Water Level Detector Based on Capacitive Sensing

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***Abstract*—This report details the development of a capacitive water level detector capable of accurately measuring liquid levels from 0mm to 300mm, achieving a maximum capacitance of 400pF. The sensor employs parallel aluminum electrode plates, each with dimensions of 2mm thickness, 30mm width, and 400mm height, and a 10mm gap between them. Utilizing Ansys Electronics for design optimization and precision mechanical fabrication, the sensor demonstrated high reliability and repeatability. Calibration confirmed a linear relationship between capacitance and water level, with a mean squared error (MSE) of 30.3645 mm^2 for training data and 33.5341 mm^2 for test data. This project underscores the efficacy of capacitive sensing technology in providing a robust and cost-effective solution for liquid level measurement across various applications.**

***Index Terms*—Capacitive water level, Electrode plates, Ansys Electronics**

I. Introduction

Liquid level measurement is a crucial aspect in various industries, including water management systems and the oil and gas industry. Numerous techniques are available for measuring liquid levels, such as pressure sensors positioned at the tank's base, optical sensors, and ultrasonic sensors. Among these methods, capacitive level sensors are widely utilized due to their unique advantages. These sensors operate by detecting changes in capacitance caused by varying liquid levels. The capacitance of a device changes as the liquid level changes, making it possible to determine the liquid level accurately.

Capacitive liquid-level sensors offer several benefits, including the absence of moving parts that could wear out over time, ensuring durability and reliability. Moreover, they provide accurate measurements irrespective of the sensor's orientation. This report focuses on the design, simulation, and practical implementation of a capacitive water level detector capable of measuring liquid levels from 0mm to 300mm, with a maximum capacitance of 400pF. Through a combination of theoretical analysis and simulation using Ansys Electronics, the design parameters were optimized to achieve accurate and repeatable measurements. The successful fabrication and calibration of the sensor further validate its efficacy in providing reliable liquid level measurements.

II. Theory

A capacitor typically comprises two metal conductive plates, called electrodes, which are charged by a voltage source and separated by thin layers of an insulating material known as a dielectric. [1] The charges are stored on the surface of the plates through the polarization of this dielectric substance. The capacitive water liquid sensor detects the water level with the dielectric constant change between two conductive plates. Figure 1 shows a schematic of two parallel capacitors with different dielectrics, which are air and water.

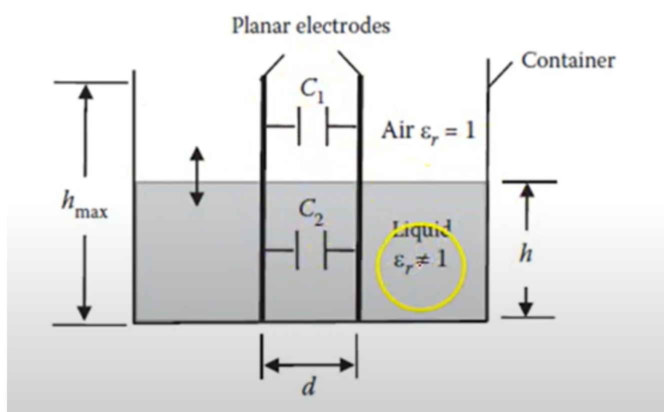

Fig. 1. parallel capacitors with different dielectrics

The capacitance of two parallel capacitors is as follows:

$$C = \epsilon_0 \epsilon_r \frac{A}{d} \tag{1}$$

As Figure 1 shows, the total capacitance of the system is the sum of the parallel capacitors with water and air dielectrics:

$$C = C_1 + C_2 \tag{2}$$

$$C = \epsilon_0 \frac{b\ h_{max}}{d} + \epsilon_0 \frac{b\ h}{d}(\epsilon_r - 1) \tag{3}$$

Where b is the width of the plates and ϵ_r for water is 81.

III. Simulation

The sensor has to measure the water levels between $0mm$ and $300mm$. One of the design assumptions of the capacitor plates is to limit the sensor capacitance to a maximum of $400pF$ at the level of $300mm$.

The theoretical approach does not give realistic results because all parameters are considered ideally. Using simulation tools can give a better result for mechanical design.

After optimizing the design parameters using Ansys Electronics, the results are as follows:

- Electrode's thickness: $2mm$
- Electrode's width: $30mm$
- Electrode's height: $400mm$
- Electrodes' gap: $10mm$

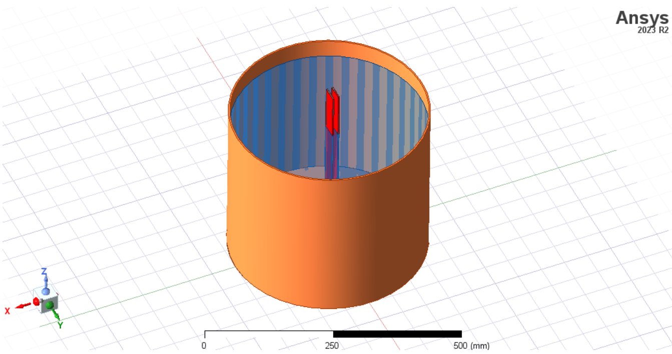

Fig. 2. Simulation in Ansys Electronics

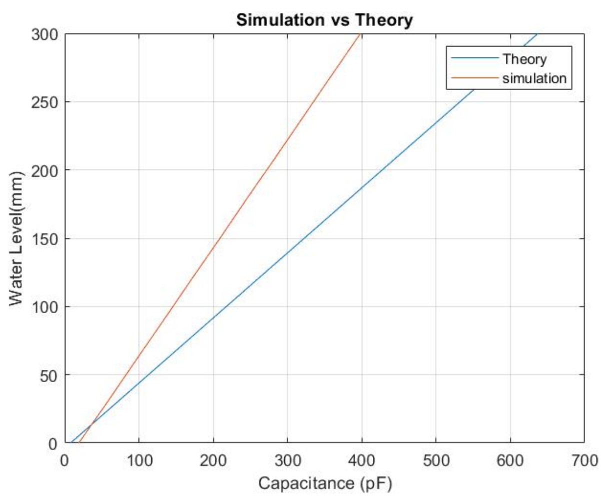

Fig. 3. Simulation vs Theory

IV. Mechanical Design

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A. Fabrication of Electrode Plates

The initial step involved cutting two electrode plates from an aluminum sheet using a guillotine. To achieve a smooth finish, machining files were employed, followed by the removal of burrs with sandpaper. This process resulted in well-finished aluminum electrode plates.Additionally, the corners of the plates were filleted to ensure that the heat shrink tubing would not tear after being attached to the electrodes.

B. Insulation of Electrodes

To prevent contact between water and the electrodes, two pieces of appropriately sized heat shrink tubing were used. The tubing was attached to the plates using an industrial dryer. The critical challenge was ensuring the ends of the tubing, which would be submerged in water, were perfectly insulated. This was achieved by heating the ends with the dryer while pressing them with pliers. To further ensure water-tightness, silicon glue was applied to the ends.

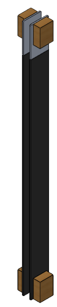

Fig. 4. Capacitive Sensor without housing

C. Housing the Electrodes

PVC tubing was used as housing for the electrodes. The challenge was to fix the electrodes inside the tubing while maintaining a consistent space between them. A temporary piece of wood with controlled thickness was placed between the plates to ensure the spacing remained fixed. Four strips of square-shaped wood were then cut and positioned at both ends of the electrodes, between the electrodes and the PVC tube. The PVC tube was then screwed to the wooden strips, and the temporary piece of wood was removed.

D. Final Assembly

A cap made of Teflon was fabricated for the system, with a hole drilled in it to allow the wires to pass through.

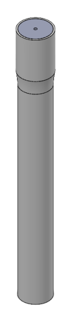

Fig. 5. Final Assembly

V. Electrical Circuit

A. Method 1: Capacitive Voltage Divider

- Requires AC excitation.
- $X_c = \frac{1}{j(\omega C)}$

- Small values of capacitance lead to large Impedances.
- Because of the tall electrodes, the noise effect is high.
- $V_{out} = V_{in} \frac{X_{C2}}{X_{C1}+X_{C2}}$
- The circuit did not work for this application.

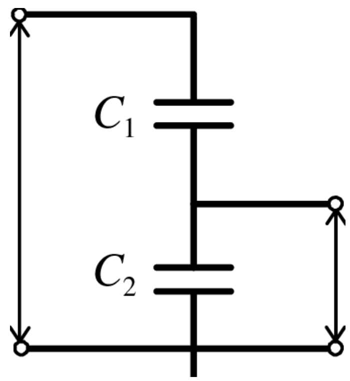

Fig. 6. Capacitive Voltage Divider

B. Method 2: Charge-Discharge Schmitt trigger Circuit

- The circuit includes a resistor and a Schmitt trigger.
- The output of the trigger is passed through the RC filter.
- The output of the RC filter is a DC value.
- The DC value changes as the capacitor value changes.
- The measurement results were not repeatable.
- The circuit did not work for this application.

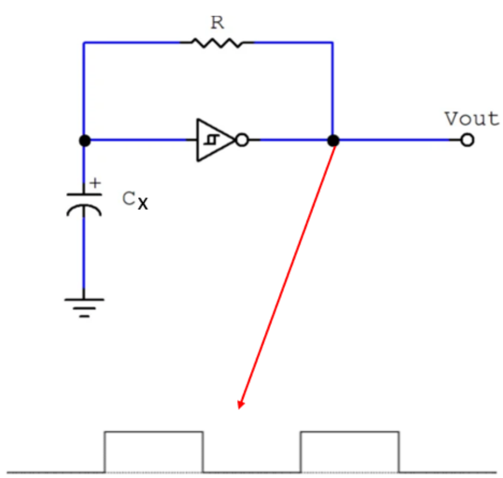

Fig. 7. Charge-Discharge Schmitt trigger Circuit

C. Method 3: Code based

- The circuit is simple.
- Works based on the Charge-Discharge of the capacitor.
- Two Arduino pins are needed, one for charge and one for discharge.
- In capacitors with low capacities, the size of the capacity is a ratio of Stray capacitance. [2]
- The circuit has worked for this application.

Before measuring the electrodes' capacitance, the microcontroller's Stray capacitance should be calibrated. The calibration has been done with the usage of a capacitive voltage divider circuit (figure 6) and a 12 pF capacitor:

$$V_{out} = V_{in} \frac{C_{Stray}}{C_{12} + C_{Stray}} \tag{4}$$

Where $V_{in} = 5V$ and $C_{12} = 12pF$. V_{out} can be measured by Arduino using analog-to-digital converter (ADC). Arduino gives a value between 0(0V) and 1023(5V). In the measurement:

$$ADC = 703 \longrightarrow C_{stray} = 26.36\ pF \tag{5}$$

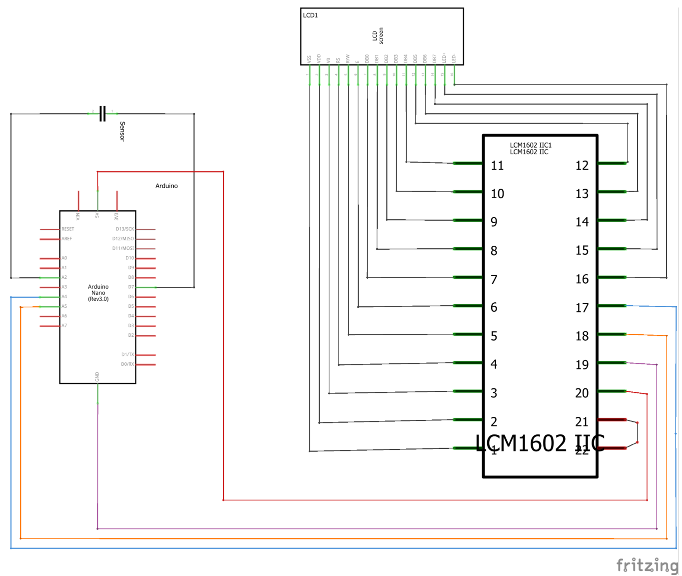

Fig. 8. Measurement circuit

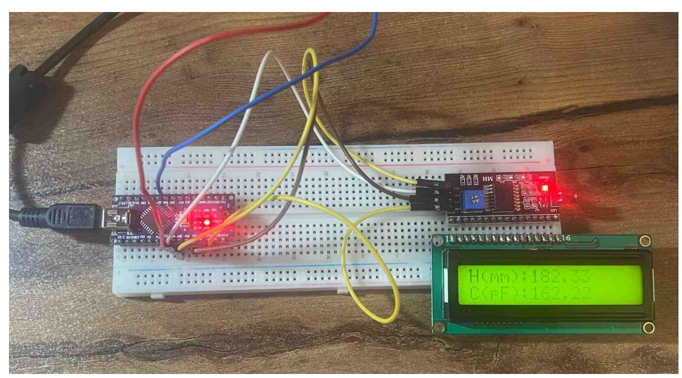

Fig. 9. Experimental circuit

VI. Firmware

A. Libraries and CapacitiveLiqSensor Class

In this part, two libraries are imported.

- TimerOne.h: For interrupt and sampling.
- LiquidCrystal_I2C.h: For LCD and Digital Display.

CapacitiveLiqSensor is an object to define the sensor. It receives two pins Out_pin (charge) and In_pin(discharge).

It has four methods:

- CapacitorMeasure(): Measure Capacitance in pF.
- CalibrateWaterLevel(float a0, float a1): Fit a linear curve to convert capacitance into water level.
- CalibrateInCapToGnd(float inCapToGnd): Calibrate Stray Capacitance of the microcontroller.
- WaterLevelMeasure(): Measure Water level in cm.

```
#include <TimerOne.h>
#include <LiquidCrystal_I2C.h>

class CapacitiveLiqSensor
{
  public:
    CapacitiveLiqSensor(int outPin, int inPin);
    float CapacitorMeasure(); //capacitance in pF
    void CalibrateWaterLevel(float a0, float a1);
    void CalibrateInCapToGnd(float inCapToGnd);
    float WaterLevelMeasure(); //Water Level in cm

  private:
    int _maxAdcValue = 1023; //10 bit
    float _inCapToGnd;   // in pF (AVR ATmega328P)
    int _outPin;
    int _inPin;
    float capacitance;
    float _a0;
    float _a1;
};
```

Listing 1. Libraries and CapacitiveLiqSensor Class

B. Parameters

In this part, the LCD and the Sensor are defined and other parameters are initialized. The sampling frequency is 10 Hz.

```
LiquidCrystal_I2C lcd(0x27, 16, 2);//Digital Display
CapacitiveLiqSensor sensor(7,A2);//Define the sensor
float capacitance = 0; //Measured Capacitance
float WaterLevel;     //Measured Water Level
float Fs = 10;         //Sampling Frequency
int flag = 0;         //Data recieved ?
```

Listing 2. Parameters

C. Setup

In this part, the LCD and the Sensor are launched and Timer1 is initialized.

```
void setup()
{
  //Setup LCD
  lcd.begin();
  lcd.backlight();

  //Timer interrupt for sampling data
  Timer1.initialize(1000000/Fs);
  Timer1.attachInterrupt(Sampling);

  //Setup the sensor
  sensor.CalibrateInCapToGnd(26.30);
  sensor.CalibrateWaterLevel(0.1450 , -5.09855);
}
```

Listing 3. Setup

D. Loop

In this part, the measured water level and capacitance are printed on LCD every 0.5 seconds.

```
void loop()
{
  if(flag == 1)
  {
    flag = 0;
    lcd.clear();          //Update LCD
    lcd.setCursor(0, 0);
    lcd.print("H(mm):");
    lcd.print(WaterLevel* 10); //Water Level (in mm)
    lcd.setCursor(0, 1);
    lcd.print("C(pF):");
    lcd.print(capacitance); //Capacitance (in pF)
    delay(500);
  }
}
```

Listing 4. Loop

E. ISR

This part is the ISR function which samples and measures water level and capacitance with a sampling frequency of 10 Hz.

```
void Sampling()
{
  //Calculate Capacitance
  capacitance = sensor.CapacitorMeasure();
  //Calculate Water Level
  WaterLevel = sensor.WaterLevelMeasure();
  flag = 1;
}
```

Listing 5. ISR

VII. Calibration

This sensor does not have reference electrodes and it has been designed for a water tank with the following specifications:

- Height = 250 mm
- Diameter = 250 mm

A. Curve fitting

The odd indices are assumed training data and even ones are test data. The number of train data point is $n_{train} = 12$ and for test data is $n_{test} = 11$.

As equation (3) shows, the relationship between capacitance and water level is linear:

$$\mathbf{X} = \begin{bmatrix} 1 & (x_{\text{train}})_1 \\ 1 & (x_{\text{train}})_2 \\ \dots & \dots \\ 1 & (x_{\text{train}})_i \end{bmatrix} \tag{6}$$

$$\mathbf{Y} = \mathbf{y}_{\text{train}} \tag{7}$$

Least-Square Coefficient Estimates:

$$\mathbf{A} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y} \tag{8}$$

After calculations:

$$\mathbf{A} = \begin{bmatrix} a_0 = -50.9855 \\ a_1 = 1.4500 \end{bmatrix} \tag{9}$$

Fig. 10. Experimental setup (The capacitive sensor and the water tank)

TABLE I
MEASURED DATA

Capacitance (pF)	Water Level (mm)
36.56	0 (train)
38.22	10 (test)
42.64	20 (train)
64.90	30 (test)
67.77	40 (train)
69.45	50 (test)
72.62	60 (train)
77.58	70 (test)
88.19	80 (train)
97.12	90 (test)
108.90	100 (train)
112.39	110 (test)
120.72	120 (train)
127.44	130 (test)
134.84	140 (train)
140.81	150 (test)
147.28	160 (train)
153.07	170 (test)
160.54	180 (train)
165.88	190 (test)
171.53	200 (train)
174.48	210 (test)
180.66	220 (train)

B. Training and test errors

Residual sum of squares:

$$\text{RSS} = \sum_{i=1}^{n} (y_i - y_{ic})^2 \tag{10}$$

Mean square error:

$$\text{MSE} = \frac{\text{RSS}}{n} \tag{11}$$

where y_i is measured output and y_{ic} is predicted output by model.

predicted values for training data:

$$\mathbf{Y}_c = \mathbf{XA} \tag{12}$$

$$y_c(x) = -50.9855 \ + \ 1.4500 \ x \tag{13}$$

For test data:

$$\mathbf{X}_{\text{test}} = \begin{bmatrix} 1 & (x_{\text{test}})_1 \\ 1 & (x_{\text{test}})_2 \\ \dots & \dots \\ 1 & (x_{\text{test}})_i \end{bmatrix} \tag{14}$$

$$\mathbf{Y}_{\text{test}} = \mathbf{y}_{\text{test}} \tag{15}$$

and predicted values for test data:

$$(\mathbf{Y}_c)_{\text{test}} = \mathbf{X}_{\text{test}}\mathbf{A} \tag{16}$$

Finally for error:

$$(\text{MSE})_{\text{train}} = 30.3645 \tag{17}$$

$$(\text{MSE})_{\text{test}} = 33.5341 \tag{18}$$

$(\text{MSE})_{\text{test}}$ and $(\text{MSE})_{\text{train}}$ are close so there is no under fitting or over fitting.

TABLE II
PREDICTED DATA AND ERRORS

Error (mm)	Water Level (mm)	Water Level Pred(mm)
-2.0283	0 (train)	2.0283
5.5647	10 (test)	4.4353
9.1555	20 (train)	10.8445
-13.1226	30 (test)	43.1226
-7.2842	40 (train)	47.2842
0.2797	50 (test)	49.7203
5.6830	60 (train)	54.3170
8.4908	70 (test)7	61.5092
3.1058	80 (train)	76.8942
0.1569	90 (test)	89.8431
-6.9247	100 (train)	106.9247
-1.9854	110 (test)	111.9854
-4.0643	120 (train)	124.0643
-3.8086	130 (test)	133.8086
-4.5389	140 (train)	144.5389
-3.1957	150 (test	153.1957
-2.5775	160 (train)	162.5775
-0.9733	170 (test)	170.9733
-1.8051	180 (train)	181.8051
0.4516	190 (test)	189.5484
2.2588	200 (train)	197.7412
7.9812	210 (test)	202.0188
9.0199	220 (train)	210.9801

C. 95% confidence interval

Independent variable:

$$x_1 = x \tag{19}$$

So $m = 1$ and the degree of the freedom is:

$$\nu = n_{\text{train}} - (m+1) = 10 \tag{20}$$

For the confidence interval of 95% we have $t_{\nu,p} = 2.2281$ Then:

$$S_{yx} = \sqrt{\frac{\text{RSS}}{\nu}} = \sqrt{\frac{(\text{MSE})_{\text{train}}(n)_{\text{train}}}{\nu}} = 6.0363 \tag{21}$$

Next:

$$t_{\nu,p}\frac{S_{yx}}{\sqrt{n_{\text{train}}}} = 3.8826 \tag{22}$$

Finally:

$$y(x) = y_c(x) \pm 3.8826 \;\; (\%95) \tag{23}$$

$$Level(Cap) = Level_{\text{model}}(Cap) \pm 3.8826\, mm \;\; (\%95) \tag{24}$$

$$Level_{\text{model}}(Cap) = -50.9855 \; + \; 1.4500\, Cap \tag{25}$$

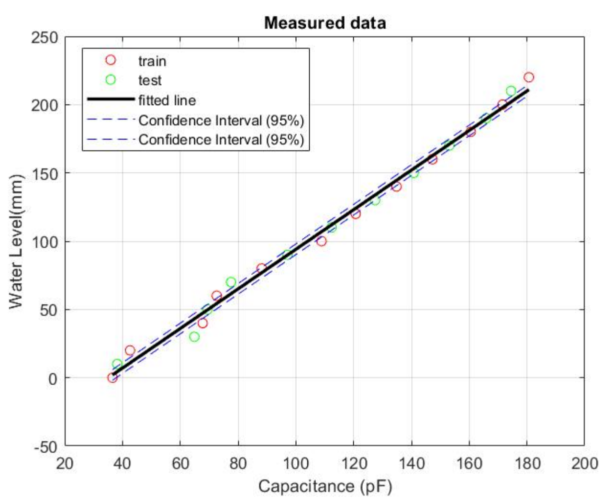

Fig. 11. Measured Data and 95% confidence interval

VIII. Conclusion

This project successfully developed a capacitive water level detector, demonstrating its ability to accurately measure liquid levels from 0mm to 300mm with a maximum capacitance of 400pF. Through a combination of theoretical analysis, Ansys Electronics simulations, and precise mechanical fabrication, the sensor achieved reliable and repeatable measurements. The optimal electrode design included dimensions of 2mm thickness, 30mm width, and 400mm height, with a 10mm gap. Calibration showed a linear relationship between capacitance and water level, with a mean squared error (MSE) of 30.3645 mm^2 for training data and 33.5341 mm^2 for test data, ensuring minimal error and high accuracy. This project highlights the potential of capacitive sensing technology in providing a cost-effective and durable solution for liquid level measurement in various applications

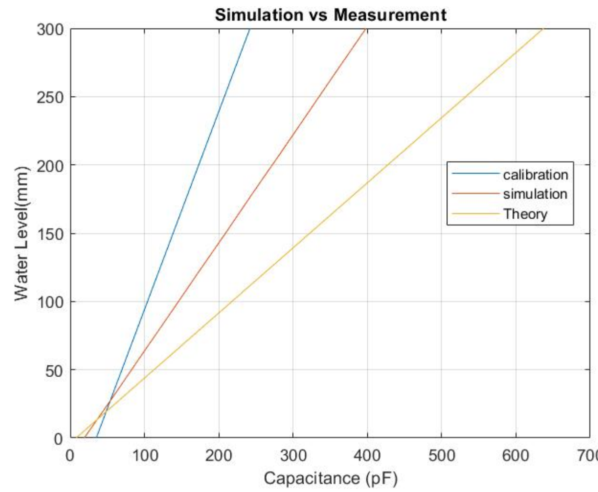

Fig. 12. Theory vs Simulation vs Calibration

References

[1] T. Bento, W. O. Silva, A. Dias, André Ferrus Filho, J. C. Pitta, ”Design, development and application of a real-time capacitive sensor for automatically measuring liquid level”

[2] https://electronoobs.com/eng_arduino_tut10_1.php ”Capacitance meter”