{R2}\right) + 2\mu\text{A} \times 10k\Omega$$

Solving the equation gives us the value of R2 as approximately 10kΩ.

4.2.2 Analog to Digital Conversion Circuit

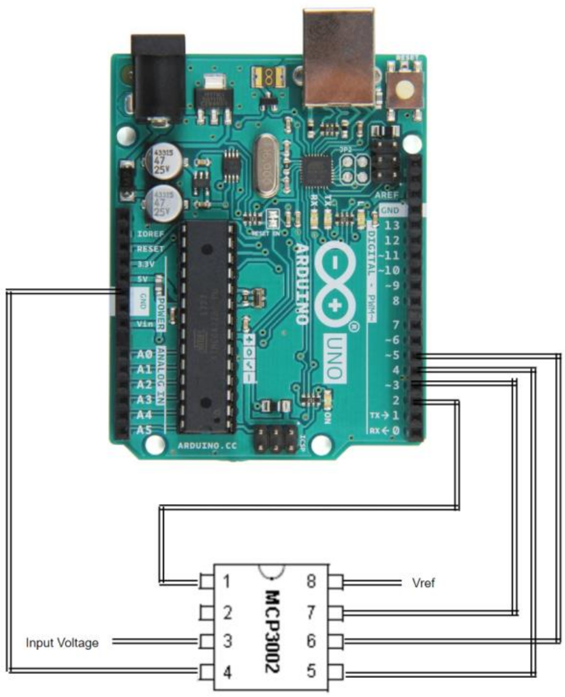


Figure 12. Circuit for reading ADC value

There are two channels in MCP3002, in this circuit, we do not use differential mode, so only channel 1 is used.

4.3 Software for Arduino UNO

The software code will be divided into several parts for the purpose of easier explanation.

The first part is about the initial setup. This part is all about declaring which pin is for output and input and defining the commands. Among all the pin being used (they are pin 2, 3, 4, 5 and 13), only pin 5 is used as an input.

The purpose of each pin is described as followed:

- Pin 2: this pin outputs signal driving the CS pin of MCP3002.
- Pin 3: this pin outputs signal driving the CLK pin of MCP3002.
- Pin 4: this pin outputs signal driving the DIN pin of MCP3002.
- Pin 5: this pin reads the ADC value bit-by-bit from the MCP3002 DOUT pin.
- Pin 13: this pin is used to control Arduino LED to signal ADC event.

```
void setup()
{
Serial.begin(9600);

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)

#define DOUT digitalRead(5)
}
```

Figure 13. Setup part of the code for Arduino UNO

After finishing the setup, it is time to move on to the loop portion of the code. In this part, the procedure of declaring variables, calling the ADC related function, calculation of temperature from the obtained result, controlling LED and transferring the value to a PC terminal program for displaying is concerned.

- Declaring variables: there are variables used in this part, they are ADC_result (integer) and temperature (4-byte floating-point real number). The former is to obtain result from a function (10-bit long) while the latter is result from calculation of temperature.
- Calling the ADC related function: this part simply call the get_AD_value, which will be explained later.
- Calculation of temperature: the 10-bit ADC value is corresponding to 1024 levels, and the temperature range is from -30 to 30 degrees Celsius (totally degrees). Thus, each level equals to 60/1023 degrees, and the starting temperature is -30. The final calculated value will be 60*ADC_result/1023-30.
- Transferring value to PC terminal: the Arduino UNO initiate a Serial transfer and display the result on PC (both ADC and temperature values).
- Controlling LED: turn LED off after finishing everything.

```
void loop()
{
// CLK_HIGH;
// CS_HIGH;
// delay(50);

int ADC_result;
  float temperature;
  ADC_result=get_AD_value();
  temperature=-(60.0/1023.0)*ADC_result+30.0;
  Serial.print("ADCC value ");
  Serial.print(ADC_result);
  Serial.println();
  Serial.print("Temperature ");
  Serial.print(temperature);
  Serial.println();
  ADC_result=0;
  temperature=0;
  LED_OFF;
  delay(50);


}
```

Figure 14. Loop part of the code for Arduino UNO

The loop portion requires a function called get_AD_value(), this function in turn will be further explained in three sub-parts.

The first one is setting up. In this sub-part, a local integer variable is created to store the ADC value and is initiated as 0. Another integer known as mask having initial value as 512. Three char variables for counting are pulse, i and k. After all, we start the process of getting the ADC value with turning LED on, turn off CLK and CS and making two consecutive delays with the bit DIN turned on in the middle.

The DIN is set to HIGH, CLK and CS to LOW during the first clock cycle to initiate a start.

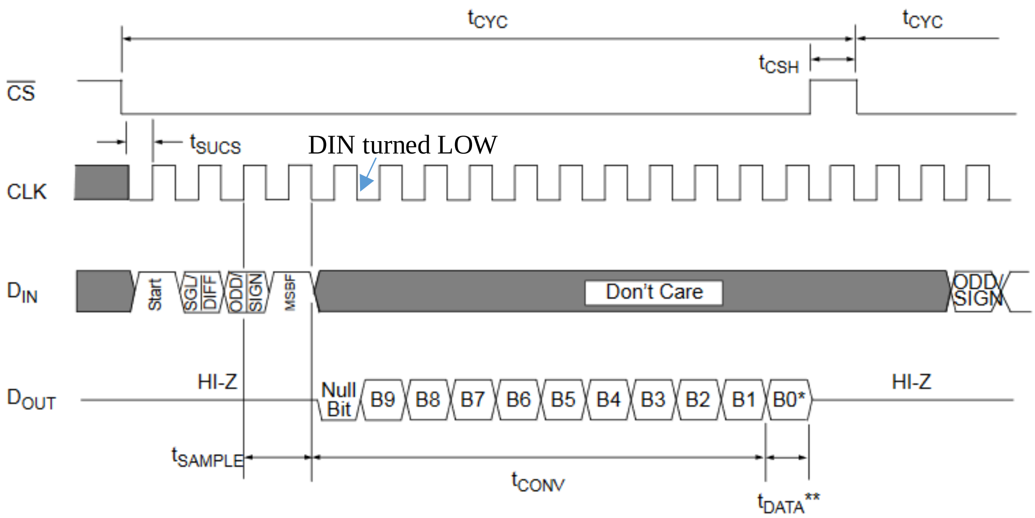


Figure 15. MCP3002 waveform

```
int ADC_result;
ADC_result=0;
 int mask=512;
 char pulse=0;
 char i=0;
 char k=0;
 CLK_LOW;
 CS_LOW;
 LED_ON; //extra LED on
 delay(10);
 DIN_HIGH;
 delay(10);
```

Figure 16.First part for Function get_AD_value

According to the waveform, before sending the result, MCP3002 requires 5 clock cycles, Start, SGL/DIFF, ODD/SIGN, MSBF and a Null Bit. Thus, the next sub-part will be a 5-time loop.

Each loop will have the CLK signal rise and fall for each half cycle. Moreover, after each loop, the value of pulse is incremented by one, and this is to check for the time to set DIN to LOW. The if statement will be true when the value of i is 3, and the DIN is set to LOW only after the CLK has been set to LOW. That point of time is marked in the waveform. Therefore, during the time for Start, SGL/DIFF, ODD/SIGN and MSBF bit, the DIN bit is always HIGH.

```
for(i=0;i<5;i++)
  {
  CLK_HIGH;
  delay(10);
  CLK_LOW;

  if(pulse==3)
    {
    DIN_LOW;
    }

  delay(10);
  pulse++;
  }
```

Figure 17. Second Part for Function get_AD_value

	CONFIG BITS		CHANNEL SELECTION		GND
	SGL/DIFF	ODD/SIGN	0	1	
Single-Ended Mode	1	0	+		—
	1	1		+	—
Pseudo-Differential Mode	0	0	IN+	IN-	—
	0	1	IN-	IN+	—

Figure 18. Configuring Bits for MCP3002

Both SGL/DIFF and ODD/SIGN bits are HIGH indicating the selected channel as 1 in Single-Ended Mode. The MSBF bit is HIGH, so the MCP3002 uses most-significant-bit-first mechanism. This leads to the last part of the function behaves in the most-significant-bit-first way.

The MCP3002 is 10-bit resolution ADC, so it will output a sequence of 10 bits in serial to pin DOUT. This is why the code for Arduino in this part will make a 10-time loop. In each loop, there will be one rise and fall of CLK signal and the acquisition of the corresponding bit. As mentioned above, the MSB first mechanism is used, so the most significant bit among the 10 bits is acquired first. The decimal value of the 9^{th} bit is $2^9 = 512$; therefore, the mask is set initially as 512. If the received bit from DOUT is 1, a bit-wise OR is executed between the ADC_result and mask variable to turn that corresponding bit to HIGH (e.g. mask=2^9=512 => 9^{th} bit is set to 1). For each subsequent loop, the mask is shifted to the left by 1 bit to collect the adjacent bit data. Finally, after finishing the loop, the CS signal is turned to HIGH to end the current session and then return the result to the loop function.

```
for(k=0;k<10;k++)
  {
  CLK_HIGH;



  if(DOUT==1)
    {
    ADC_result=(ADC_result|mask);
    }

  mask=mask>>1;


  delay(10);
  CLK_LOW;
  delay(10);
  }

CS_HIGH;
delay(20);

return ADC_result;
```

Figure 19. Last Part of Function get_AD_value

5 BREADBOARD CIRCUIT

Photos of breadboard circuit test are shown in the following figures.

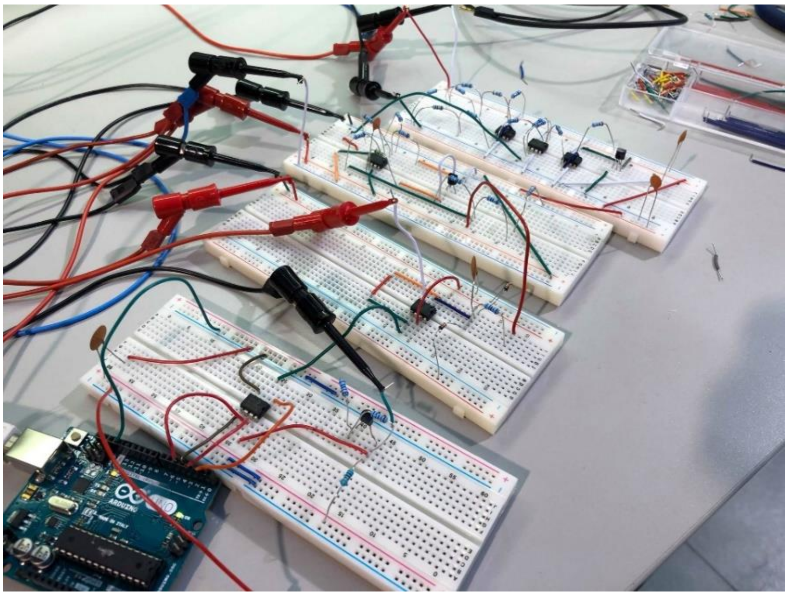


Figure 20. Breadboard Circuit Photo 1

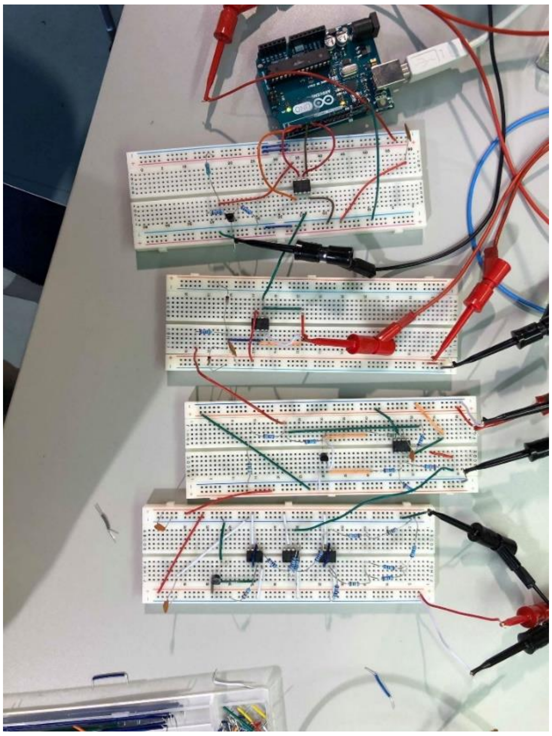


Figure 21. Breadboard Circuit Photo 2

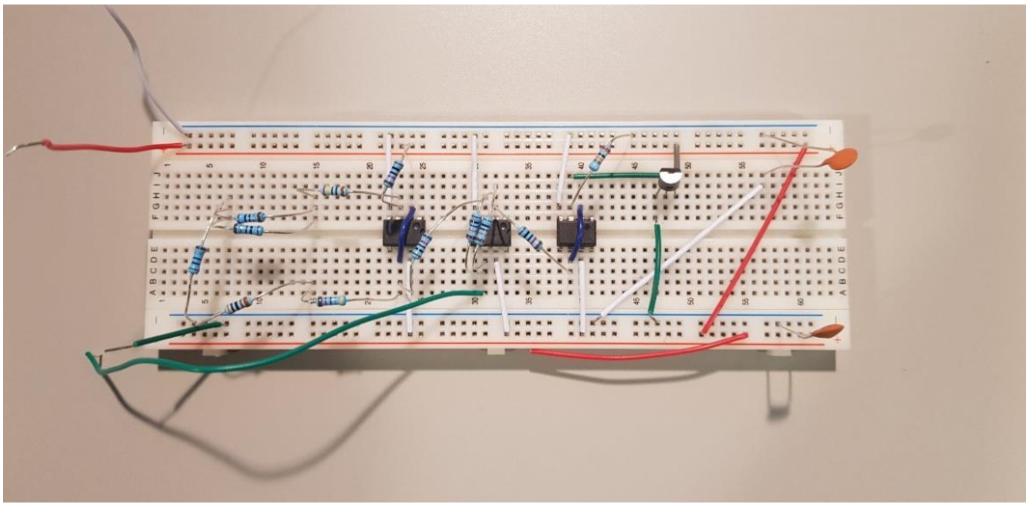


Figure 22. Analog Signal Processing Circuit on Breadboard

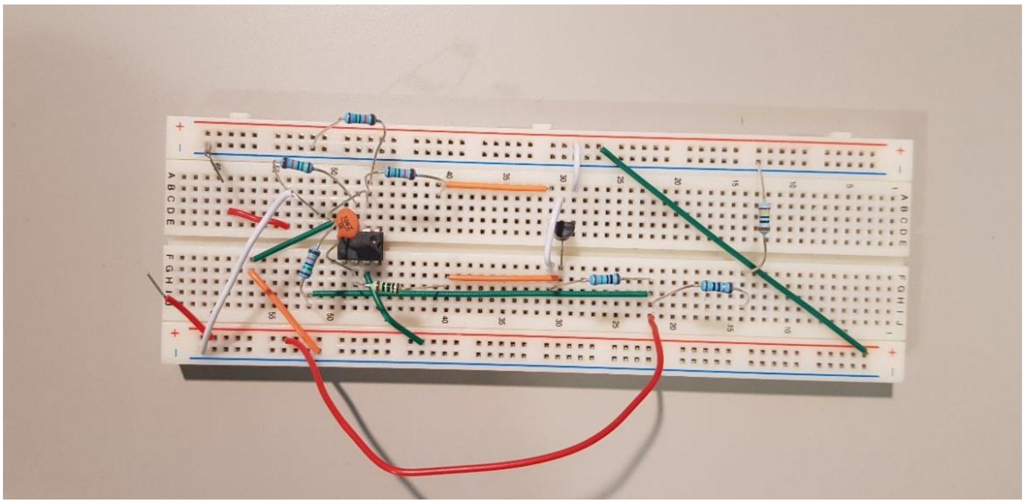


Figure 23. Transmitter Circuit on Breadboard

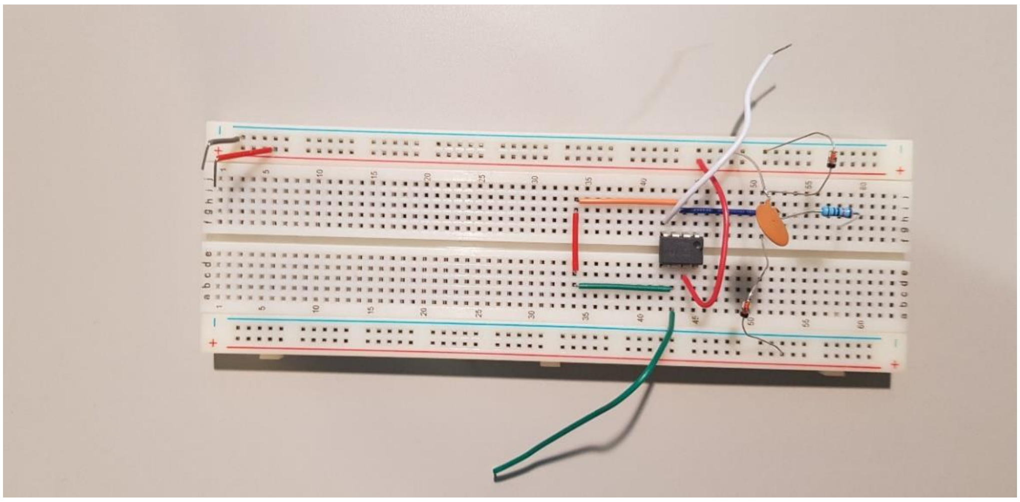


Figure 24. Receiver Circuit on Breadboard

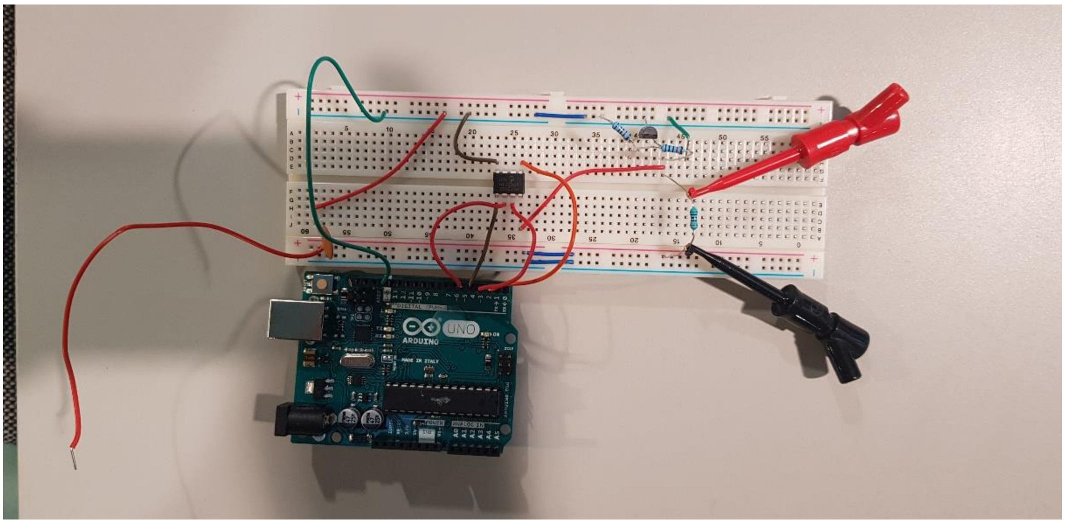


Figure 25. Analog to Digital Circuit on Breadboard

6 PADS LOGIC AND PRINTED CIRCUIT BOARD

The process of creating the product also involves the creating of PAD Logic and printed circuit boards. In this section, the transmitter and receiver circuits are demonstrated.

In order to complete the PCB, two softwares are needed, they are PADS Logic and PADS Layout.

6.1 Transmitter Circuit

The process of creating a proper PCB involves several stages, namely schematic design (PADS Logic), PCB design (both top and bottom layers) and finally pouring copper on both layers.

The PADS Logic circuit will be displayed to demonstrate the schematic of the circuit.

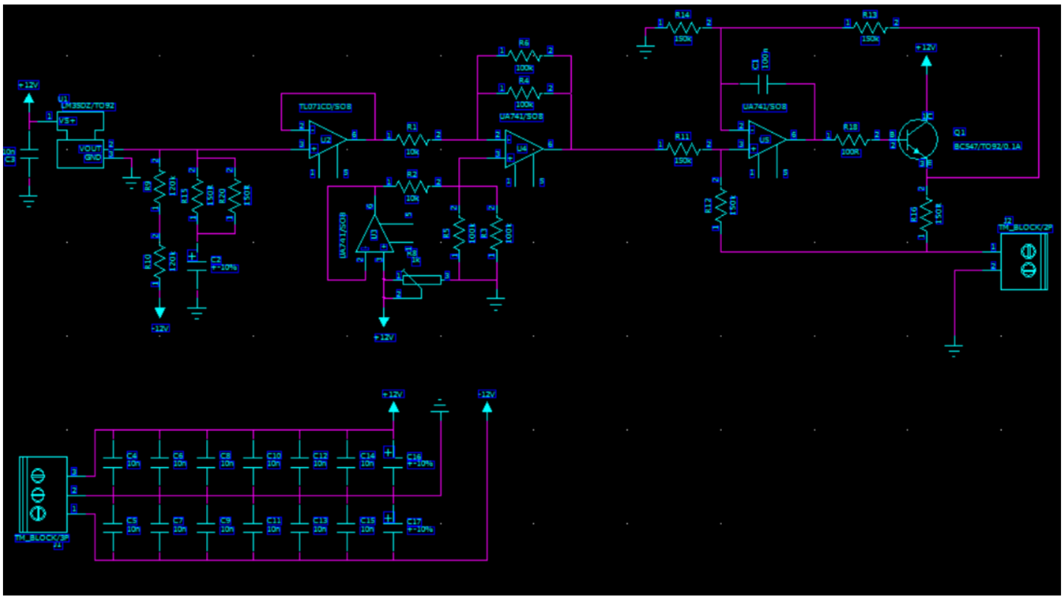


Figure 26. Schematic circuit for Tranmitter

The following figure describes the parts list for the transmitter circuit.

Bill Of Materials for transmitter.sch on Thu Dec 19 07:30:30 2019					
Item	Qty	Reference	Part Name	Manufacturer	Description
1	4	R3-6	100K/5%/0.125W,100k,+-5%	Multicomp	SMD resistor
2	1	C1	100NF/50V/CER, 100n,+-10%	Kemet	Multilayer ceramic SMD capacitor
3	1	R18	100R/5%/0.125W,100R,+-5%	Multicomp	SMD resistor
4	2	C16-17	100UF/10V/TAN, 100u,+-10%	Kemet	Tantalum SMD capacitor (polarized)
5	2	R1-2	10K/5%/0.125W, 10k,+-5%	Multicomp	SMD resistor
6	13	C3-15	10NF/50V/CER, 10n,+-10%	Kemet	Multilayer ceramic SMD capacitor
7	2	R9-10	120K/5%/0.125W,120k,+-5%	Multicomp	SMD resistor
8	4	R11-14	150K/5%/0.125W,150k,+-5%	Multicomp	SMD resistor
9	3	R15-16R20	150R/5%/0.125W,150R,+-5%	Multicomp	SMD resistor
10	1	C2	1UF/35V/TAN, 1u,+-10%	Kemet	Tantalum SMD capacitor (polarized)
11	1	Q1	BC547/TO92/0.1A, BC547/TO92/0.1A	NATIONAL SEMICONDUCTOR	AMPLIFIER NPN SILICON TRANSISTOR
12	1	U1	LM35DZ/TO92, LM35DZ/TO92		Analog PRECISION TEMPERATURE SENSOR
13	1	U2	TL071CD/SO8, TL071CD/SO8		LOW NOISE, JFET INPUT, OPERATIONAL AMPLIFIER
14	1	J2	TM_BLOCK/2P, Socket, Power Terminal Block, 3 way		Socket, Power Terminal Block, 3 way
15	1	J1	TM_BLOCK/3P, Socket, Power Terminal Block, 2 way		Socket, Power Terminal Block, 2 way
16	1	R8	TRIMMER/1K,1k		Trimmer, 1k
17	3	U3-5	UA741/SO8, UA741/SO8		OPERATIONAL AMPLIFIER

Figure 27. Parts list for Transmitter Circuit

After finishing the schematic part, it is time to design the PCB layout for the transmitter circuit. The PCB layout which includes both layers is depicted in the figure below.

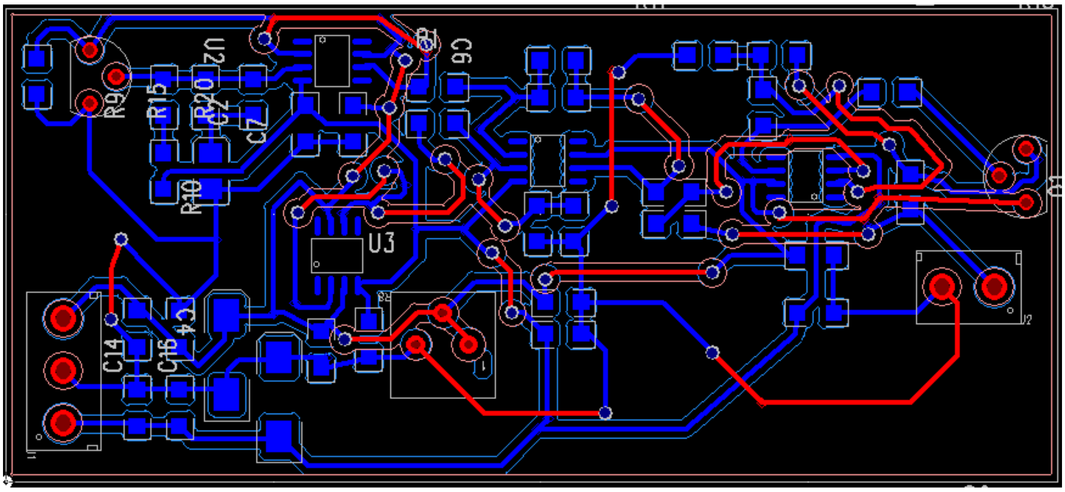


Figure 28. Transmitter PCB before pouring copper

The circuit has two layers, so there are two instances of copper-poured circuit PCB. The first figure is for the top-layer circuit.

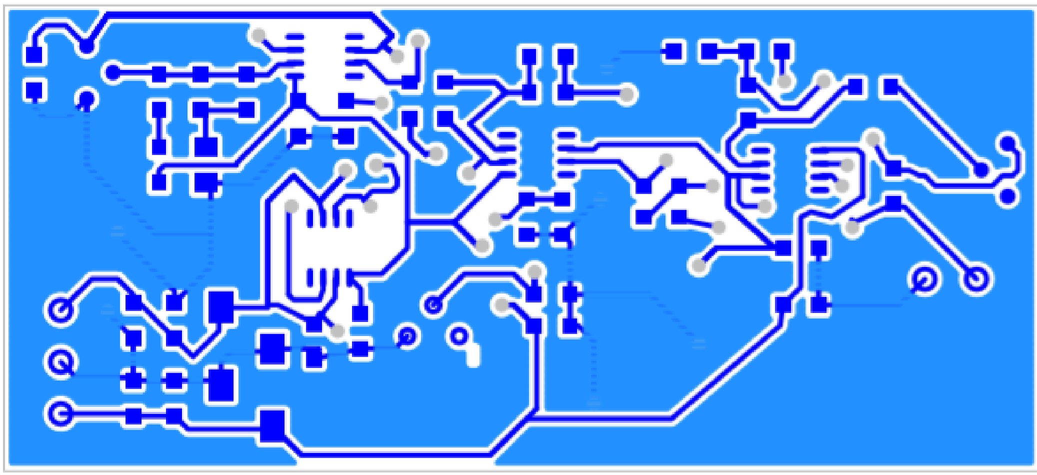


Figure 29. Transmitter PCB top layer after pouring copper

The bottom layer follows in the second figure, which uses a different color to depict the copper.

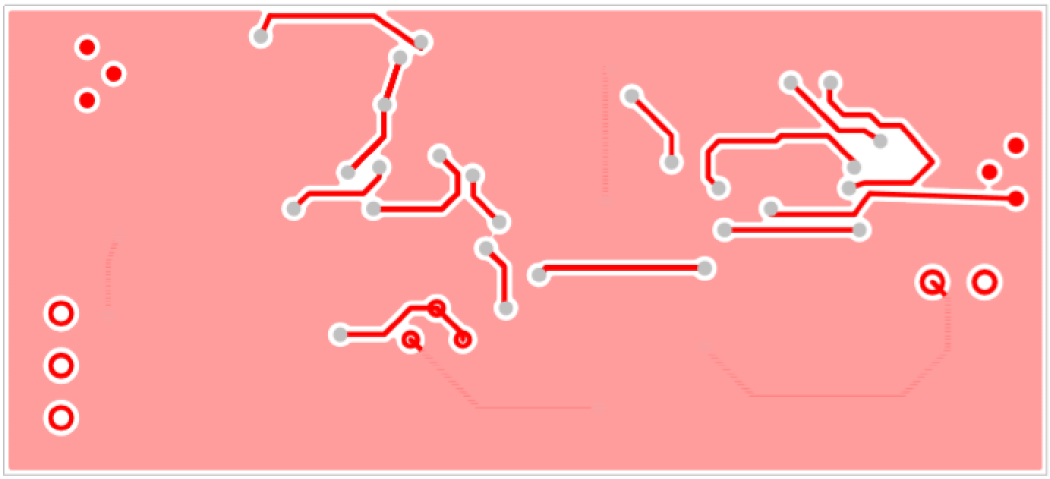


Figure 30. Transmitter PCB bottom layer after pouring copper

6.2 Receiver Circuit

Similar to the transmitter circuit, the receiver also has two layers and requires the same stages to be completed.

The figure below is about the schematics for the receiver circuit.

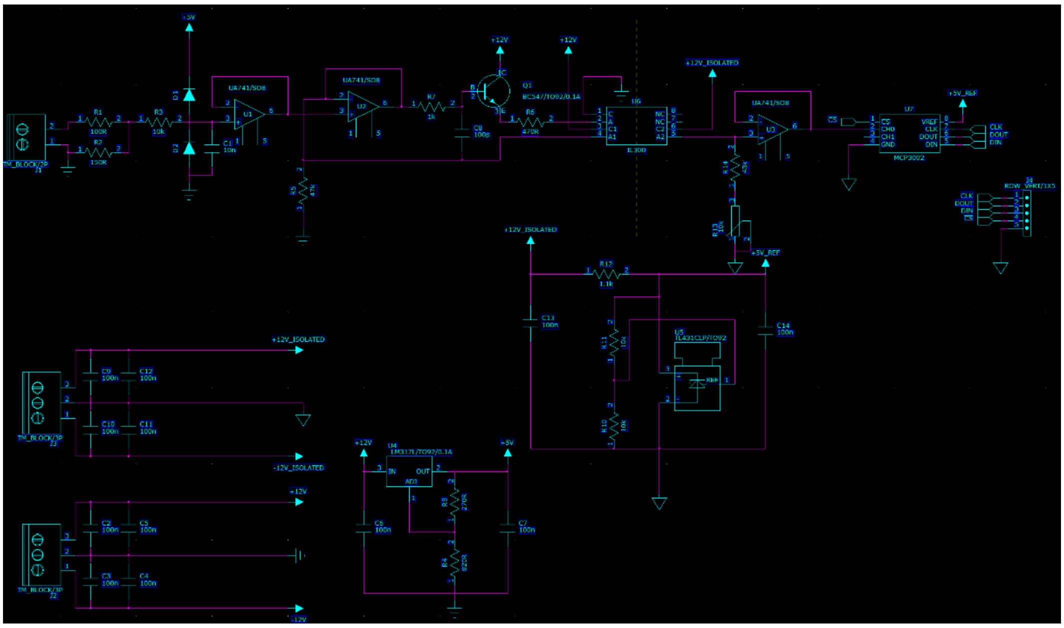


Figure 31. Schematic Circuit for Receiver

The following figure describes the parts list for the receiver circuit.

Bill Of Materials for receiver.sch on Thu Dec 19 07:23:12 2019

Item	Qty	Reference	Part Name	Manufacturer	Description
1	1	R12	1.1K/1%/0.6W, 1.1k,+-1%	Firstronics	Precision Metal Film Resistor
2	12	C2-7C9-14	100NF/50V/CER, 100n,+-10%	Kemet	Multilayer ceramic SMD capacitor
3	1	C8	100PF/50V/CER, 100p,+-5%	Kemet	Multilayer ceramic SMD capacitor
4	1	R1	100R/5%/0.125W,100R,+-5%	Multicomp	SMD resistor
5	2	R10-11	10K/1%/0.6W, 10k,+-1%	Firstronics	Precision Metal Film Resistor
6	1	R3	10K/5%/0.125W, 10k,+-5%	Multicomp	SMD resistor
7	1	C1	10NF/50V/CER, 10n,+-10%	Kemet	Multilayer ceramic SMD capacitor
8	1	R2	150R/5%/0.125W,150R,+-5%	Multicomp	SMD resistor
9	1	R7	1K/5%/0.125W, 1k,+-5%	Multicomp	SMD resistor
10	2	D1-2	1N4148/0.2A, 1N4148	Philips	High-speed diodes
11	1	R8	270R/5%/0.125W,270R,+-5%	Multicomp	SMD resistor
12	1	R14	43K/1%/0.6W, 43k,+-1%	Firstronics	Precision Metal Film Resistor
13	1	R6	470R/5%/0.125W,470R,+-5%	Multicomp	SMD resistor
14	1	R5	47K/5%/0.125W, 47k,+-5%	Multicomp	SMD resistor
15	1	R4	820R/5%/0.125W,820R,+-5%	Multicomp	SMD resistor
16	1	Q1	BC547/TO92/0.1A, BC547/TO92/0.1A	NATIONAL SEMICONDUCTOR	AMPLIFIER NPN SILICON TRANSISTOR
17	1	U6	IL300		
18	1	U4	LM317L/TO92/0.1A, LM317L/TO92/0.1A	NATIONAL SEMICONDUCTOR	POSITIVE VOLTAGE REGULATOR; ADJUSTABLE
19	1	U7	MCP3002		
20	1	J4	ROW_VERT/1X5, Plug, Vertical Row Header		Plug, Vertical Row Header
21	1	U5	TL431CLP/TO92, TL431CLP/TO92		Adjustable Micropower Voltage Reference 1,24-5,30V
22	1	J1	TM_BLOCK/2P, Socket, Power Terminal Block, 3 way		Socket, Power Terminal Block, 3 way
23	2	J2-3	TM_BLOCK/3P, Socket, Power Terminal Block, 2 way		Socket, Power Terminal Block, 2 way
24	1	R13	TRIMMER/10K, 10k		Trimmer, 10k
25	3	U1-3	UA741/SO8, UA741/SO8		OPERATIONAL AMPLIFIER

Figure 32. Parts List for Receiver Circuit

Now, it is time to move on to the PCB design for the transmitter circuit. Each layer is shown in each figure below. The first one is for top, and the second is for bottom.

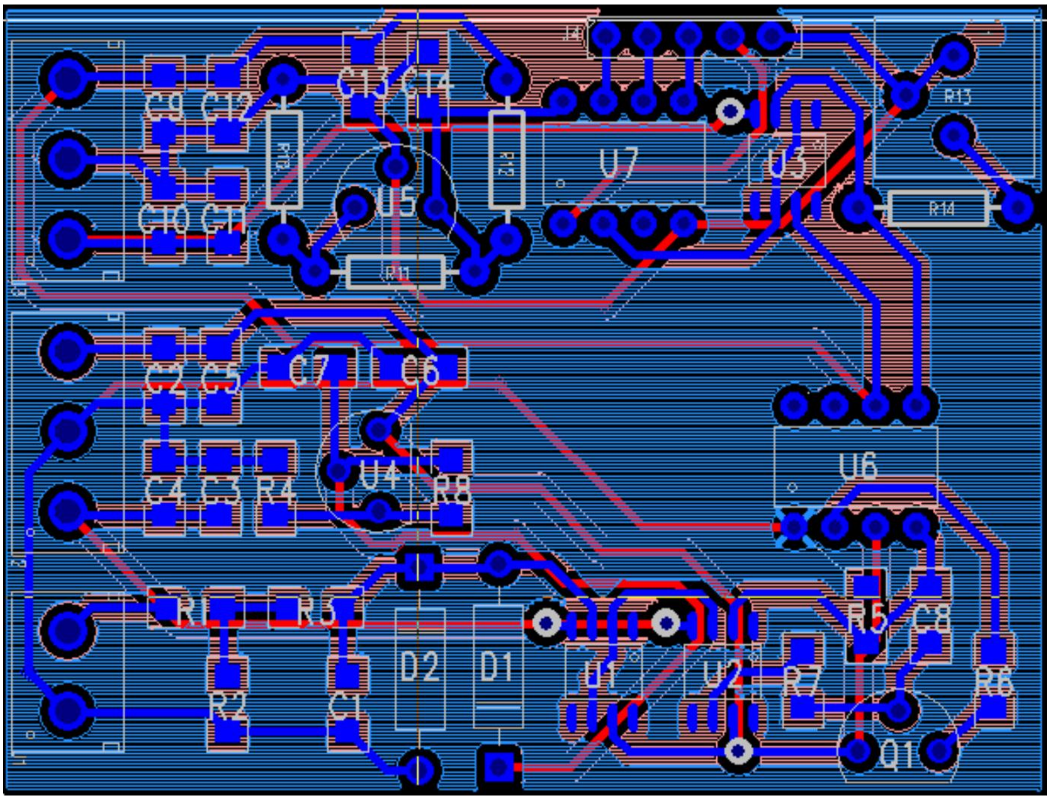


Figure 33. Top-layer PCB for Receiver

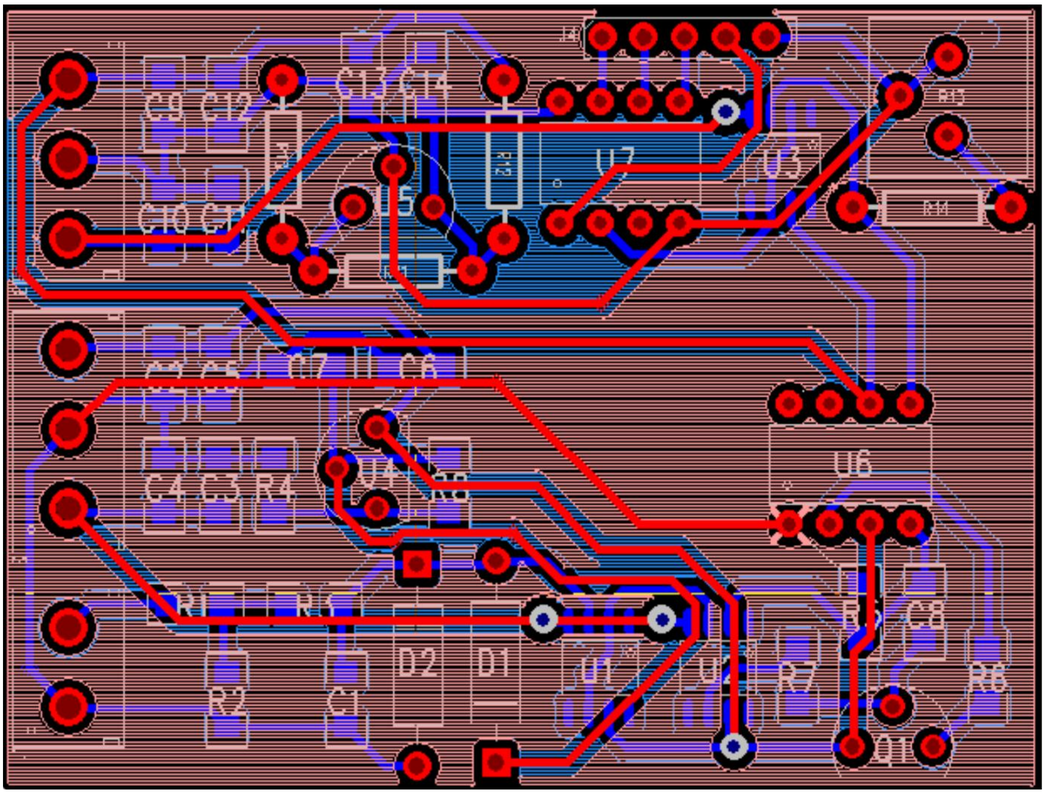


Figure 34. Bottom-layer PCB for Receiver

7 PRODUCT

7.1 Transmitter

The following two figures depict the transmitter circuit.

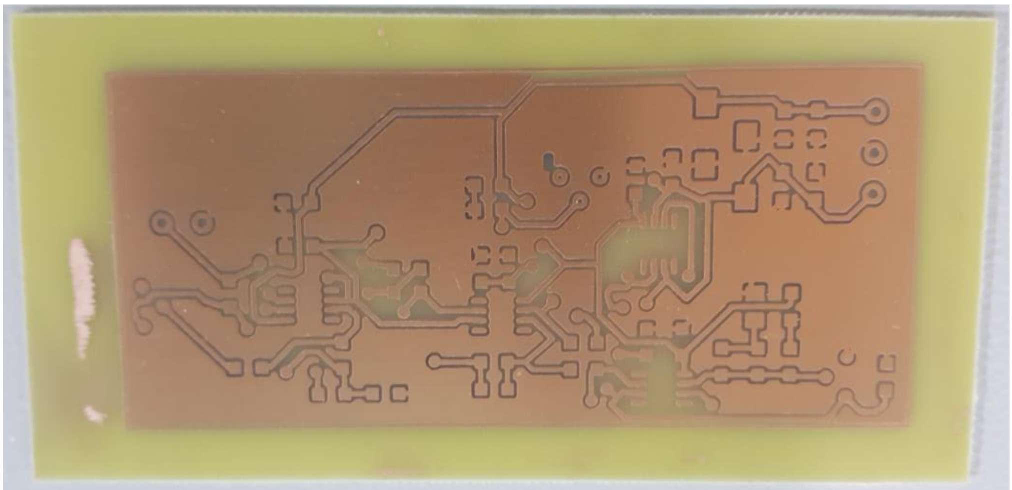


Figure 35. Top Layer for Transmitter

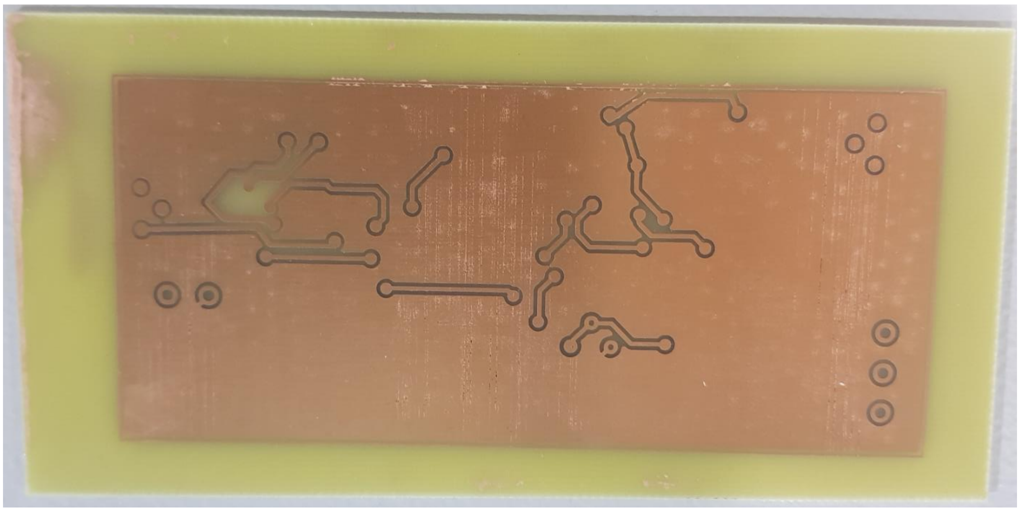


Figure 36. Bottom Layer for Transmitter

7.2 Receiver

The two figures below show the circuit for the receiver.

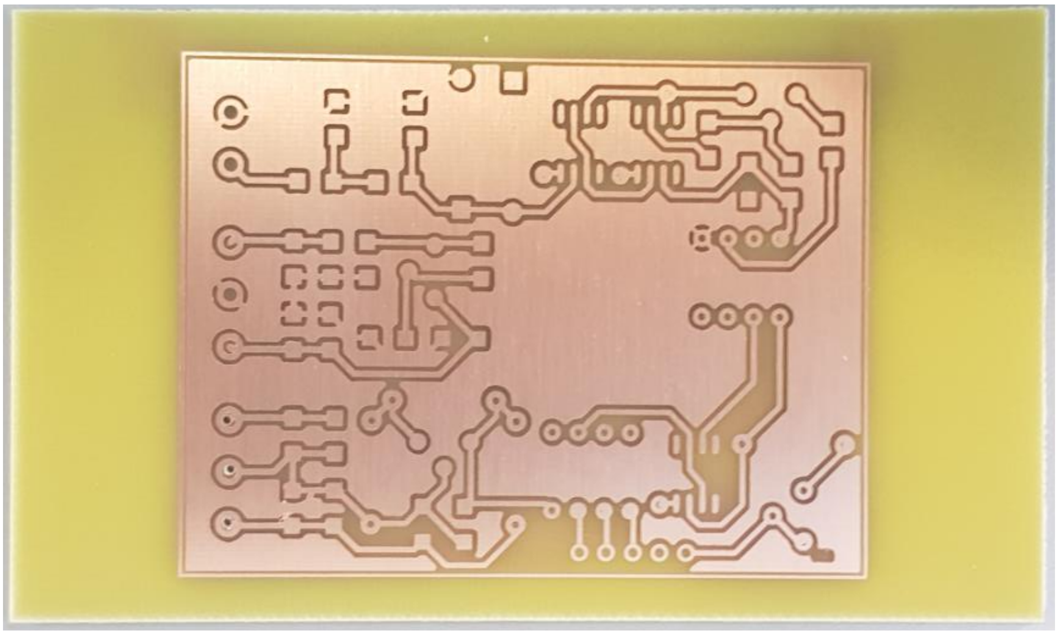


Figure 37. Top Layer for Receiver

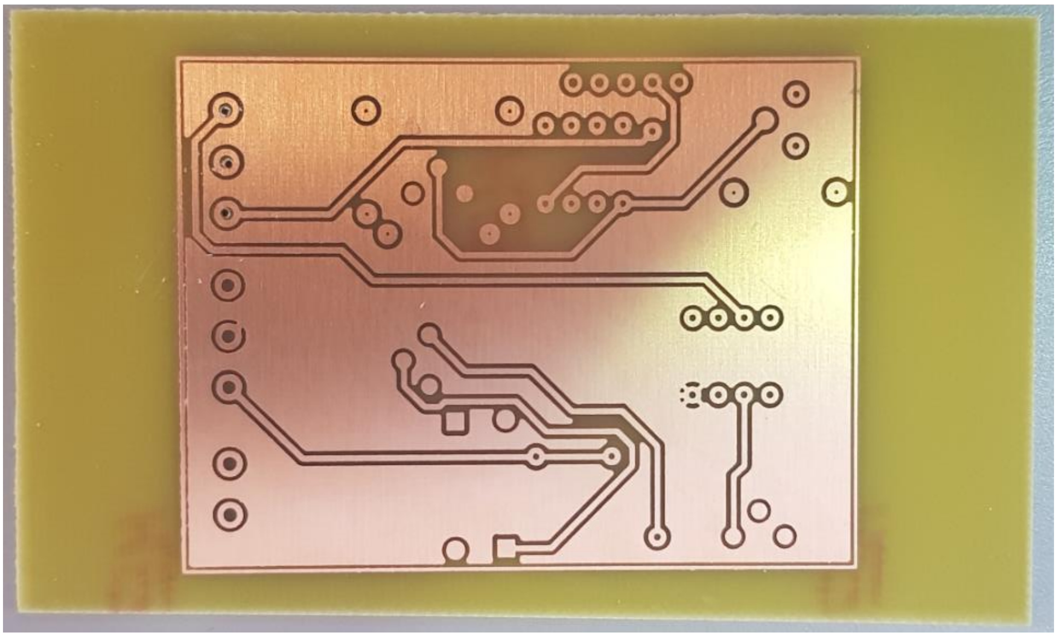


Figure 38. Bottom Layer for Receiver

8 CONCLUSION

Although, our team cannot manage to complete everything within the timeframe of the course (soldering the components have not been finished), our members manage to learn a lot of things. First but also the most important, despite having learnt the process of making a circuit board in one previous course, this is the first time our team do the job on our own with proper supervision, not simply observing the teacher doing everything. This includes but does not limit to designing the circuit, testing on the breadboard, drawing schematics in PADS Logic and PCB, printing on transparent papers, making the board, drilling and soldering components. Moreover, we are able to apply the theoritcal knowledge we studied in class to the reality. Last but not least, as a team, we learn to share, to cooperate effectively and to aid one of us facing difficulty. All in all, our team is now able to manufacture our very own first circuit.

9 REFERENCES

Operational Amplifier Calculation : https://portal.vamk.fi/pluginfile.php/552902/mod_resource/content/0/ophandbook.pdf

Requirement: http://www.cc.puv.fi/~ja/dsd/Requirement%20specification2.htm