Indian Institute of Space Science and Technology

Single Element Resistive Sensor using Direct Microcontroller Approach

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1 Aim of the experiment

To analyse the working and implementation of a single-element resistive sensor using direct Microcontroller Approach.

2 Resistance to Digital Converter

A single element resistive sensor is designed with a resistance to digital converter using the microcontroller approach.

The sensor is designed to find the resistance value of the resistor R_x. This is done by finding the time taken for the discharging of the capacitor C in the following two cases:

i. Discharging via pin P_{10} of the microcontroller

ii. Discharging via pin P_9 of the microcontroller

The resistance R_x is given using the formula:

$$R_x = \left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right]$$

where,

R: a resistor of 150Ω

T_{11}: time taken by the capacitor to discharge via P_10

T_{22}: time taken by the capacitor to discharge via P_9

2.1 Equipments Required

- Capacitor
- Resistors
- Connecting Wires
- Decade Resistance Box
- Microcontroller i.e. Arduino Due
- Personal Computer
- Oscilloscope
- USB connector

2.2 Theory

We are using Direct Microcontroller Approach for designing a Single-Element Resistive Sensor. The microcontroller consists of both, digital and analog pins. In this experiment, we are using three digital ports, P_4,P_9 and P_{10}. These pins are connected to the passive components like resistors and capacitor to these digital pins as shown in Figure 1. For measuring the resistance R_x, we are making use of two resistors R and R_c, and a capacitor C. The circuit shown in Figure 1 works on the principle of charging and discharging of the capacitor. The resistor R is used for charging the capacitor C and the resistance R_x is used for charging the capacitor C. We can control the HIGH/LOW states of the pins by writing a simple Arduino Code on Arduino IDE and then uploading it on the Arduino Due.

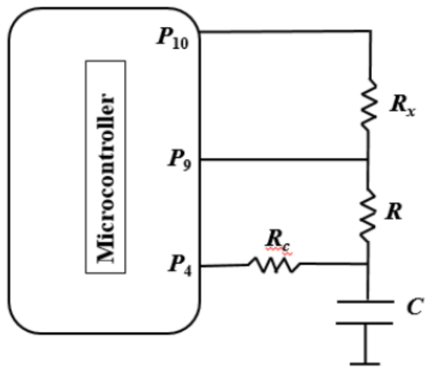

Figure 1: Circuit Diagram

The entire process includes **4 stages** of which steps 1 and 3 are the charging phase of the capacitor and steps 2 and 4 are the discharging phase of the capacitor.

i.) **Step 1**
In this stage, the pin P_4 is in the HIGH state or Low Impedance state. It is connected with voltage V_{DD} = 3.3V. The pins P_9 and P_{10} are in LOW state or High Impedance state.
The pins P_9 and PIN_{10} will act as Open circuit and hence, current will flow only throw the resistor R and the capacitor C. The capacitor C will get charged from the pin P_4 via the path shown in Figure 2.

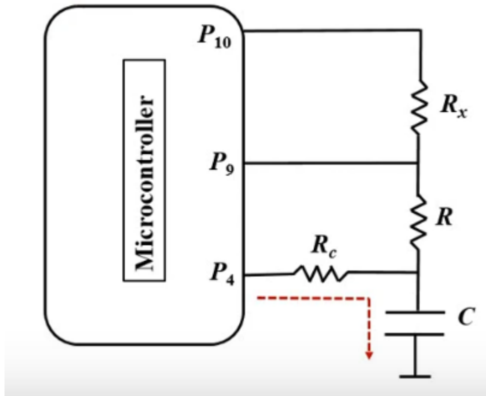

Figure 2: Charging of Capacitor Via P_4

The circuit has a time constant of $\tau = R_c C$. The capacitor will get charged to 3.3V in almost 5τ. Therefore, the time duration of $step1$ will be set around 5τ. When the capacitor gets charged, the microcontroller will change the state of the pin P_4 from HIGH to LOW state and that of the pin P_{10} to ground voltage. This starts the **Step 2** of the process.

ii.) **Step 2**
Now, the pins P_4 and P_9will act as an Open circuit and the capacitor gets discharged via pin P_{10} as shown in the Figure 3

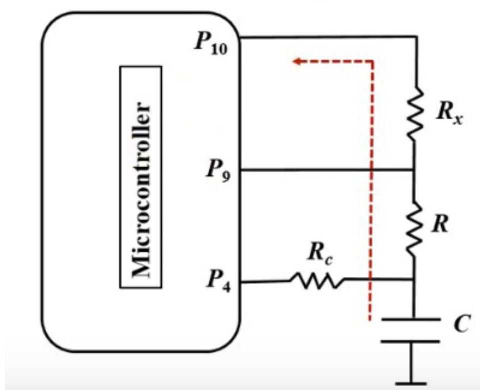

Figure 3: Discharging of Capacitor Via P_{10}

with a time constant of:

$$\tau_1 = R_{eq1} C$$

Where, $R_{eq1} = R + R_x$

We need to measure the time taken by the capacitor to discharge from V_{DD}=V_c=3.3V to the threshold voltage V_{TH}=V_c=1.2V.
Where, V_c *is the capacitor voltage.*

The time taken for the discharging of the capacitor is given by the equation:

$$V_c(t) = V_c(0) e^{-T_1/R_{eq1}C}$$

By substituting the values of $V_c(t)$ in the above equation, we get T_{11} as:

$$T_{11} = R_{eq1}K_m$$

$$K_m = Cln(V_{dd}/V_{th})$$

Where, $R_{eq1} = R + R_x$

The waveform obtained till phase-B is shown in Figure 4.

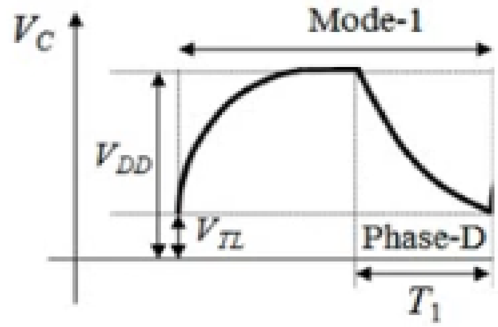

Figure 4: Waveform upto Step2

When the capacitor gets charged to the threshold voltage, the microcontroller will change the state of the pin P_4 to HIGH and that of pin P_{10} to OFF. This starts the **Step 3** of the process.

iii.) **Step 3**
This step is same as that of the Step1. The capacitor gets charged to 3.3V just as in Step1. When the capacitor gets charged, the microcontroller will change the state of pin P_4 to OFF state and that of pin P_9 to ground state. This starts the **Step 4** of the process.

iv.) **Step 4**
Now, the pins P_4 and P_{10} will act as an Open circuit and the capacitor gets discharged via PIN $_9$ as shown in the Figure 5
with a time constant of:

$$\tau_1 = R_{eq2}C$$

Where, $R_{eq2} = R$
We need to measure the time taken by the capacitor to discharge from V_{DD}=V_c=3.3V to the threshold voltage, V_{TH}=V_c=1.2V.
Where, V_c *is the capacitor voltage.*

The time taken for the discharging of the capacitor is given by the equation:

$$V_c(t) = V_c(0)e^{-T_2/R_{eq2}C}$$

By substituting for the values of $V_c(t)$ in the above equation, we get T_{22} as:

$$T_{22} = R_{eq2}K_m$$

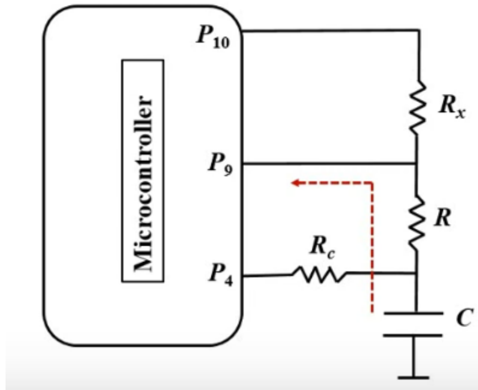

Figure 5: Discharging of Capacitor Via P_9

$$K_m = Cln(V_{dd}/V_{th})$$

Where, $R_{eq2} = R$

The waveform obtained till Step 4 is shown in Figure 6.

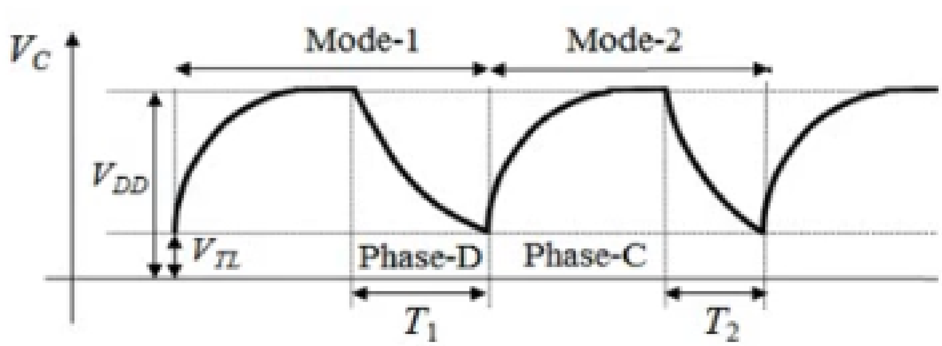

Figure 6: Waveform of the entire process

When the capacitor is charged to the threshold voltage of the digital PIN_4, i.e., it has completed the four steps, the microcontroller will delay the process for 500seconds after which the process starts again.

The resistance R_x can be calculated from the discharging times, T_{11} and T_{22} obtained in the above process using the equation given below:

$$\left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right] = \left[\frac{(R_{eq1} - R_{eq2})\cancel{K_m}}{R_{eq2}\cancel{K_m}} \times R\right] = R_x$$

Where, $R_{eq1} = R + R_x$ *and* $R_{eq2} = R$

2.2.1 Error analysis

The theory discussed above is for Ideal Case in which the pin resistances of microcontroller is considered to be negligible. But in the real situation, the pins will have some resistance and can

also have some offset resistance between them.
The pin resistances are shown in the Figure 7 below.

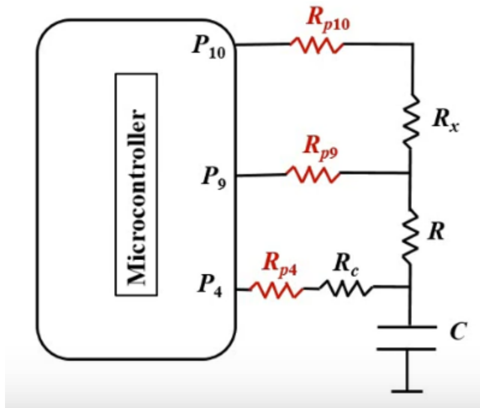

Figure 7: Circuit Diagram showing the Pin resistances

Considering the effect of Pin resistances, the equation can be modified as:

$$\left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right] = \left[\frac{(R_{eq1} - R_{eq2})\cancel{K_m}}{R_{eq2}\cancel{K_m}} \times R\right]$$

$$\Rightarrow \left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right] = \left[\frac{R_x + (R_{p10} - R_{p9})}{R + R_{p9}} \times R\right] \neq R_x$$

$$Where,\ R_{eq1} = R + R_x + R_{p10}\ and\ R_{eq2} = R + R_{p9}$$

which is not exactly equal to R_x. Hence we will experience some error in the measurement.

2.3 Procedure

i.) Connect all the passive components on the breadboard and connect them to the required digital pins of the microcontroller as per the circuit diagram.

ii.) Write an Arduino code on Arduino IDE based on the above theory and then upload it to the Arduino Due usind a USB Connector.

iii.) Set the resistance value on the decade resistance box and check the connections.

iv.) Run the Arduino code.

v.) Observe the output waveform obtained on the oscilloscope.

vi.) Compare the resistance values obtained on the Serial monitor of the computer with the resistance value set on the decade resistance box.

2.4 Observations

We obtained the following observations:

i. The waveform obtained in the oscilloscope is the same as the expected waveform.

ii. When $R_x = 100\Omega$, the value of resistance obtained on the serial monitor is $85/86\Omega$.

iii. When $R_x = 110\Omega$, the value of resistance obtained on the serial monitor is 97Ω.

iv. When $R_x = 120\Omega$, the value of resistance obtained on the serial monitor is $105 - 107\Omega$.

2.5 Inferences

We obtained the following inferences:

i. The measured resistance values are found to be lower than the actual value of R_x

ii. The non-linearity in the measurement is mainly due to the pin resistances which was not taken into account.

iii. The error in the measurement can also be due to the tolerance of the resistors or the non-idealities of the capacitor

3 Simulation Exercise

The following common measurements need to be done for the circuit shown in Figure 1. Consider the resistor R_c and R is 150Ω, charging time of 5 ms, $V_{DD}= 3.3V$, and $V_{TH}= 1.2V$. The inferences observed from the simulation studies should be present in the assignment.

(a) Find the % Non-linearity between input R_x and measured R_x without rounding the discharge times to microseconds. Assume there is no mismatch in microcontroller pin-resistance and the pin resistance is 50Ω.

(b) Find the % Non-linearity between input R_x and measured R_x after rounding the discharge times to microseconds. Assume there is no mismatch in microcontroller pin-resistance and the pin resistance is 50Ω.

(c) Find the % Non-linearity between input R_x and measured R_x without rounding the discharge times to microseconds. Assume the mismatch between the microcontroller pin-resistance is 10Ω.

(d) Find the % Non-linearity between input $R_x$and measured R_x after rounding the discharge times to microseconds. Assume the mismatch between the microcontroller pin-resistance is 10Ω.

4 Simulations

4.1 Simulation of the Microcontroller in $L_T Spice$

The simulations of the above experiment is done using $L_T Spice$. The $L_T Spice$ does not provide the arduino microcontroller in its components. Therefore, in the simulations, switches are being used to mimic the functions of the microcontroller.

We have made use of switches in place of the microcontroller pins for doing the simulations. We have used a **Controlled Switch** along with a suitable control voltage source. The voltage source is controlled using a monostable multivibrator, comparator and D Flip Flop.

The time taken for the charging of the capacitor and discharging of the capacitor from 3.3V to 1.2V at each stage is measured using the **.meas** command in $L_T Spice$. The resistance R_x is varied in the required range using the **.step** command in $L_T Spice$. The measured resistance value is also calculated using the **.meas** command. The pin resistances are set to 50Ω by changing the R_{on} of the switches.

4.2 Spice Model

The spice model for a Single-Element Resistive Sensor using Direct Microcontroller Approach is shown in Figure 8.

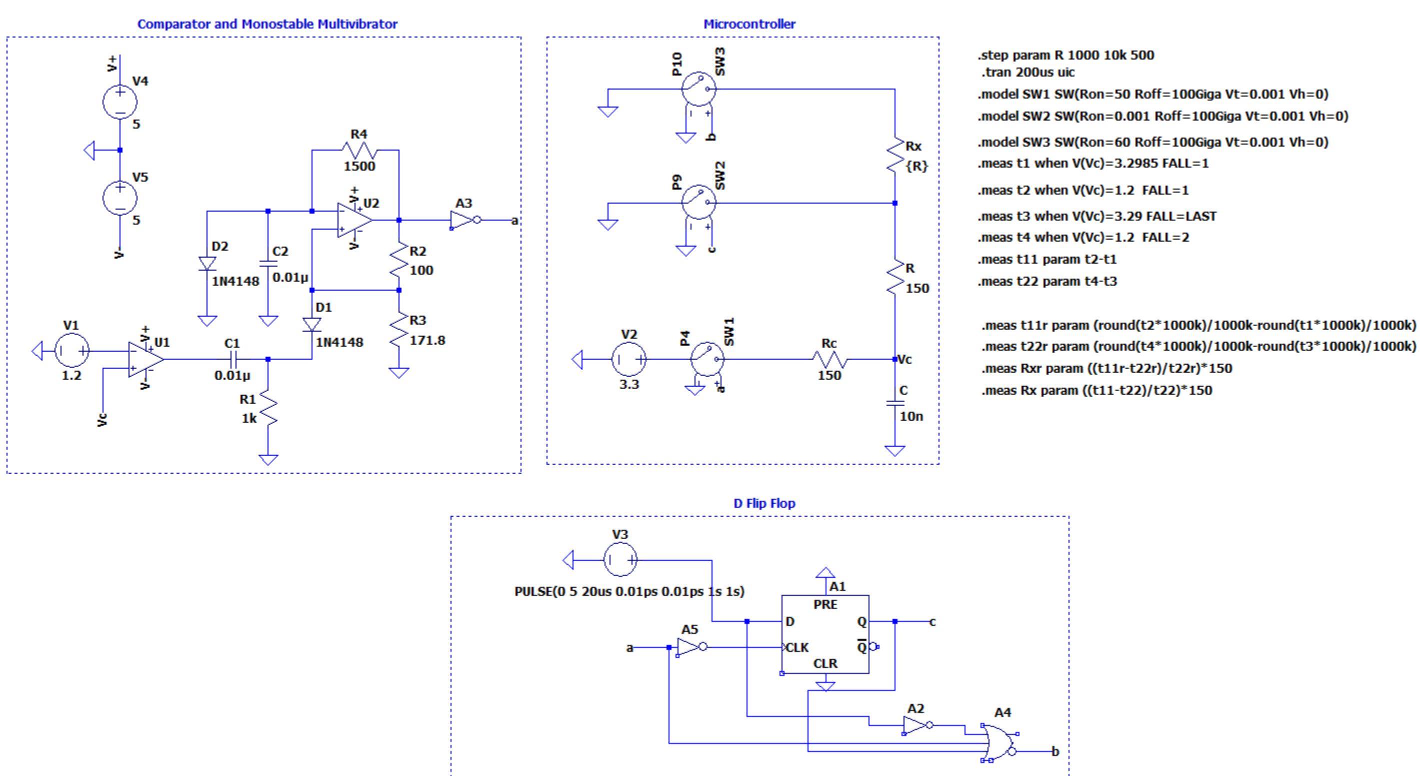

Figure 8: Spice Model

4.3 Design Conditions

The opening and closing time of the switches is controlled by the time taken for the charging and discharging of the capacitor.

The time constant of the resistance R_c and capacitor C is given by:

$$\tau = R_c C = 150 \times 10nF = 1.5\mu s$$

The minimum time required for changing the capacitor is $5\tau = 7.5\mu$.

4.3.1 Comparator and the Monostable Multivibrator

The comparator and the monostable multivibrator together control the opening and closing of the switch, $\mathbf{P_4}$. The comparator is used to produce a trigger to operate the monostable multivibrator. The comparator compares the voltage of the capacitor with 1.2V. Whenever the voltage across the capacitor exceeds 1.2V, the comparator output voltage changes from low to high state and hence provides a negative trigger for the monostable multivibrator. The monostable multivibrator when triggered, goes to the unstable state and hence provides a negative output. The monostable multivibrator is designed such that the duration of the unstable state is equal to the time required for charging the capacitor. The output from the monostable multibrator is negated and then, used for controlling the switch P_4.

The duration of the unstable event of the monostable multivibrator is designed using the equation:

$$T_E = R_4\ C_2\ ln \left[1 + \frac{R_3}{R_2}\right] = 15\mu s$$

The values chosen are: $R_4 = 150\Omega$, $C_2 = 1\mu F$, $R_2 = 100\Omega$, $R_3 = 171.8\Omega$.

Figure 9: Control Signal of P_4

4.3.2 D Flip flop

The switches, $\mathbf{P_9}$ and $\mathbf{P_{10}}$ are operated using a D Flip Flop. The output of the monostable multivibrator is provided as the clock for the D Flip flop. A voltage signal which remains at low state for a short duration and remain high for the rest of the cycle is given as input to the D flip flop. The output of the D flip flop will be 0 in the positive level of the first clock cycle, i.e, after the first charging, since the initial state of the input is low. The output of the D flip flop will be 1 in the positive level of the next clock cycle, i.e, after the second charging, since the initial state of the input is low. The output of the D flip flop is used to control the switch P_9, so that it remains open during the first discharging and remains closed during the second discharging. The input to the D flip flop, the output of the monostable multivibrator and the output of the D flip flop together determine the opening and closing of the switch P_{10}.

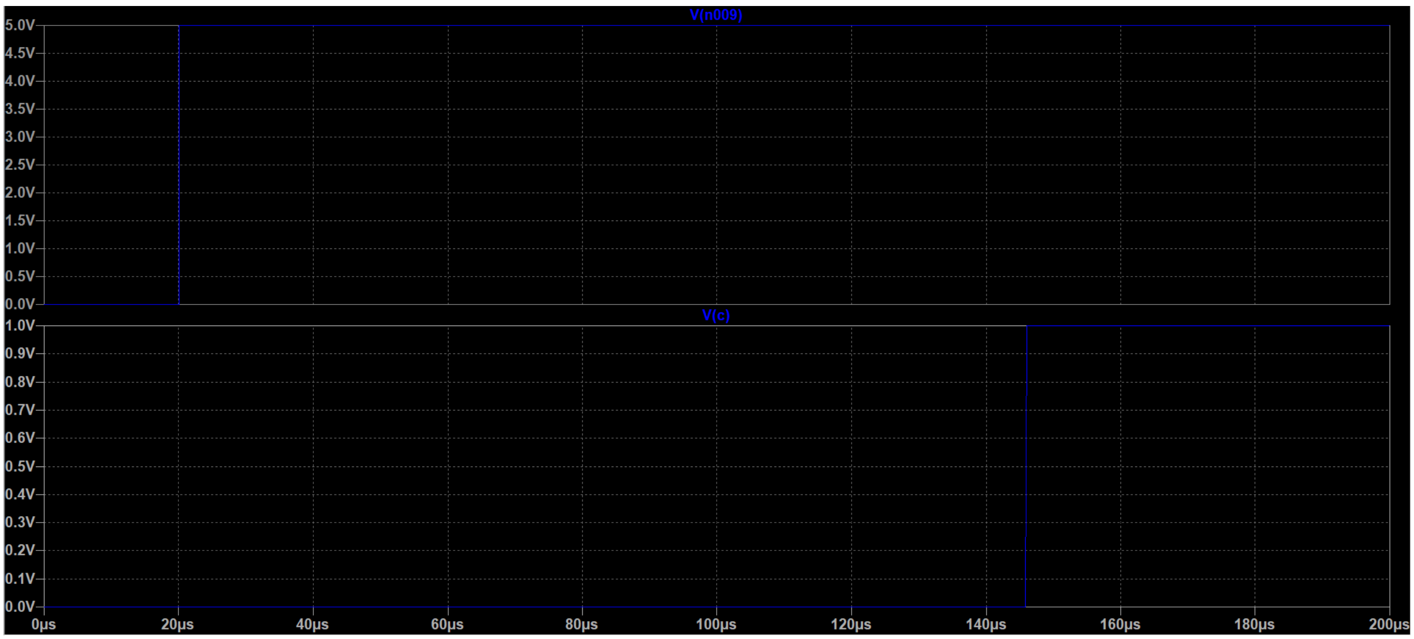

Figure 10: Control Signal of P_4

4.4 Simulation Results

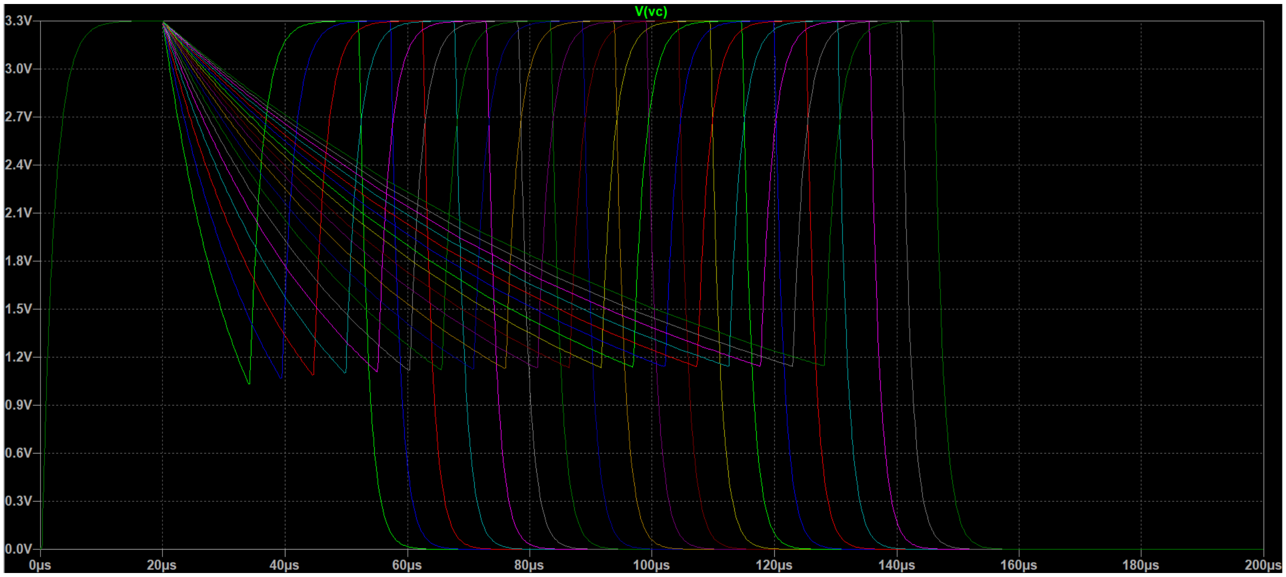

Figure 11: Waveform showing the charging and discharging of the capacitor for varying values of R_x

4.5 Calculation of % Non-Linearity

The values of T_{11}, T_{22} and Measured R_x for varying values of Input R_x are obtained in the Spice Error Log of $L_T Spice$. These values are then exported as a text file using the EXPORT data as text option in $L_T Spice$. These values are the exported in MS Excel for carrying out the further calculations.

The Regression tool in Data Analysis Package in MS Excel has been utilized to obtain the **best fit line**, **predicted values of R_x** and the **residuals**.

The % Non-Linearity is given by:

$$\%Non-Linearity = \frac{Residual}{OutputSpan} \times 100$$

$$\%SensorNon-Linearity = |individual \quad \%non-linearity|_{MAX}$$

Where,

$Residual = y - \widehat{y}$

$OutputSpan = (MeasuredR_x)_{MAX} - (MeasuredR_x)_{MIN}$

4.5.1 Question (a)

Considering $R_{P_10} = R_{P_9} = R_{P_4} = 50\Omega$,

Input Rx	***T11***	***T22***	***Measured Rx***
1000	1.21346E-05	2.2242E-06	668.359
1500	1.71901E-05	2.12578E-06	1062.97
2000	2.22456E-05	2.08891E-06	1447.41
2500	2.73012E-05	2.22423E-06	1691.17
3000	3.23567E-05	2.0903E-06	2171.92
3500	3.74123E-05	2.22188E-06	2375.72
4000	0.000042468	2.12764E-06	2844.01
4500	4.75236E-05	2.08978E-06	3261.15
5000	5.25792E-05	2.08985E-06	3623.9
5500	5.76349E-05	2.09057E-06	3985.35
6000	6.26905E-05	2.0843E-06	4361.62
6500	0.000067746	2.23002E-06	4783.86
7000	7.28016E-05	2.09054E-06	5073.64
7500	7.78572E-05	2.09017E-06	5437.39
8000	8.29127E-05	2.09019E-06	5800.14
8500	8.79683E-05	2.08913E-06	6166.14
9000	9.30238E-05	2.09018E-06	6525.78
9500	9.80794E-05	2.24599E-06	6842.29
10000	0.000103135	2.08717E-06	7262.04

Table 1: Values obtained from Simulation

The best fit line of measured values of R_x has been plotted against input R_X.

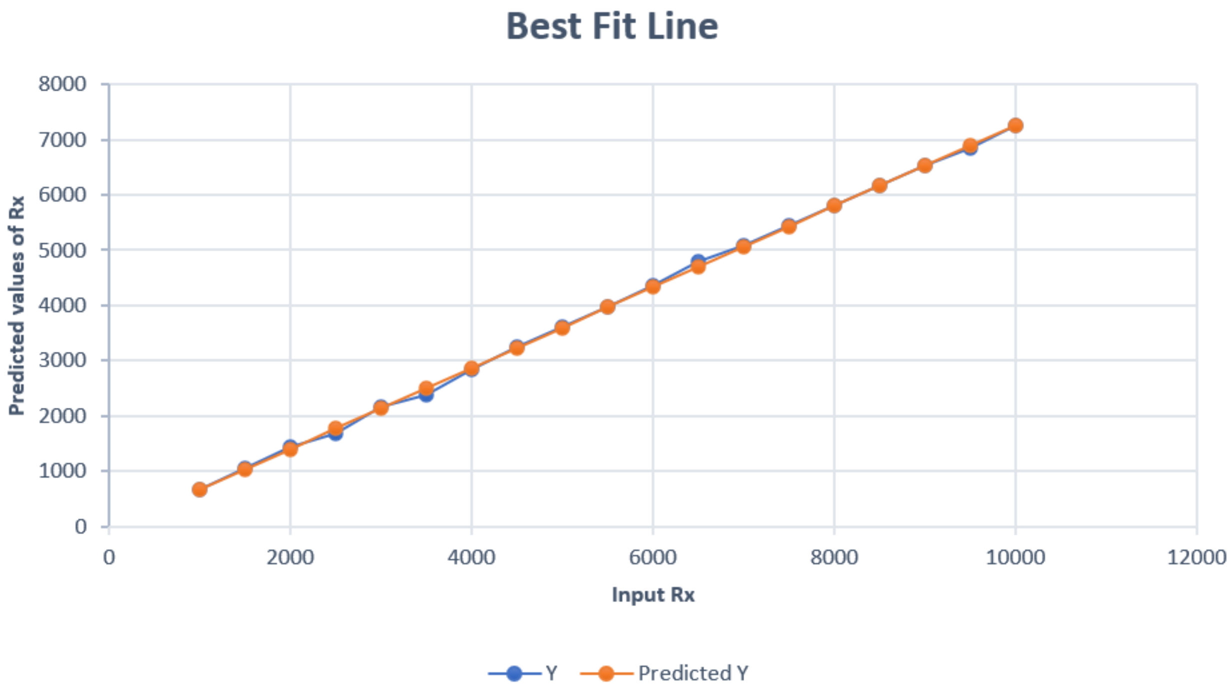

Figure 12: Best Fit Line

Measured Rx	***Predicted Y***	***Residuals***	***% Non-Linearity***
668.359	670.2150684	-1.856068421	-0.028144346
1062.97	1036.593856	26.37614386	0.399952556
1447.41	1402.972644	44.43735614	0.673822309
1691.17	1769.351432	-78.18143158	-1.185497908
2171.92	2135.730219	36.1897807	0.548760856
2375.72	2502.109007	-126.389007	-1.916489638
2844.01	2868.487795	-24.47779474	-0.37116709
3261.15	3234.866582	26.28341754	0.398546508
3623.9	3601.24537	22.65462982	0.343521674
3985.35	3967.624158	17.72584211	0.268784394
4361.62	4334.002946	27.61705439	0.418769004
4783.86	4700.381733	83.47826667	1.265816045
5073.64	5066.760521	6.879478947	0.104316431
5437.39	5433.139309	4.250691228	0.064455018
5800.14	5799.518096	0.621903509	0.009430184
6166.14	6165.896884	0.243115789	0.003686467
6525.78	6532.275672	-6.49567193	-0.098496604
6842.29	6898.65446	-56.36445965	-0.854677993
7262.04	7265.033247	-2.993247368	-0.045387868

Table 2: % Non-Linearity

% **Sensor Non-Linearity = 1.916489638**%

4.5.2 Question (b)

Taking the rounded values for T_{11} and T_{22} and considering $R_{P_10} = R_{P_9} = R_{P_4} = 50\Omega$,

Input Rx	*T11*	*T22*	*Measured Rx*
1000	0.000012	0.000002	750
1500	0.000017	0.000002	1125
2000	0.000022	0.000002	1500
2500	0.000027	0.000002	1875
3000	0.000032	0.000002	2250
3500	0.000037	0.000002	2625
4000	0.000043	0.000002	3075
4500	0.000048	0.000002	3450
5000	0.000053	0.000002	3825
5500	0.000058	0.000002	4200
6000	0.000063	0.000002	4575
6500	0.000068	0.000002	4950
7000	0.000073	0.000002	5325
7500	0.000078	0.000002	5700
8000	0.000083	0.000002	6075
8500	0.000088	0.000002	6450
9000	0.000093	0.000002	6825
9500	0.000098	0.000002	7200
10000	0.000103	0.000002	7575

Table 3: Values obtained from Simulation

The best fit line of measured values of R_x has been plotted against input R_X.

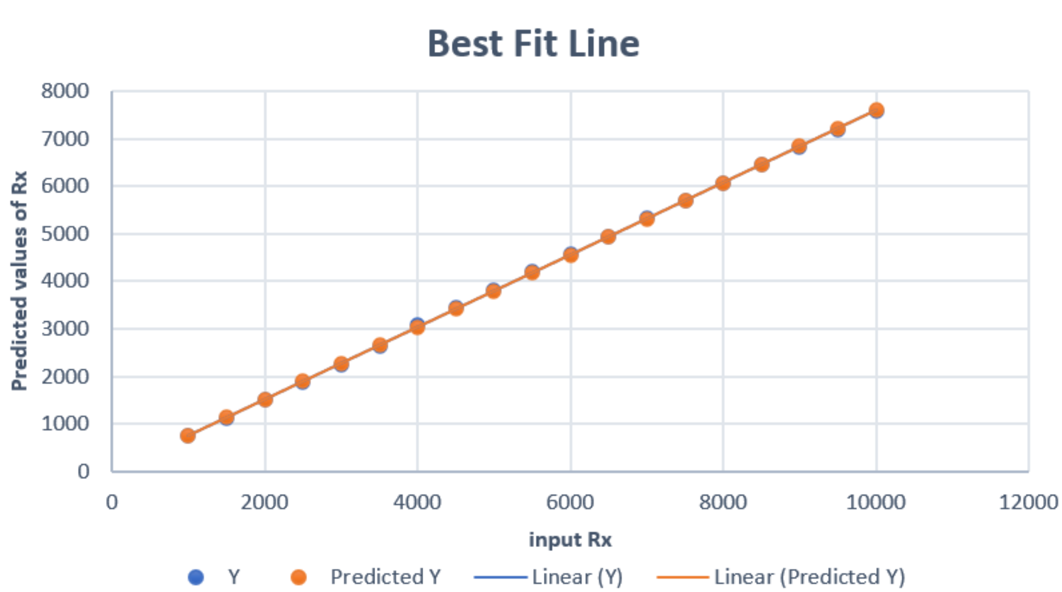

Figure 13: Best Fit Line

Measured Rx	***Predicted Y***	***Residuals***	***% Non-Linearity***
750	755.1315789	-5.13158	-0.07519
1125	1135.263158	-10.2632	-0.15038
1500	1515.394737	-15.3947	-0.22556
1875	1895.526316	-20.5263	-0.30075
2250	2275.657895	-25.6579	-0.37594
2625	2655.789474	-30.7895	-0.45113
3075	3035.921053	39.07895	0.572585
3450	3416.052632	33.94737	0.497397
3825	3796.184211	28.81579	0.422209
4200	4176.315789	23.68421	0.347021
4575	4556.447368	18.55263	0.271833
4950	4936.578947	13.42105	0.196645
5325	5316.710526	8.289474	0.121457
5700	5696.842105	3.157895	0.04627
6075	6076.973684	-1.97368	-0.02892
6450	6457.105263	-7.10526	-0.10411
6825	6837.236842	-12.2368	-0.17929
7200	7217.368421	-17.3684	-0.25448
7575	7597.5	-22.5	-0.32967

Table 4: % Non-Linearity

% **Sensor Non-Linearity = 0.572585**%

4.5.3 Question (c)

Here, we need to consider an mismatch of 10Ω between the two pins.

Taking $R_{P_9} = R_{P_4} = 50\Omega \;\; and \;\; R_{P_10} = 60\Omega$

Input Rx	***T11***	***T22***	***Measured Rx***
1000	1.22355E-05	2.08356E-06	730.862
1500	1.72909E-05	2.12799E-06	1068.82
2000	2.23466E-05	2.08893E-06	1454.65
2500	2.74023E-05	2.22377E-06	1698.36
3000	3.24579E-05	2.12279E-06	2143.53
3500	3.75135E-05	2.08276E-06	2551.71
4000	4.25692E-05	2.22181E-06	2723.95
4500	4.76248E-05	2.09054E-06	3267.17
5000	5.26803E-05	2.22409E-06	3402.93
5500	5.77359E-05	2.08379E-06	4006.07
6000	6.27915E-05	2.09057E-06	4255.34
6500	6.78471E-05	2.2279E-06	4418.01
7000	7.29027E-05	2.2247E-06	4865.46
7500	7.79583E-05	2.09051E-06	5443.73
8000	8.30139E-05	2.09041E-06	5806.77
8500	8.80694E-05	2.23367E-06	6164.21
9000	9.31249E-05	2.08962E-06	6534.83
9500	9.81805E-05	2.24426E-06	6812.09
10000	0.000103236	2.09069E-06	7256.82

Table 5: Values obtained from Simulation

The best fit line of measured values of R_x has been plotted against input R_X.

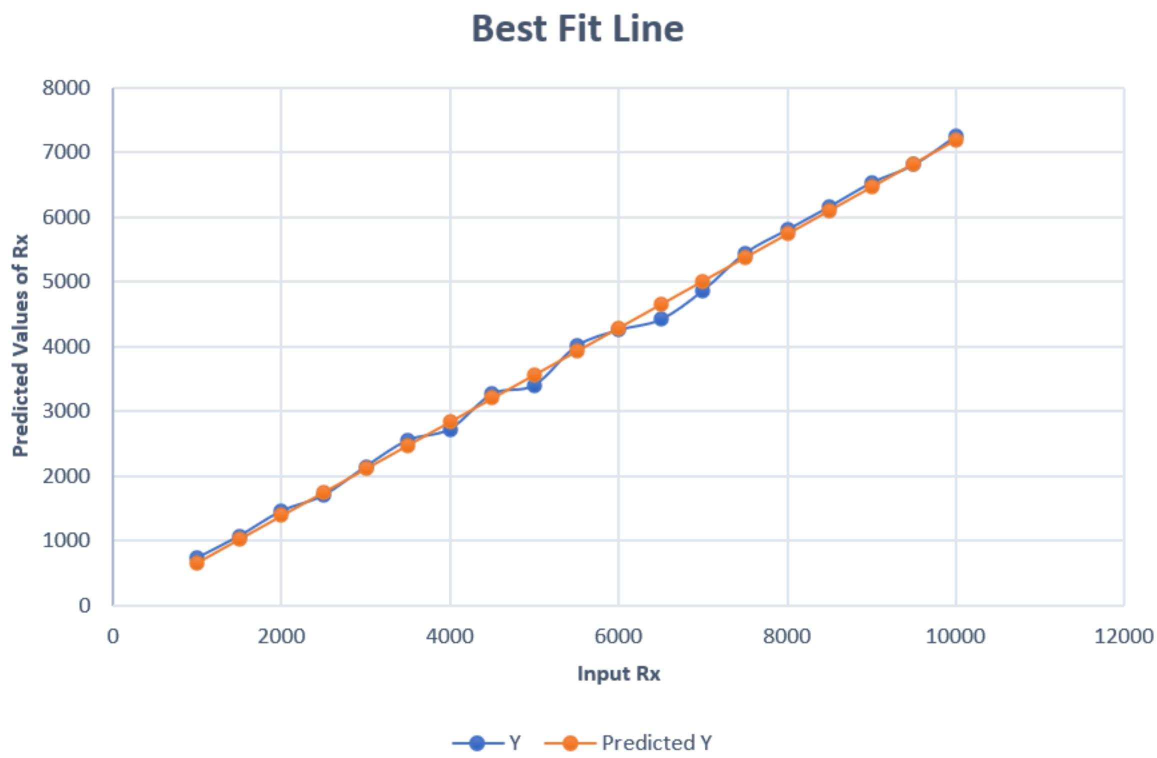

Figure 14: Best Fit Line

Measured Rx	***Predicted Y***	***Residuals***	***% Non-Linearity***
730.862	666.0841789	64.77782105	0.992617805
1068.82	1028.3632	40.4568	0.619936567
1454.65	1390.642221	64.00777895	0.980818126
1698.36	1752.921242	-54.56124211	-0.836064867
2143.53	2115.200263	28.32973684	0.434108476
2551.71	2477.479284	74.23071579	1.137468488
2723.95	2839.758305	-115.8083053	-1.774579384
3267.17	3202.037326	65.13267368	0.998055361
3402.93	3564.316347	-161.3863474	-2.472990898
4006.07	3926.595368	79.47463158	1.217823216
4255.34	4288.874389	-33.53438947	-0.513861558
4418.01	4651.153411	-233.1434105	-3.572554566
4865.46	5013.432432	-147.9724316	-2.267443823
5443.73	5375.711453	68.01854737	1.042276818
5806.77	5737.990474	68.77952632	1.053937618
6164.21	6100.269495	63.94050526	0.979787263
6534.83	6462.548516	72.28148421	1.107599592
6812.09	6824.827537	-12.73753684	-0.195182636
7256.82	7187.106558	69.71344211	1.068248403

Table 6: % Non-Linearity

4.5.4 Question (d)

The values of T_{11} and T_{22} obtained in Question (c)are rounded up.

Considering $R_{P_9} = R_{P_4} = 50\Omega$ and $R_{P_10} = 60\Omega$,

Input Rx	***T11***	***T22***	***Measured Rx***
1000	0.000012	0.000002	750
1500	0.000017	0.000002	1125
2000	0.000022	0.000002	1500
2500	0.000027	0.000002	1875
3000	0.000032	0.000002	2250
3500	0.000037	0.000002	2625
4000	0.000043	0.000002	3075
4500	0.000048	0.000002	3450
5000	0.000053	0.000002	3825
5500	0.000058	0.000002	4200
6000	0.000063	0.000002	4575
6500	0.000068	0.000002	4950
7000	0.000073	0.000002	5325
7500	0.000078	0.000002	5700
8000	0.000083	0.000002	6075
8500	0.000088	0.000002	6450
9000	0.000093	0.000002	6825
9500	0.000098	0.000002	7200
10000	0.000103	0.000002	7575

Table 7: % Non-Linearity

The best fit line of measured values of R_x has been plotted against input R_X.

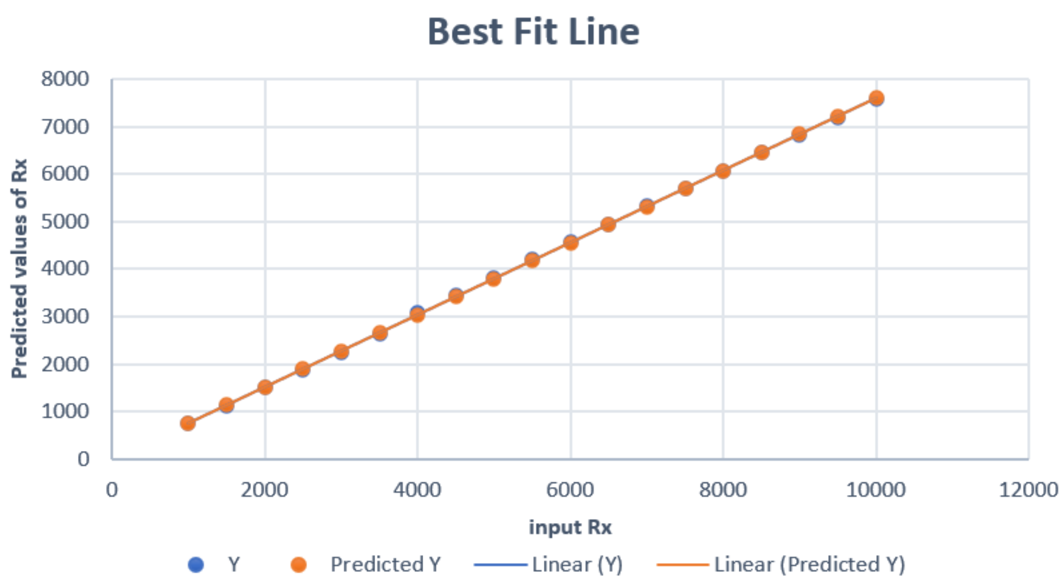

Figure 15: Best Fit Line

Measured Rx	***Predicted Y***	***Residuals***	***% Non-Linearity***
750	755.1315789	-5.13158	-0.07519
1125	1135.263158	-10.2632	-0.15038
1500	1515.394737	-15.3947	-0.22556
1875	1895.526316	-20.5263	-0.30075
2250	2275.657895	-25.6579	-0.37594
2625	2655.789474	-30.7895	-0.45113
3075	3035.921053	39.07895	0.572585
3450	3416.052632	33.94737	0.497397
3825	3796.184211	28.81579	0.422209
4200	4176.315789	23.68421	0.347021
4575	4556.447368	18.55263	0.271833
4950	4936.578947	13.42105	0.196645
5325	5316.710526	8.289474	0.121457
5700	5696.842105	3.157895	0.04627
6075	6076.973684	-1.97368	-0.02892
6450	6457.105263	-7.10526	-0.10411
6825	6837.236842	-12.2368	-0.17929
7200	7217.368421	-17.3684	-0.25448
7575	7597.5	-22.5	-0.32967

Table 8: % Non-Linearity

% Sensor Non-Linearity = 0.572585%

4.6 Inferences

i. From the waveform obtained by simulation, it can be seen tat the capacitor first gets charged to a value of 3.3V, then gets discharged,again get charged and then gets discharged.

ii. The Measured R_x is much smaller than that of the input R_x. This is because of the pin resistances.

iii. The Measured R_x in case of a mismatch of pin resistances varies from that when there is no mismatch.

iv. Since the resistance R=150Ω, a small variation in the pin resistance of P_9 causes a great difference in measured R_x.

v. When the pin resistance of P_9 is lesser than that of P_{10}, the measured R_x is higher than in case of absence of mismatch. This is because T_{22} decreases.

vi. When the pin resistance of P_9 is greater than that of P_{10}, the measured R_x is lower than in case of absence of mismatch. This is because T_{22} increases.

vii. The % Non-Linearity when T_{11} and T_{22} are rounded is higher than when they are not rounded.

viii. The % Non-Linearity obtained in questions(b) and (d) are equal. This is because the time constants are in the range of microseconds. Hence the rounded values of T_{22} is same in both the questions.

4.7 Result

We designed a **Single-Element Resistive Sensor** using Direct Microcontroller Approach and simulated it using $L_T Spice$. The % Non-Linearity for each of the four parts of the simulation exercise has been calculated using MS Excel.