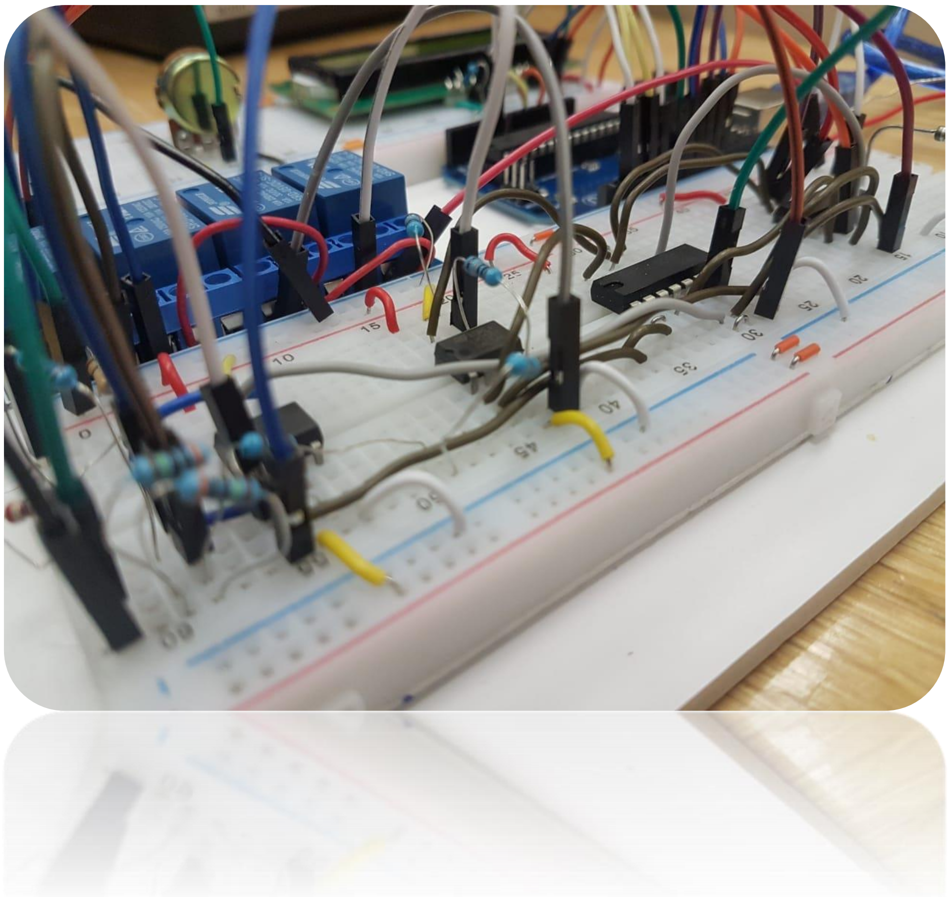
SPRING 2019



VOLTAGE AUTO-RANGING SENSOR (VARS)

EE306 PROJECT

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Introduction

Learning about electrical circuits and how to theoretically analyze them is one thing, being able to apply this knowledge to a real-life circuitry is another. In the course of EE-306, we learned many non-ideal behaviors for circuit components. These behaviors can have a tremendous impact on the functionality of any circuit and therefore must be accounted for in all successful practical designs. In this project we took what we learned about electrical circuits and components and applied this knowledge to build a functional circuit that solves a real-life problem. We started by finding and more precisely defining the problem that we are trying to solve. We then moved on to review existing approaches that were used to solve this specific problem. Afterward, we started designing a circuit that can solve the problem. The design process included many preliminary designs, various component comparisons, and cost analysis. Finally, we simulated, built, and tested our design. In what follows in this report, we will document the whole process mentioned as well as reflect on what we did and how we could have done it better.

Problem Statement

It is difficult for controllers to measure varying voltages that have a high range of values. We need to construct a circuit that makes it safe for controllers and ADCs to measure high voltage ranges without any human intervention.

Objectives

- Design a circuit that uses the simple voltage division concept to reduce the voltage to a value readable by controllers (ie. 3.3V, 5V, 12V).
- Accommodate different ranges of operation to maintain high measuring accuracy.
- Automate the switching process (So that logical circuits can work unattended).
- Simulate, build, and test the design.
- Deliver a final functioning and well-documented artifact that solves the problem.

Existing Alternatives

Voltmeter

Figure 2 Manual Range Multimeter

Figure 1 Auto range multimeter

Many devices exist to measure a large range of voltages, currents, resistances and much more all in a single package. Some of them even incorporate automated ranging so that the appropriate range of measurement does not have to be manually chosen. These devices however are hard to integrate into other circuits since they usually come sealed and with their own displays made for human usage only. This prevents logic circuit designers from being able to use the information that these instruments provide in their circuits.

Voltage Sensors

Voltage sensors enable circuit designers to incorporate the voltage readings in their designs. The

Figure 3 Voltage sensor

only issue with these sensors is that they usually operate on one range (Typically 0-25V) thus they cannot measure very high voltages. Moreover, due to using one range only, small voltage measurements will lack accuracy (Measuring 0.6V on a 25V scale can introduce large errors).

In our design, we wanted to combine the versatility of multimeters and their ability to measure a very wide range of voltages with high accuracy, with the voltage sensors' ability to be incorporated in electrical circuits. Thus, we decided to design the voltage auto-ranging sensor.

Design steps

We have searched for many existing auto ranging circuit designs and have found them to be either too complicated or too simple. Therefore, we decided to come up with our own circuit design so that we can customize it to fit both our limitations and objectives. In what follows, we will list our design process and how we managed to reach the final design.

Multi-range design

Before going into how we make the process of switching automated, we must first design resistor circuits that will use voltage division to scale down the voltage to different ranges. Initially we decided to design for the following ranges where each range scales its maximum value to 5V (The most common voltage used in logical circuits):

- 0-5V
- 0-10V
- 0-20V

Three resistances in series can give us those ranges as follows:

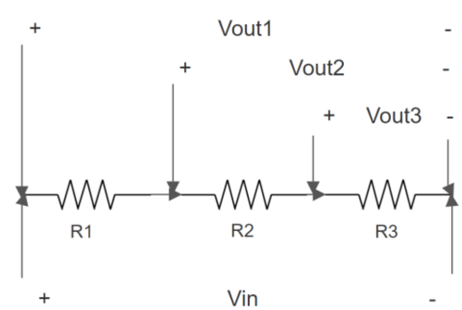


Figure 4 3-Range voltage division circuit

From there, we used simple voltage division equations to calculate the needed ratios between the resistors.

$$\frac{R2 + R3}{R1 + R2 + R3} = \frac{5}{10}$$

$$\frac{R3}{R1 + R2 + R3} = \frac{5}{20}$$

So, if R3 = R then R2= R and R1 = 2R

Using these ratios gives: Vout1 = Vin, Vout2 = Vin/2, Vout3 = Vin/4 which gives us the three ranges we specified above. Now the problem becomes how can we automatically switch between ranges so that the output is taken from the appropriate place. This brings us to the challenging part of the design.

Design 1

For our first design we considered using shift registers to store which range the voltmeter is operating at. We can then change the contents of the register as we go up and down the range list depending on the output of comparators.

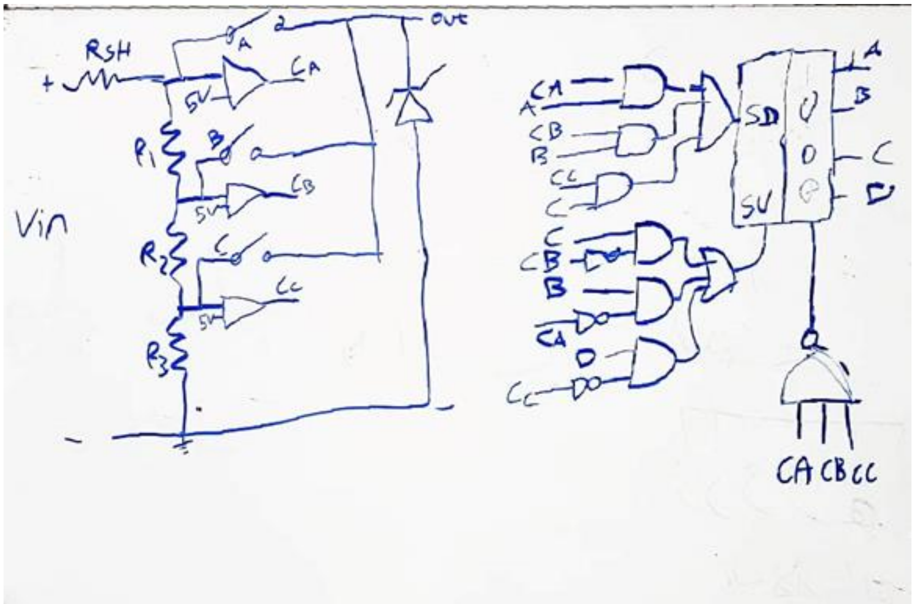


Figure 5 Design 1

Each range has a comparator that compares the input voltage to that range with 5V. If the input is larger than 5V, that suggests that we need to shift to a bigger range. If it is smaller than 5V and we are not at that range, then we can shift down to that range (It means a smaller range can handle the input).

Problems with this approach:

- Slow to change to needed range
- Needs clock
- Complicated

Design 2

In this design, we tried to use the same comparison and switching concept as in design 1, however we wanted to eliminate the need for a shift register and a clock. Doing that can save us a lot of time and resources. So we went ahead and came up with certain logical combinations of the outputs of the comparators to simulate the same switching behavior.

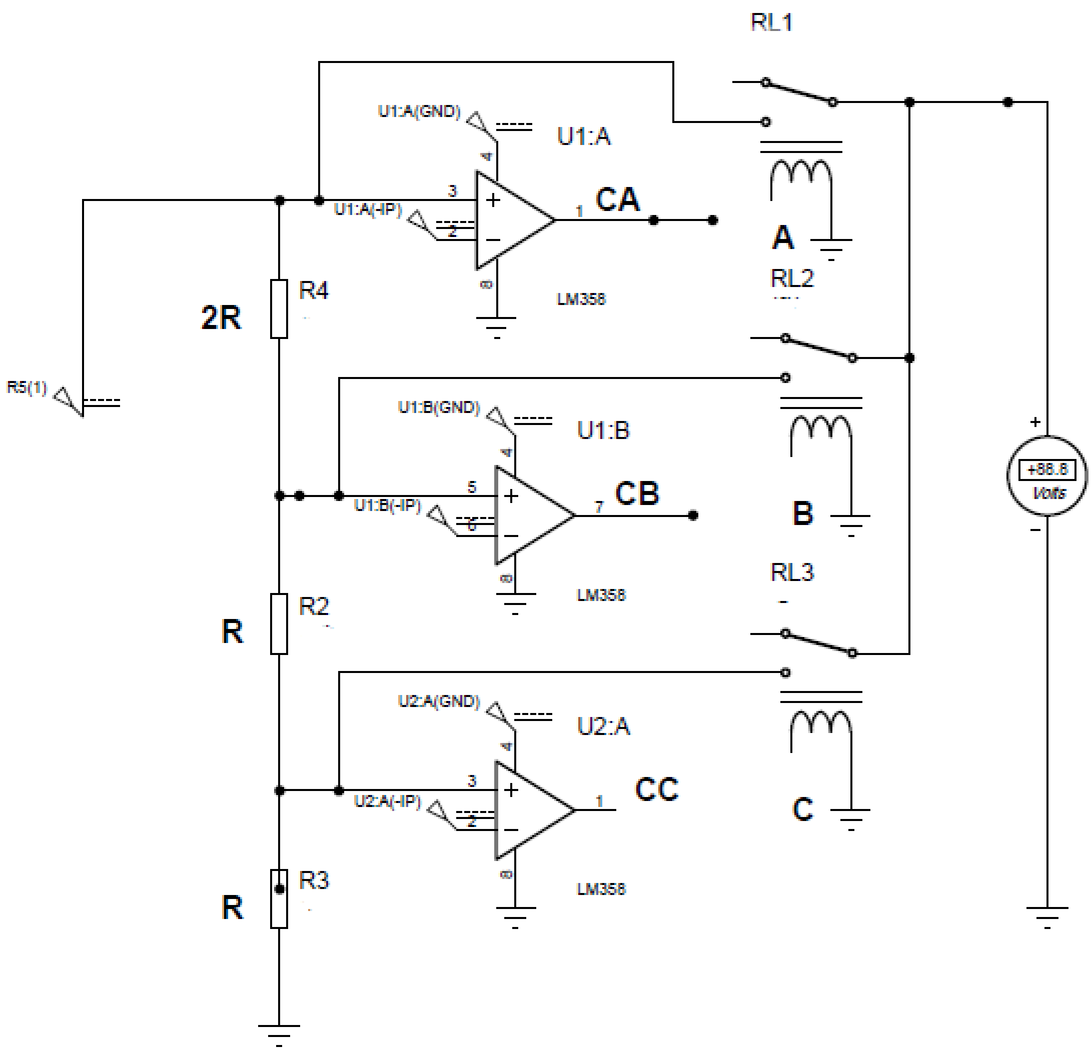


Figure 6 Design 2

CA, CB, and CC refer to the comparator outputs. A,B, and C refer to the logic that closes the switch. The logic used was as follows:

A = NOT CA

B = CA AND NOT CB

C = CB AND NOT CC

So the first range is used if CA is false (Input is less than 5V), the second range is used if CA is true and CB is false (Input is greater than 5V but less than 10V), and lastly, the third range is used if CB is true and CC is false(Input is greater than 10V but less than 20V). If the input exceeds 20V then all of the ranges are not used and the output becomes in an open circuit state. This helps protect our external microcontroller in the case where our circuit cannot scale down the input voltage to a safe 5V or less.

At this point we were confident in our design and its functionality. So we decided to improve it a little bit more by including more ranges. We asked ourselves "Can we increase the number of ranges without adding many components?"

Design 2x

This design answers the mentioned question. We managed to **double** the number of ranges we can accommodate by simply adding one more switch and one more op amp. We did not need to double the number of switches or op amps. The idea is simple, we consider our circuit to have two significant ranges and 3 sub-ranges in each significant range. This gives us a total of 6 ranges.

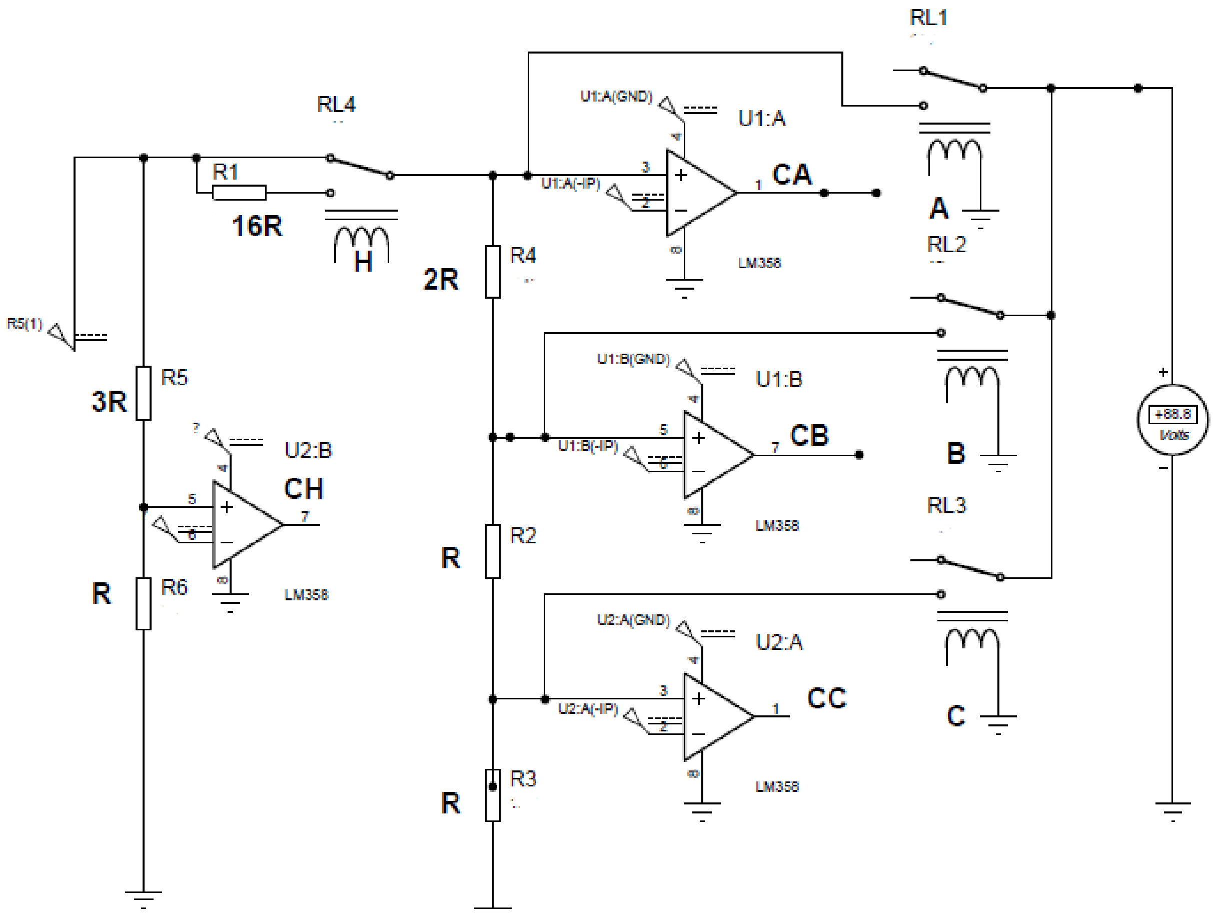


Figure 7 Design 2x

Notice how the part on the right is exactly the same as in Design 2. The extra comparator is setup in a way that determines the significant range of operation. It controls the switch H directly. So if CH is true that means that we have to switch to the higher significant range. If it is false, that means that the lower significant range can handle the input and we should use it. The extra resistance introduced when we are operating at the higher significant range was chosen to be 16R this gives us the following sub ranges:

- 0-25V
- 0-50V
- 0-100V

It can be calculated similarly to the multi-range design part.

$$\frac{2R + R + R}{16R + 2R + R + R} = \frac{1}{5}$$

which means that the input will be divided by 5 hence increasing our range to 25V

$$\frac{R + R}{16R + 2R + R + R} = \frac{1}{10}$$

which means that the input will be divided by 10 hence increasing our range to 50V

$$\frac{R}{16R + 2R + R + R} = \frac{1}{20}$$

which means that the input will be divided by 20 hence increasing our range to 100V

Components explanation

Op-amps

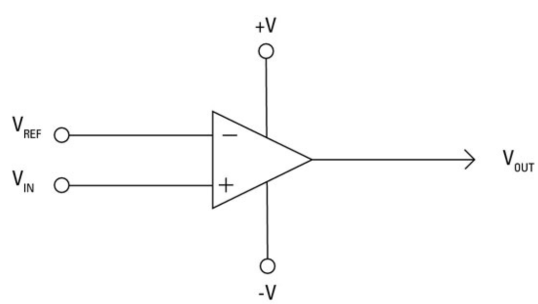


Figure 8 OP AMP Diagram

One of the many uses of operational amplifiers is to be used as a voltage comparator, which compares the magnitudes of two voltage inputs and determines which is the largest of the two.

In each range of our design, a comparator is used to compare the input value with V_{reff} = 5 V as explained previously.

Switching

There are few ways to make auto switching possible between circuit's paths, Relays are on the common switches that operates be opening and closing circuits electromechanically. A relay can control one electrical circuit by opening and closing contacts in another circuit.

As the figure above shows, when a relay contact is normally open (N.O.), there is an open contact

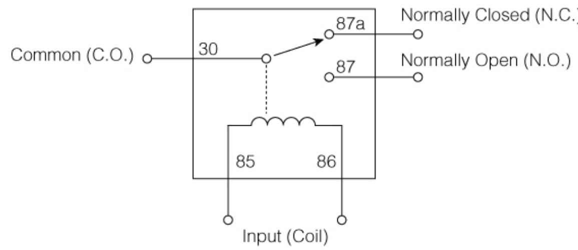


Figure 9 Relay Diagram

when the relay is not energized.

Zener Diode

Zener diodes work exactly like standard diodes with the exception that Zener diodes have a specified reverse breakdown voltage, also known as the "Zener Voltage". Hence, if you reverse-bias a zener diode, it will prevent current flowing in a circuit only up to a certain voltage. The Zener diode we chose have a breakdown voltage of 5V, which is the maximum amount of voltage that the controller can take.

Logic Gates

Logic gates were connected in between each relay and the output of each corresponding comparator to satisfy these boolean equations:

1. $A = {}'CA$
2. $B = {}'(CA \cdot CB)$
3. $C = {}'(CB \cdot CC)$
4. $H = CH$

NAND gates were used to implement the second and third equations, while a single inverter (not gate) was used to satisfy the first equation.

Components comparison *(M)*

Op-amp

	LM741	**LM358**	**LM2904**

Voltage sources needed	2	1 or 2	1 or 2
Number of Op-amps in a single package	1	2	2
Supply voltage	4.5V to 22V	3V to 32V	3V to 26V
Max input voltage	15V	32V	26V

Cost analysis

Part	**Cost**
2 x LM358 (Op-Amp)	4.00 S.A.R
TTL 6 INVERT (NOT) Logic Gate IC (7404)	6.00 S.A.R
4 Channels Relay Module	24.00 S.A.R
Zener Diode 1N751	3.00 S.A.R
Resistors	5.00 S.A.R
Arduino Uno	40.00 S.A.R
2 x Breadboards	20.00 S.A.R
Total	**102.00 S.A.R**

Validation and testing:

Arduino setup with LCD

To test our project and the accuracy of its reading we used an Arduino along with an LCD module. We connected the Arduino with the LCD as demonstrated on the following figure:

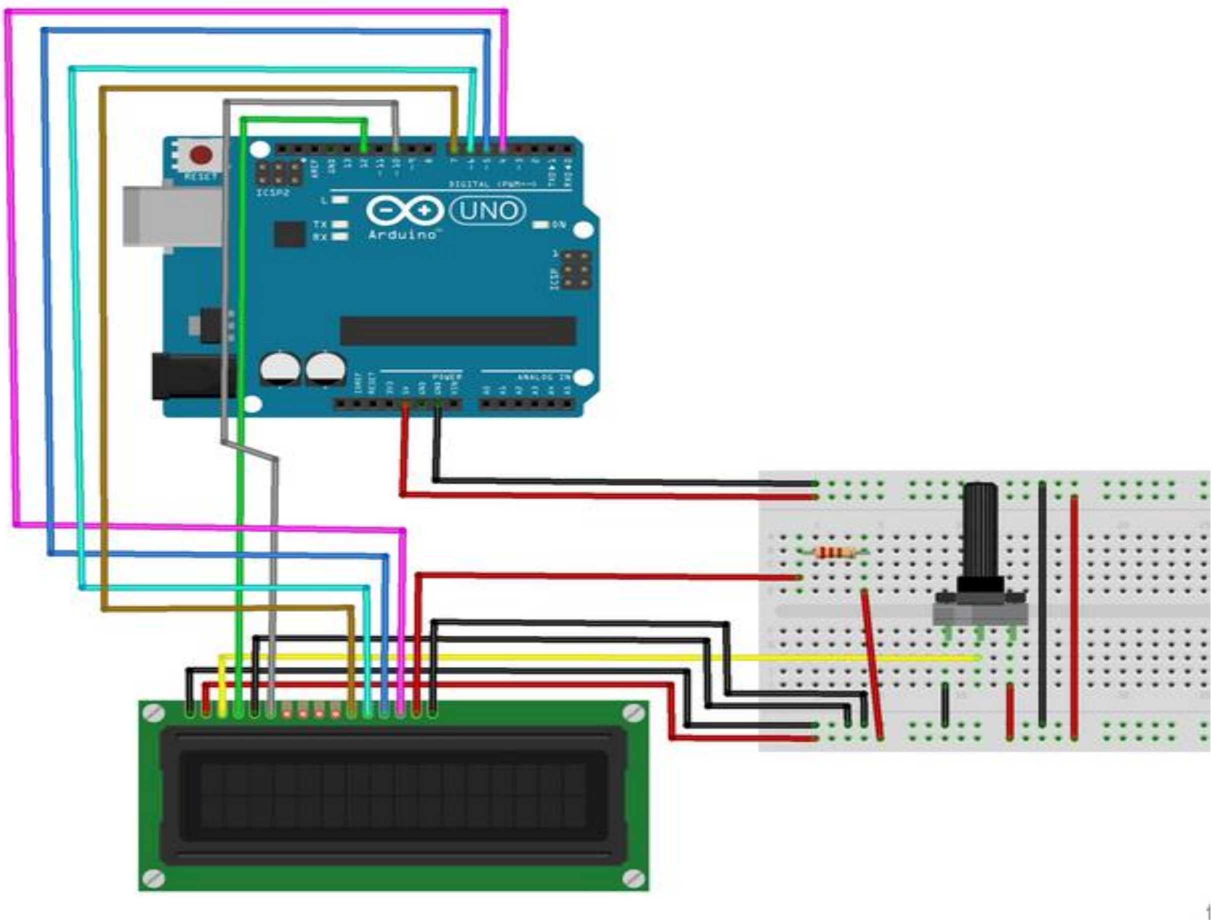


Figure 10 Arduino LCD Connection

Then we connected the rest of our system to the Arduino to display the reading of the system (reading value) and to display the scaled value (measured value) depending on the range.

The scaled value depends on the range and we have six ranges. For each range, we will multiply the reading value from the system by the range factor as the following:

Range	Range factor	Example
0 to 5 volt	1	If input voltage = 4 V The reading = 4/1 = 4 V The scaled = 4*1 = 4 V
0 to 10 volt	2	If input voltage = 10 V

		The reading = 10/2 = 5 V The scaled = 5*2 = 10 V
0 to 20 volt	4	If input voltage = 16 V The reading = 16/4 = 4 V The scaled = 4*4 = 16 V
0 to 25 volt	5	If input voltage = 25 V The reading = 25/5 = 5 V The scaled = 5*5 = 25 V
0 to 50 volt	10	If input voltage = 30 V The reading = 30/10 = 3 V The scaled = 3*10 = 30 V
0 to 100 volt	20	If input voltage = 80 V The reading = 80/20 = 4 V The scaled = 4*20 = 80 V

In order to define the current range of the system to the Arduino to multiply the reading value by the correct range factor, we connect a wire from each relay to the Arduino (because each relay will allow output only in its range).

Programming the Arduino

We used a very simple program that displays the exact read voltage and the scaled voltage (After multiplying with the range factor). The program reads the input of the relays to determine the current functioning range. It then chooses the multiplier based on that range.

```
// include the library code:
#include <LiquidCrystal.h>
const int rs = 12, en = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
const int r[] = {10,9,8,7};
const int inputVoltagePin = A0;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
const int refreshDelay = 500;
const float bias = 0;

void setup() {
  lcd.begin(16, 2);
  for(int i = 0; i < 4; i++){
    pinMode(r[i],INPUT);
  }
  pinMode(inputVoltagePin,INPUT);
  Serial.begin(9600);
}

void loop() {
  int state = 0;
  for(int i = 0; i < 4; i++){
```

```
    int j = digitalRead(r[i]);
    j = j == HIGH? LOW: HIGH;
    state += j << i;
  }
  Serial.println(state);
  int binaryReading = analogRead(inputVoltagePin);
  float voltageReading = binaryReading * 5.0 / 1024.0;
  lcd.clear();
  lcd.print("Reading: ");
  if(state != 0 ) {
    lcd.print(formatFloat(voltageReading,2));
    lcd.print("V");
    lcd.setCursor(0,1);
    lcd.print("Scaled: ");
    float voltageScaled = 0;
    switch(state) {
      case 4: // 0100 Range 5V
        voltageScaled = voltageReading * 1;
        lcd.print(formatFloat(voltageScaled,2));
        break;
      case 2: // 0010 Range 10V
        voltageScaled = voltageReading * 2;
        lcd.print(formatFloat(voltageScaled,2));
        break;
      case 1: // 0001 Range 20V
        voltageScaled = voltageReading * 4;
        lcd.print(formatFloat(voltageScaled,2));
        break;
      case 12:// 1100 Range 25V
        voltageScaled = voltageReading * 5;
        lcd.print(formatFloat(voltageScaled,2));
        break;
      case 10:// 1010 Range 50V
        voltageScaled = voltageReading * 10;
        lcd.print(formatFloat(voltageScaled,2));
        break;
      case 9:// 1001 Range 100V
        voltageScaled = voltageReading * 20;
        lcd.print(formatFloat(voltageScaled,2));
        break;
    }
    lcd.print("V");
  } else {
    lcd.setCursor(0,1);
    lcd.print("Out Range");
  }
  delay(refreshDelay);
}

String formatFloat(float f, int decimals) {
  String r = String((int)((f + bias)*pow(10,decimals)));
  if(r.length() == 1 ) {
    return "." + r;
  }
  r = r.substring(0,r.length() - decimals) + "." + r.substring(r.length()-decimals,r.length());
  return r;
}
```

Testing approach

We tested our system by applying an input voltage gradually to our system, starting from 1 to 60 volts. We did not apply more than 60 volts due to the limitation of not have a power supply that produces more than 60 volts in the universities labratories. The labratory's power supply can produce 30 volts only. So, we connected two power supply in series to get 60 volts to test the sixth range.

Results

Input Voltage	Experiment Reading	Experiment Scaled	Theoretical Reading	Error reading	theoretical Scaled	Error scaled
1	1.09	1.1	1	0.09	1	0.1
2	2.04	2.04	2	0.04	2	0.04
3	3.22	3.21	3	0.22	3	0.21
4	2.2	4.37	2	0.2	4	0.37
5	2.72	5.44	2.5	0.22	5	0.44
6	3.25	6.44	3	0.25	6	0.44
7	3.74	7.48	3.5	0.24	7	0.48
8	4.14	8.27	4	0.14	8	0.27
9	2.52	10.15	2.25	0.27	9	1.15
10	2.79	11.15	2.5	0.29	10	1.15
11	3.02	12.08	2.75	0.27	11	1.08
12	3.3	13.26	3	0.3	12	1.26
13	3.55	14.21	3.25	0.3	13	1.21
14	3.24	16.16	2.8	0.44	14	2.16
15	3.42	17.06	3	0.42	15	2.06
16	3.59	17.95	3.2	0.39	16	1.95
17	3.74	18.72	3.4	0.34	17	1.72
18	3.78	19.43	3.6	0.18	18	1.43

19	2.26	22.8	1.9	0.36	19	3.8
20	2.37	23.77	2	0.37	20	3.77
21	2.5	24.95	2.1	0.4	21	3.95
22	2.57	25.97	2.2	0.37	22	3.97
23	2.7	26.95	2.3	0.4	23	3.95
24	2.81	28.27	2.4	0.41	24	4.27
25	2.91	29.15	2.5	0.41	25	4.15
26	3.02	30.22	2.6	0.42	26	4.22
27	3.12	31.2	2.7	0.42	27	4.2
28	3.21	32.37	2.8	0.41	28	4.37
29	3.33	33.15	2.9	0.43	29	4.15
30	3.36	33.72	3	0.36	30	3.72
32	3.57	35.61	3.2	0.37	32	3.61
34	3.75	37.41	3.4	0.35	34	3.41
36	3.9	39.01	3.6	0.3	36	3.01
38	4.01	40.28	3.8	0.21	38	2.28
40	2.33	46.48	2	0.33	40	6.48
42	2.42	48.33	2.1	0.32	42	6.33
44	2.53	50.78	2.2	0.33	44	6.78
46	2.64	52.73	2.3	0.34	46	6.73
48	2.74	55.07	2.4	0.34	48	7.07
50	2.85	57.12	2.5	0.35	50	7.12
52	2.95	59.17	2.6	0.35	52	7.17
54	3.09	61.71	2.7	0.39	54	7.71
56	3.19	64.06	2.8	0.39	56	8.06
58	3.31	66.4	2.9	0.41	58	8.4
60	3.43	68.84	3	0.43	60	8.84

Table remarks

From this table you can see the following:

1- The input voltage: the voltage we are measuring.

2- The experiment reading: the reading of the result of our system
3- The experiment scaled: the result after multiply the reading by the range factor
4- Theoretical reading: the expected reading value mathematically
5- Error reading: the difference between the experiment reading and the theoretical reading
6- Theoretical scaled: the expected scaled value mathematically
7- Error scaled: the difference between the experiment scaled and theoretical scale

As shown on the results, the following can be observed:

- There was a difference between the expected and measured values of the ranges. For instance, the expected ranges were 5, 10 , 20, 25, 50 and 100 volts but after testing the circuit these values appeared to be 3, 8, 13, 18, 38 volts. We were unable to test the maximum range of 100 V, we concluded our tests on the fifth range with 60 V,
- The reading error varies from 0.2 to 0.4 and it does not increase linearly. This error is usually caused by the internal error in each component and the early switching to higher ranges.
- The scaled error varies from 0.1 to 8.4 volts and it increases linearly. If we suppose that the reading error is fixed, and it is 0.2 then the scaled error will increase when the system switch to a higher range because the range factor increase in each range.

Graphical representations of the data

This figure shows the relation between the experiment scaled voltages and the theoretical scaled voltages.

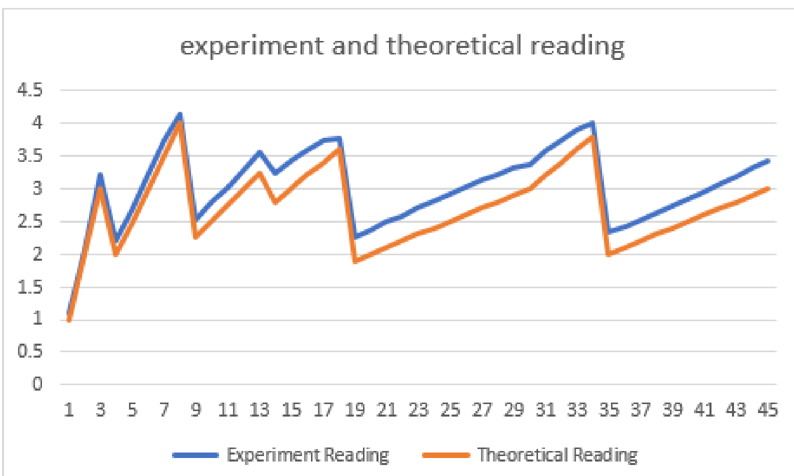
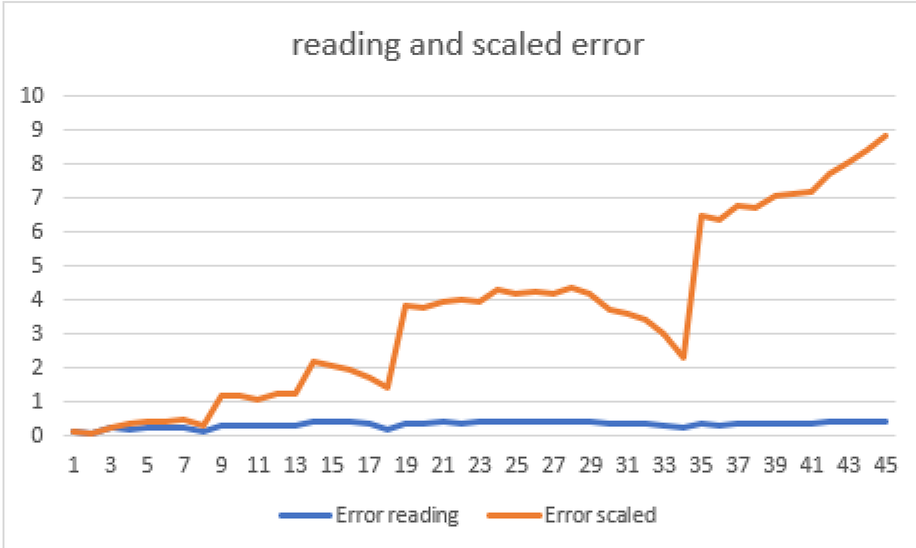
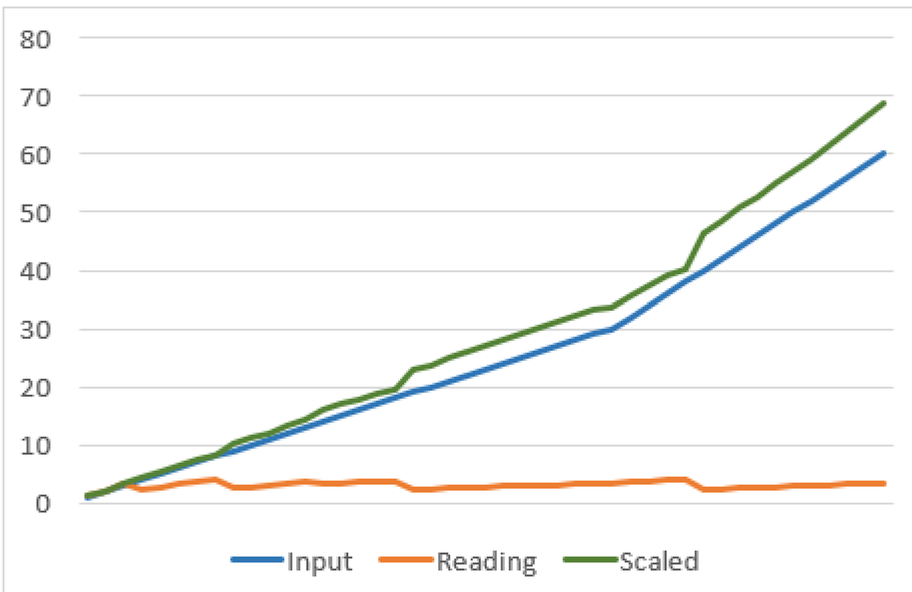


Figure 11 Experiment & Theoretical readings

As you can see in the above figure that the experimental reading and theoretical reading are have approximately the same value.



The figure above shows that the reading error is having a constant value throughout the experiment while the value of the scaled error increases when the input voltage increase.



This figure above shows the relation between the input voltage, the reading value and the scaled value. We can observe the reading value does not exceed 5 volts and whenever the range change to a higher range, the error increases in the scaled value.

Final Product

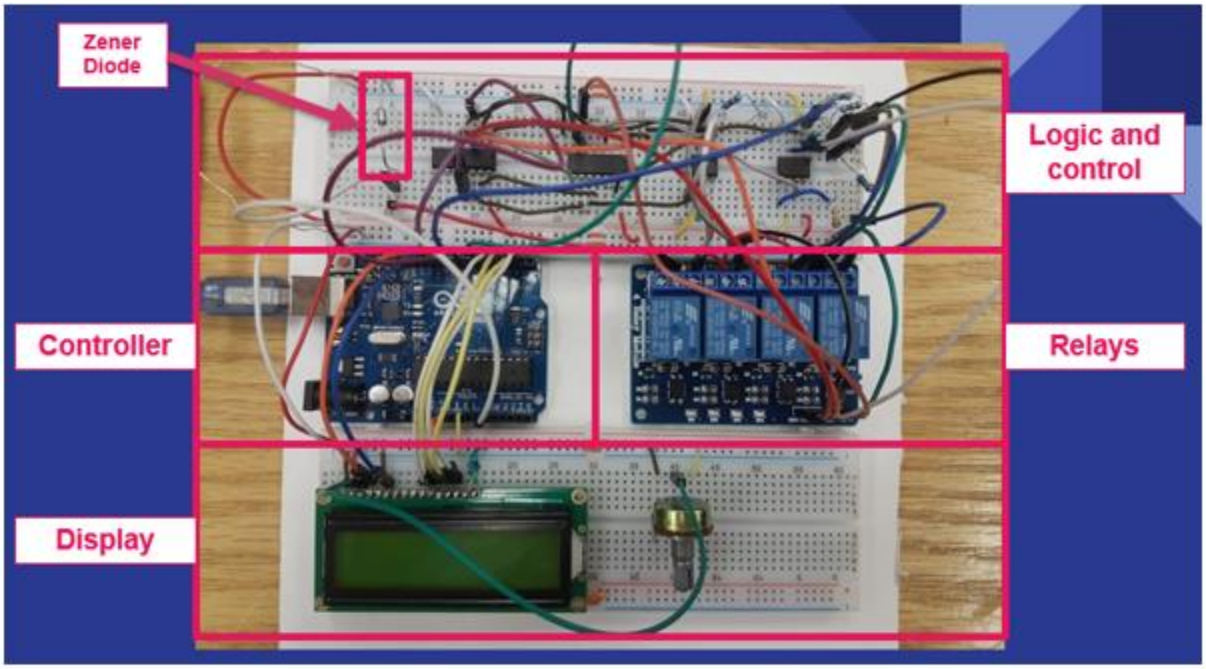


Figure 12 Final product

Problems and possible improvements

The most difficult phase in the project was solving the problems and passing the constraints that faces the project after testing it. While we build our project, we faced many problems and we tried to resolve them or reduce them if we couldn't solve them. We faced many problems but the most significant problems that we faced are:

Problem 1: Relay not switching in circuit:

Relays need a higher current than gates can provide

When we built a project for the first time using a standard relay,When we tested our circuit it did not work as expected. After debugged the voltage at each component, we found that the voltage output from the logic gates (which were responsible of opening relays) was 5 volts, while the input voltage to the relay was 2.1 volt, the relay did not open due to that problem. We realized that the relays need higher current than gates can provide which caused a voltage drop.

Relays (Coils) have a reverse current that needs to be taken care of

The relay is coil and it produce a reverse current that will damage the circuit

To solve these problem, we used a relay module where this relay has a circuit(Zener diode and other things) that protect the circuit from the reverse current and to reduce the voltage drop when use the output of the logic gate to open the relay (the relay module opened when the voltage input is zero)

Problem 2: Relay has resonance points:

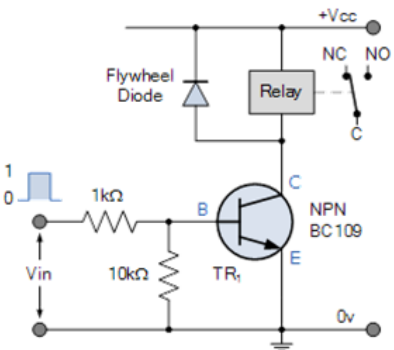


Figure 15 Relay module circuit

Figure 14 Relay module image

Figure 13 Single relay image

The relay in certain volt it cannot determine it must open or close so it still open and close. We cannot resolve this problem because the Op Amp that we used is not stable and it does not give us the sharp output. If there is a better Op Amp this problem will solve.

Problem3: Sudden changes in voltage

In our project the switching between ranges depend on some logic gates and comparator. When a voltage applies to measure and this voltage belong to the higher ranges, the comparator and the logic gates will take time to switch from lower range to higher range. The circuit damage through this time.

To solve this problem, you need a component that make delay where the voltage input reach to the circuit after switching from lower range to higher rang. We cannot solve this problem, but we reduce it by putting a Zener diode to protect the circuit.

Problem4: Switching and output error

	Range switching error	**Output error**
Components contributing	Op amp, logic gates, relays, resistors.	Resistor, ADC in arduino
Error amount	Large	Small
Importance	Not important	Important

As you can see from the table above and as demonstrated in the results section, there is an error in the output of the system and there are multiple reasons for its occurance. The basic reason is the internal error produced from each component. Each component has an internal error value and when all these components connected to each other the error of each component will affect the error of another component and all component will affect to the overall error in the output. The solution to this problem is using better components that has a small error and improved component should reduce the overall error. There is no perfect solution that can solve this problem. As you saw on the results section we cannot solve this problem, therefore we tried to reduce it.

Conclusion

(time, budget and tools constraints; prevented us from allowing our project to solve all the problems we encountered and also measure a voltage higher than 60V)

In conclusion, a special circuit was designed and implemented to allow standard controllers to measure varying voltages that have a high range and switch between ranges without human intervention. Through each phase of this process, the team had to overcome many difficulties to make this design functional. The circuit was not tested on it's maximum range yet. In the future, this can be done by providing a higher voltage using a better DC voltage supply or more than two connected in series. The next step to enhance this project can be done by expanding its circuit to be able to handle voltages higher than 100 volts and still send safe readings to the controller. Another improvement can be done by simply replacing the components we used with better grade components that has a smaller internal error margin.

References

- The datasheet of the project component :
  1- LM358 Op Amp:
  http://www.alldatasheet.com/view.jsp?Searchword=Lm358%20datasheet&gclid=CjwKCAjwhbHlBRAMEiwAoDA341-iCZTPfU_HtEk70fNY_MiW_fe-6TuB2qw-06uLO50R___ZqsYGCkBoCx8QQAvD_BwE
  2- NOT gate 7404:
  https://www4.ujaen.es/~gnofuen/Hoja%20caracteristicas%207404.pdf
  3- NAND 7400:
  http://www.alldatasheet.com/view.jsp?Searchword=7400%20datasheet&gclid=CjwKCAjwhbHlBRAMEiwAoDA348jJqg45pzxlKxtwqH9UQee-CgK3_lnjTGSWddNLOG71rfg6FtBhzxoCED8QAvD_BwE
  4- AND 7408:
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