

EE5901 Assignment 2: Capacitive Based Water Level Sensor

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I. INTRODUCTION

Capacitive sensing is widely used in various applications and industries. It detects the change in the electrical field between two conductive plates to determine the target measurement values. The advantage of capacitive sensing is that it can detect most of the environmental variables. Owing to these advantages, a wide range of measurements can be conducted using capacitive sensing. However, capacitive sensing's advantages of sensitive to the change of the environment condition and choice of materials also bring disadvantage. For example, temperature, background humidity, operation frequency, and other inferences result in poor performance in target measurements [1]. Therefore, an additional circuit is generally required to compensate for these unwanted variations [2]. In this practical, our objective is to build a capacitive based water level sensor that can be used in most environments.

II. LITERATURE REVIEW

A. Capacitive sensing types

Capacitive sensing is a technology that can detect and measure both conductive and non-conductive objects with different dielectric constants. The sensing modality of a capacitive sensor is to detect changes in the dielectric constant, the distance between electrodes, or the distance between electrodes and objects [3]. Capacitive sensors can be categorised into three types based on sensing modality: volume sensing, deformation sensing, and displacement sensing.

1) Volume sensing

The volume sensing modality measures the capacitance in difference in the object's shape, size, dielectric constant, and the alteration in the electric field that is generated by the object itself [3]. For example, in a capacitive-based gas and vapour detector, the structural variation of dielectric properties is used to identify gases and vapours, such as H₂, O₂, NH₃, NO₂, and NH₃ [4]. Similarly, because capacitance is sensitive to changes in the environment, it can also be used to detect variations in temperature and humidity to measure its value [5].

2) Deformation sensing

Deformation sensing detects changes in the shape of capacitive sensors. One early study proposed that a capacitive based strain sensor called soft-matter sensor can detect a change of 500 μ m and 5 kPa sensitivity [6], these flexible and stretchable strain sensors is widely distributed; thus, they are now very popular for application in wearable devices and soft robotics [7].

3) Displacement sensing

Displacement sensing has a wide range of applications and has the advantage of non-contact distance measurement. This includes precision and non-precision measurements. Precision measurement can make use of linear displacement measurement in very small range distance detection, which can accurately detect ranges from 0.05 to 20 mm [8]. Non-precision can be used for longer range distance measurements when precision is not very important. One example is the use of robot tactile sensors and proximity sensors. The dual implementation of a tactile proximity sensor can detect the proximity information of nearby objects, which allows moving robots to avoid collisions [9]. Therefore, capacitated sensors are widely used in robotic technology.

B. Applications of capacitive sensing to robotics

Human-like robotics are generally described in Si-fi movies or novels. The key feature of a human-like robot is that it must have a human-like skin that can detect external environmental information input. Capacitive sensing

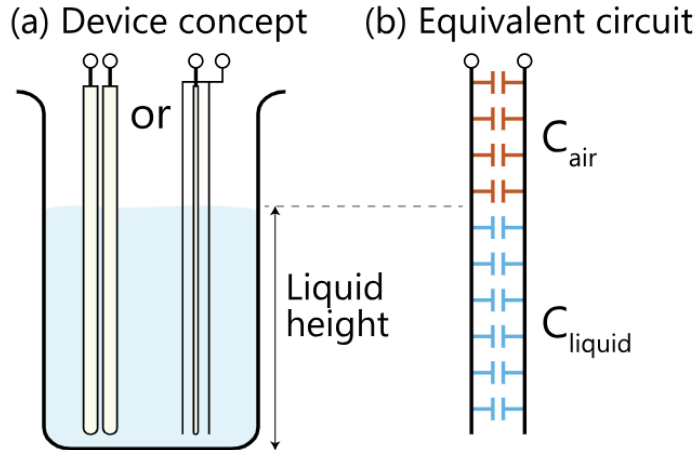


Fig. 1: The idea of liquid level sensing. (a) positioning capacitive electrodes in or close to the liquid. (b) From an electrical perspective, this configuration functions similarly to a parallel arrangement of numerous capacitors. [15]

has been widely used in robotic skins in recent years owing to its cost efficiency [10]. A previous study combined capacitive sensors with resistive sensors that can detect object temperature, distance, and force. Primarily, the sensor includes two modes: resistance mode (R-mode) and capacitance mode (C-mode). The R-mode measures long distances and the C-mode measures short distances. Both modes work together to sense the temperature and force. This sensor can potentially enable skin-like applications [11]. Previously, these skin-like capacitive sensors normally only targeted non-precision measurements. In recent years, with the development of high-performance process units, it has become possible to convert these non-precision data into precision data using advanced algorithms. For example, a study used a series of algorithms, starting with K-mean clustering and fuzzy recognition, to classify the different areas in the sensor, and the Artificial Neural Network trained a model for force detection. This approach improved the detection accuracy of force measurements in electronic skin [12]. In industrial robot settings, a precise pretouch system is important, such as sorting unknown materials, which may damage the sensor or system. The combination of a displacement sensing capacitive sensor and a magnetic sensor has also been proven to provide precise measurement of the pretouch system in a robot grasper, particularly when the target materials can be both dielectric and ferromagnetic [13]. These sensing technologies made use of the relative permittivity difference of the dielectric objects. These can be implemented in humanlike robotics in future.

As a result, the potential of capacitive sensing is huge, and the advantages of low cost and multiple uses can accelerate the development and distribution of human-like robotics. However, there are challenges that still need to be overcome; for example, in soft robotic applications, the change in pressure measurement is from 1 to 60pF and the proximity is 0.1 to 2.4pF [14], such small changes can easily be affected by environmental interference, so the issue of false detection remains a big challenge. More effort is needed to investigate how to address environmental interference when integrating capacitive sensing.

III. COMPUTATIONAL MODELLING

The goal of this practical is to precisely determine the water level within a container by utilising the permittivity difference of the material. First, it is essential to understand that the relative permittivity of water varies with temperature. Moreover, other environmental noise is unpredictable. Thus, our objective is to design a method that can effectively address these issues.

A. Capacitance and Water Level

First, we employed the fact that air and liquid possess distinct relative permittivity values, which lead to a dissimilar total capacitance when the water level changes, as shown in Fig. 1. The calculation of the total capacitance is given by:

$$C_{total} = C_{air} + C_{liquid} \quad (1)$$

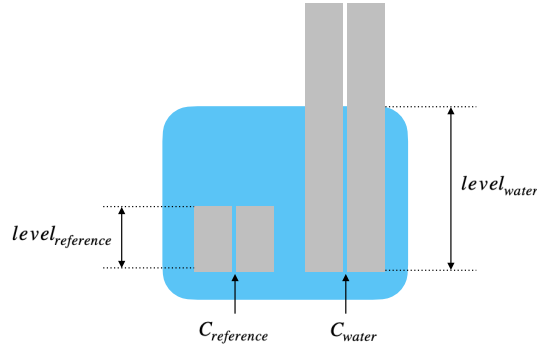


Fig. 2: A design to compensate relative permittivity difference of temperature.

The relative permittivity of air is approximately 1, whereas that of water varies from 88 at 0°C to 55°C at 100°C. Owing to the large difference, we approximated the total capacitance to the liquid capacitance is:

$$C_{total} \approx C_{liquid} \quad (2)$$

The capacitance of plane parallel electrodes is:

$$C = \frac{\epsilon_0 \epsilon_r A}{d} \quad (3)$$

Where A is the surface area of each electrode, d is the distance between the electrodes, ϵ_0 is the permittivity of free space, which is a constant, and ϵ_r is the relative permittivity of the material. Based on this, we can obtain

$$C_{water} = \frac{\epsilon_0 \epsilon_{water} \times level_{water} \times thickness_{electrode}}{d} \quad (4)$$

In this formula, it is assumed that all values except the water level remain constant. Consequently, the measurement of the capacitance is equivalent to the water level multiplied by a constant value.

B. Compensation for the Relative Permittivity

In practical circumstances, environmental data can be unpredictable and water temperatures may fluctuate. As a result, the value of ϵ_{water} is not constant. To address this issue, a reference level is introduced, as shown in Fig. 2 and the given Equation 5.

$$C_{reference} = \frac{\epsilon_0 \epsilon_{water} \times level_{reference} \times thickness_{electrode}}{d} \quad (5)$$

We can use this formula to compensate ϵ_r in the given environment, after combining Equations 4 and 5, we obtain:

$$level_{water} = \frac{C_{water} \times level_{reference}}{C_{reference}} \quad (6)$$

According to this, to calculate the water level, we need to first measure $C_{reference}$ before measuring C_{water} .

C. Design Factors Investigation

When designing a sensor to measure the water level, because water is not a hazardous and corrosive material, there are two methods to choose from: external and internal. To determine the most effective method, several simulations were conducted using MATLAB and AUTODESK FUSION. The simulation was conducted on geometry; thus, the capacitance result in the simulation was represented by the capacitance per depth (pF/mm). For example, if the result of the simulation was 1pF/mm, the level of 10 mm was 10pF in the real measurements. However, this value could be lower or higher owing to the environmental noise in real applications. This section

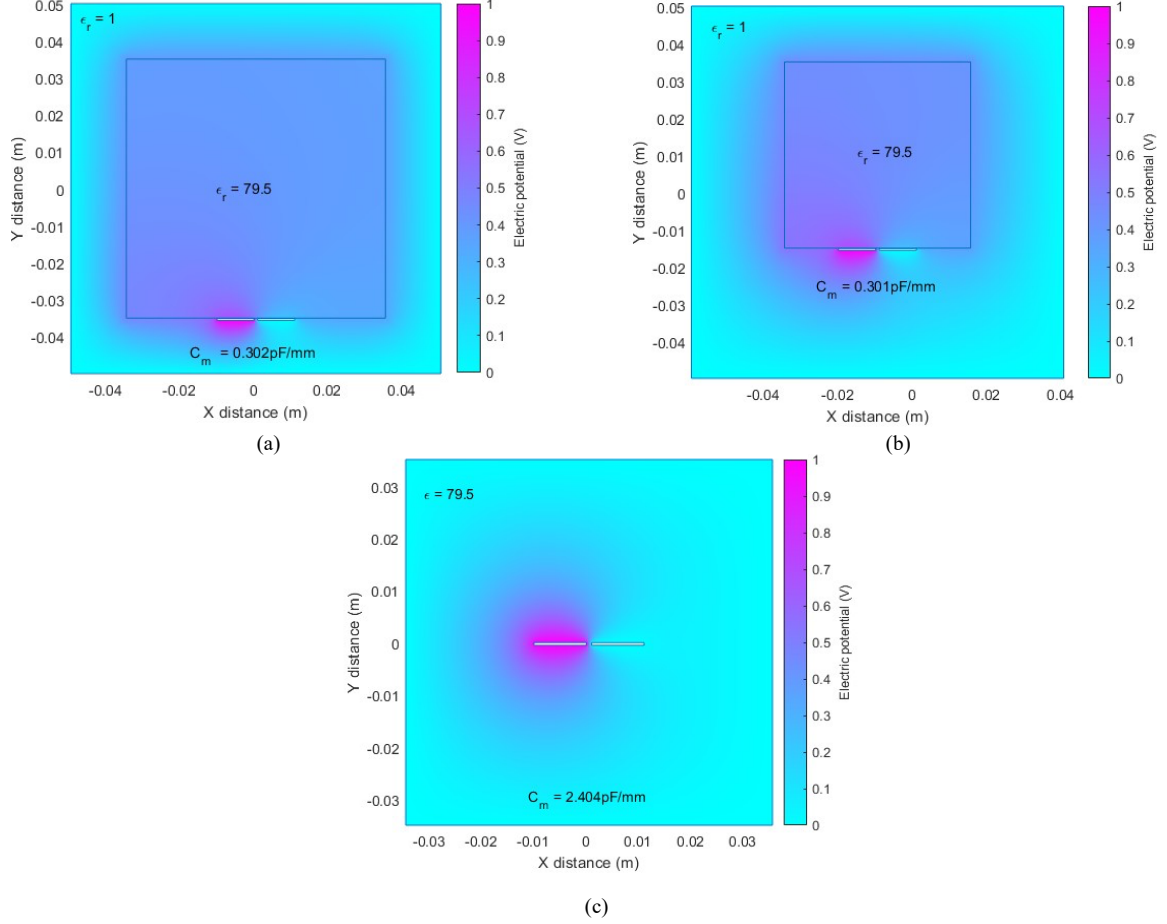


Fig. 3: (a) Electrodes were placed externally as a reference setting to compare other changes. (b) Decreased the measuring area of the container. (c) Simulation of the electrodes submerged in the water

is divided into two parts. First, we conducted a simulation to determine whether our sense should be submerged in the water and whether to constrain the water area that the electrodes touch. Second, several simulations were performed to determine the dimensions of our design.

1) Design Simulation Part I

Part I of the simulation process is illustrated in Fig. 3. The results are presented in Table 1. As a result, the attached area of water is not significantly related to the change in capacitance; however, submerging the sensor with water significantly increases the value. This means that, if the sensor is submerged in water, the change in capacitance is more easily detectable and less sensitive to external interference. Therefore, internal design is an optimal choice for this application. However, this design has some limitations. First, if the sensor is too large and the water container is too small, the size of the sensor may affect the water level. Second, a reliable insulation layer must be present, and the sensor can easily be damaged if the layer is broken. Third, underwater pressure might distort the shape of the sensor, which may affect the capacitance.

TABLE 1: CHANGES IN THE CHARACTERISTIC FEATURES OF DESIGN.

Factor	Action	Change on capacitance(pF/mm)
Measurement area	Reduce by double	No significant change
Relative permittivity	Submerge into water	+2.1

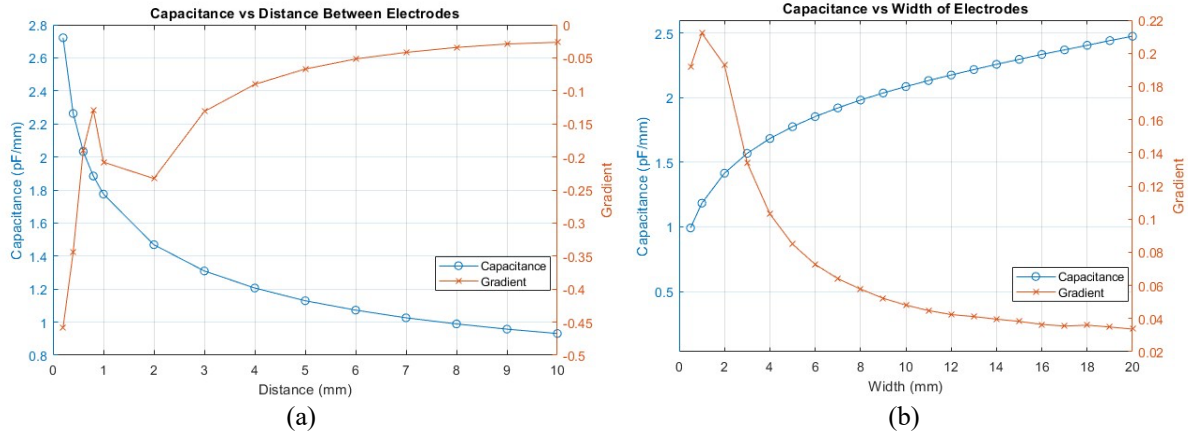


Fig. 4: Outcomes of simulations that investigated two design factors. (a) Capacitance changed by the distances between electrodes. The width was set at 5mm, while the distance was varied from 0 to 10mm. As the distance increased, the capacitance decreased, and the decrease was particularly sharp for the first 2mm. (b) Capacitance changed by the widths of the electrodes. The distance was set at 1mm, while the width of the electrodes was varied from 0 to 20mm. An increase in the width of the electrodes resulted in an increase in capacitance. The capacitance increased by 0.8pF/mm from 0.5 to 5mm, and only increased by 0.3pF/mm from 5 to 10mm. Also, gradient is very small from 10mm and dropped slightly.

2) Design Simulation Part II

The results for Part II are shown in Fig. 4. Fig. 4(a) indicates that the distance between the electrodes should be kept as small as possible. However, in physical design, there is a limit to how close the electrodes can be placed in a handmade sensor, the achievable distance is 1 mm. Fig. 4 (b) shows that the electrodes should be as wide as possible to increase the sensitivity. However, the optimal width would be to find a balance between the width of the electrodes and the overall size of the sensor while also considering the cost efficiency of the design. In addition, if we set it too wide, it would be too close to the outer environment, which is prone to interference. Therefore, we selected 8 mm as the width of the electrodes, where the change in the gradient becomes very small.

D. Shielding

Considering the consequences of external factors on capacitance, it is essential to minimise interference when designing sensors. Shielding is a widely used strategy for addressing this problem. There are two primary methods of shielding: active and passive. Active shielding entails introducing a voltage into the sensor, whereas passive shielding entails adding an additional delay by connecting a component to either the high potential or ground wire [16]. Fig. 5 shows a comparison between the sensors with and without shielding. Our design is internal and the external environment may not have a significant influence. Nonetheless, a simulation was conducted to understand the possible interference of the measurements. Fig. 6 shows that placing any dielectric or electrode does not significantly affect the measurement.

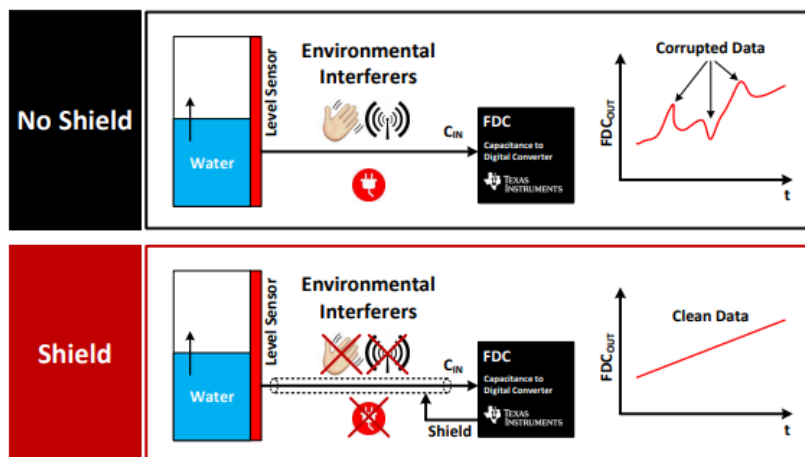


Fig. 5: Comparison on shielding and no shielding [17]

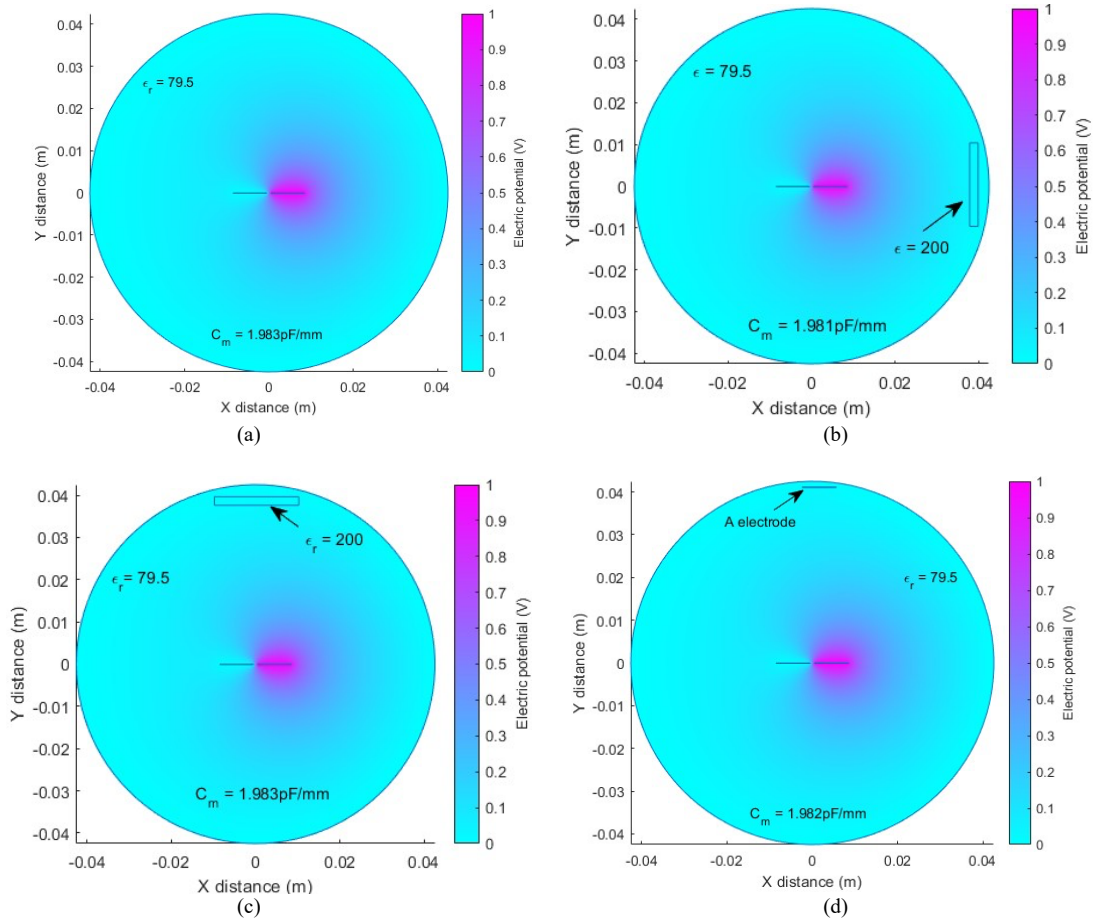


Fig. 6: Interference simulation. In (a), there is no interference present. In (b), a high-permittivity dielectric material is placed on the right side. In (c), a high-permittivity dielectric material is placed on the top, and in (d), an electrode is placed on the top.

We should also consider the copper wire connected to the reference electrodes because other electrical properties, such as resistance and inductance, can create noise in the measurement. To minimise this impact, we used a very small wire with a diameter of only 0.1 mm in our design. Additionally, the static electrical charge of water may also add uncertainty to the measurement. Therefore, we conducted an experiment on the physical ground and encircled the beaker to reduce the environmental noise, as shown in Fig. 7. This experiment aimed to evaluate these differences and discover potential improvements for future design.

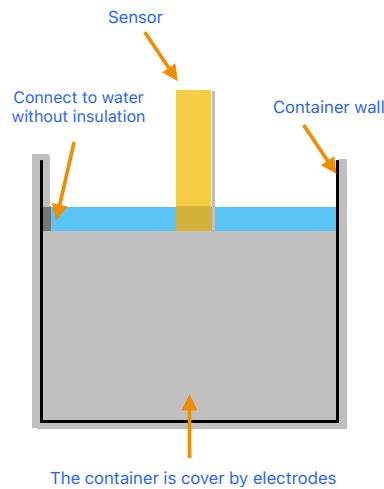


Fig. 7: An experiment aims for investigate a shielding method to reduce environmental noise.

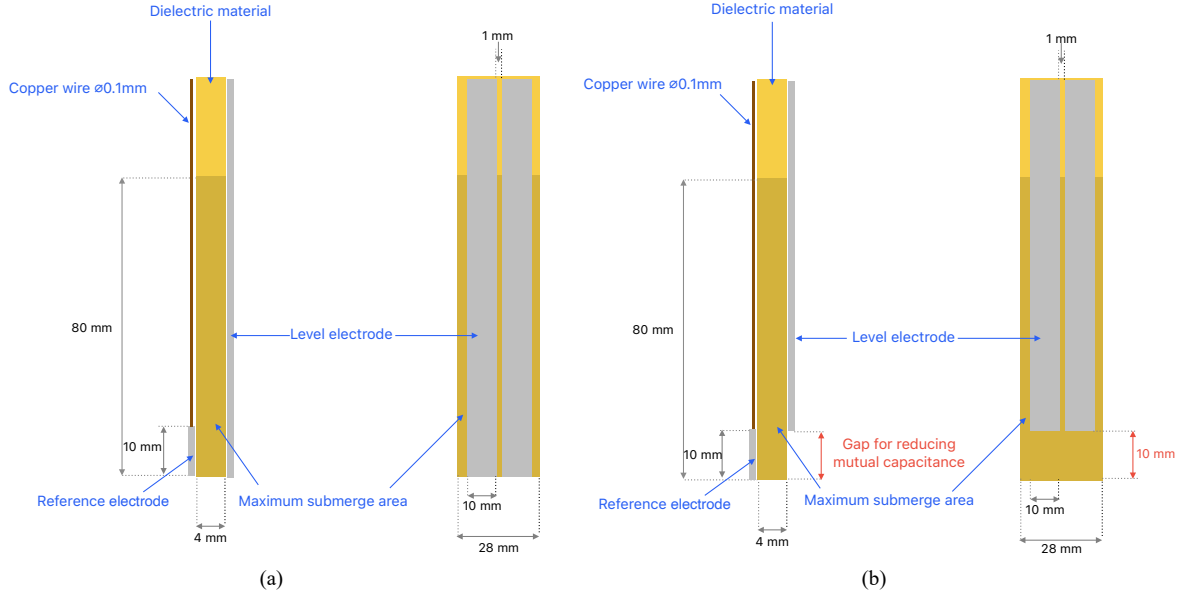


Fig. 8: Drawings of our design. (a) Design A, (b) Design B.

E. Sensor Design

Fig. 8 illustrates two distinct sensor designs. Design A may experience greater mutual capacitance from the opposite side of the reference electrode. Simulations were performed to determine the extent of this interference. As shown in Fig. 9, as expected, Design B exhibits a slightly lower level of interference than Design A. Because this difference is not substantial, we retained both designs because Design A is capable of measuring levels below the reference level when the reference value is known. Design B, however, must be connected to the LCR meter at the reference junction to measure when the level is lower than the reference value. Our experiment was conducted using both designs to verify our results.

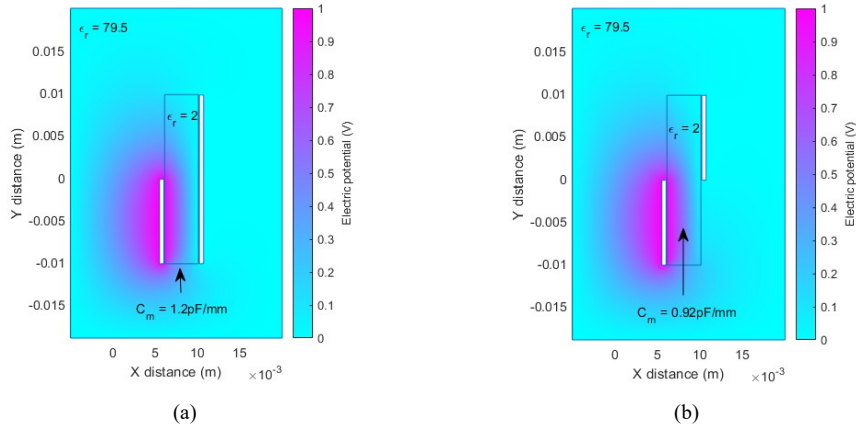


Fig. 9: Simulation on both design of how much mutual capacitance of two design can produce. Design A in (a) is 0.3pF/mm higher than Design B in (b).

IV. FABRICATION

The fabricated sensor employed a wooden ruler that was appropriately cut and aligned according to design specifications. A dry wood plate served as the dielectric material which had a permittivity of 2-3, and aluminium paper served as the electrode. Additionally, electrical insulation tape was applied to the copper wire to ensure proper insulation. Our design incorporated transparent tape to cover the submerged area of the sensor. The completion of the sensor is shown in Fig. 10. In the simulation, capacitance was calculated without additional insulation layers. Thus, we expected the capacitance in the experiment would be lower than that in the simulation. Furthermore, the front of the sensor was marked with levels at the reference level. This reference level could provide observation error into our experiment as well, it might be up to a 0.5 mm of uncertainty. However, in

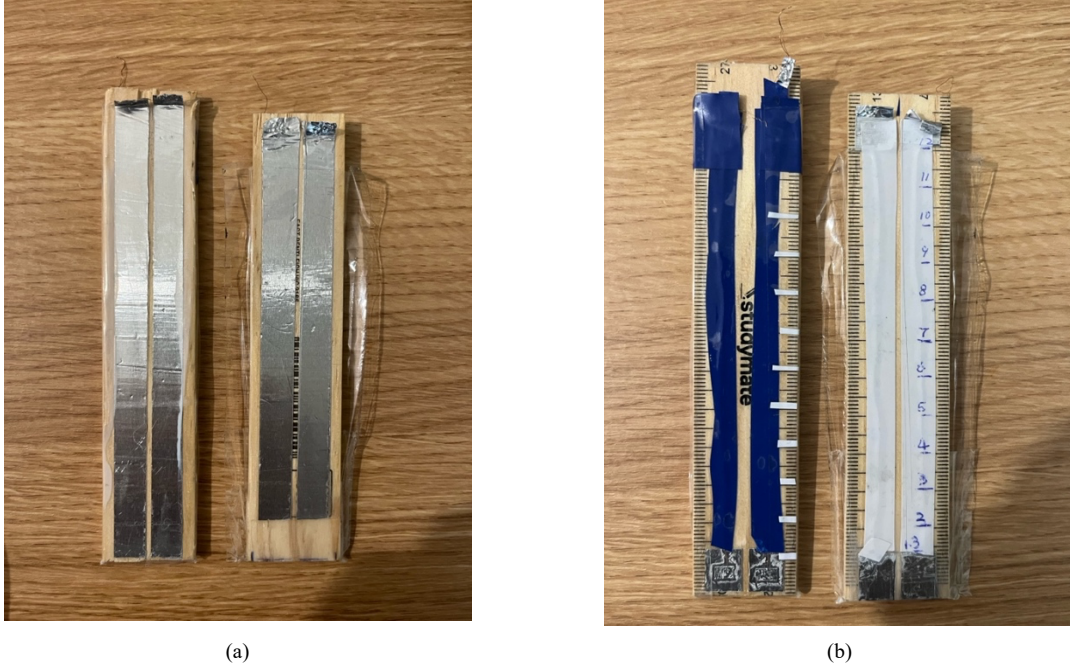


Fig. 10: (a) Back of the sensor. Left side design, we stuck the Aluminium tape to the bottom of the sensor, right side is Design B, there is a gap that equally to the reference level tape in front of the sensor. (b) Front of the sensor. For reference purpose, we marked both our sensor at the front of sensor. As they are hand-made sensors, it hard to ensure all numbers 100% align with the design.

our experiment, we assumed that the reference level is correct. In the future, when a better reference instrument becomes available, we can recalibrate our sensor.

V. TESTING AND CALIBRATION

A. Part I

Because of time and resource constraints, we divided our experiment into two parts. The first part was conducted in the laboratory, this part of the experiment was conducted under ambient temperature. The purpose of this part is to conduct a shielding experiment, as shown in Fig. 11. Design B was used for this experiment. To obtain accurate results, we tested each value thrice and calculated the mean as the measurement value. We first measured the reference capacitance value, and then followed the recording chart provided in Table 2 to obtain other readings. These readings were used to calculate the water level, using the following equation:

$$level_{water} = \frac{C_{water}}{C_{reference}} \times level_{reference} + level_{reference} \quad (7)$$

TABLE 2: RECORDING CHART FOR CALIBRATION

Reference level (mm)	Readings (pF)				Measurement level (mm)
	1	2	3	Mean	
20					
30					
40					
50					
60					
70					
80					

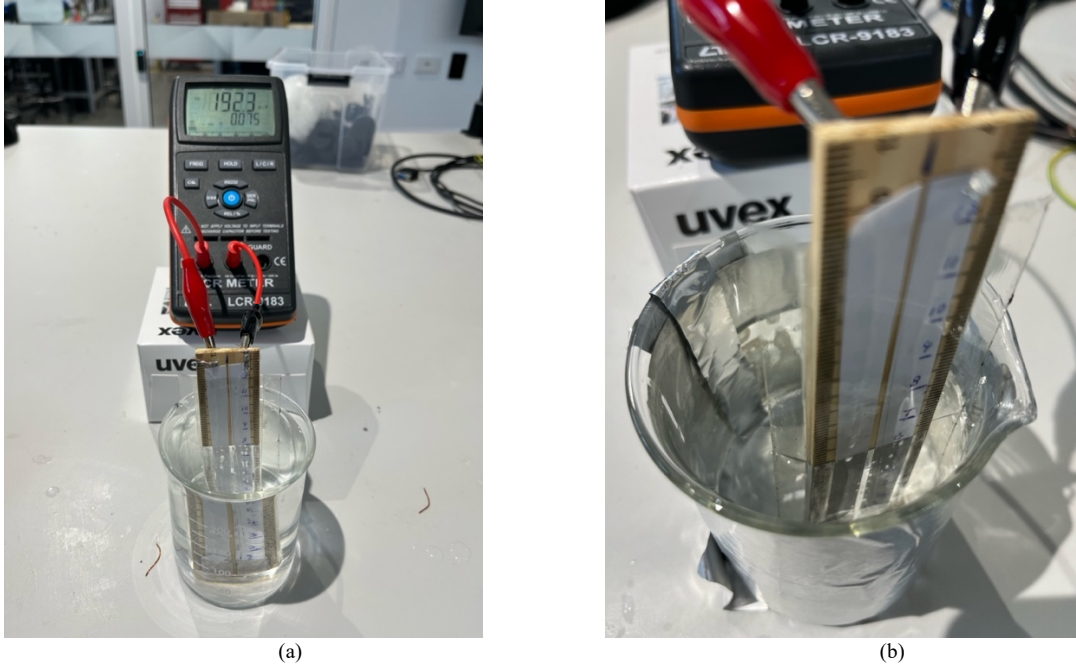


Fig. 11: Test conducted on our Design B sensor. (a) shows the process when No shielding provided. (b) shows the shielding experiment. Aluminium tape stuck around the beaker and connected to water and physical ground.

The raw results, as shown in Fig. 14(a), were subjected to an error known as zero error, which could arise from issues such as uneven cutting of the aluminium paper, non-parallelism, air bubbles in the transparent tape and so on. However, we can perform zero adjustment to offset this error. The calibration model is given by:

$$level_{calibration} = level_{water} \pm offset_{zero} \quad (8)$$

$$C_{reference_cal} = C_{reference} \pm offset_{linear} \quad (9)$$

If the system has a linear error, we adjust $offset_{linear}$ and calibration on $C_{reference}$, if there is a zero error we adjust $offset_{zero}$. However, if the sensor exhibited nonlinearity, it was suspected that it was damaged. In this experiment, we observed a zero error. To perform zero adjustment, we calculated the mean of the errors and subtracted it from the measurement value. After calibration, as shown in Fig. 12(b) and Table 3, both methods achieved an error rate of less than 1.5% within the full scale, except for the final readings. In addition, in the shielding experiment, the LCR meter exhibited a very stable reading at a frequency of 10kHz.

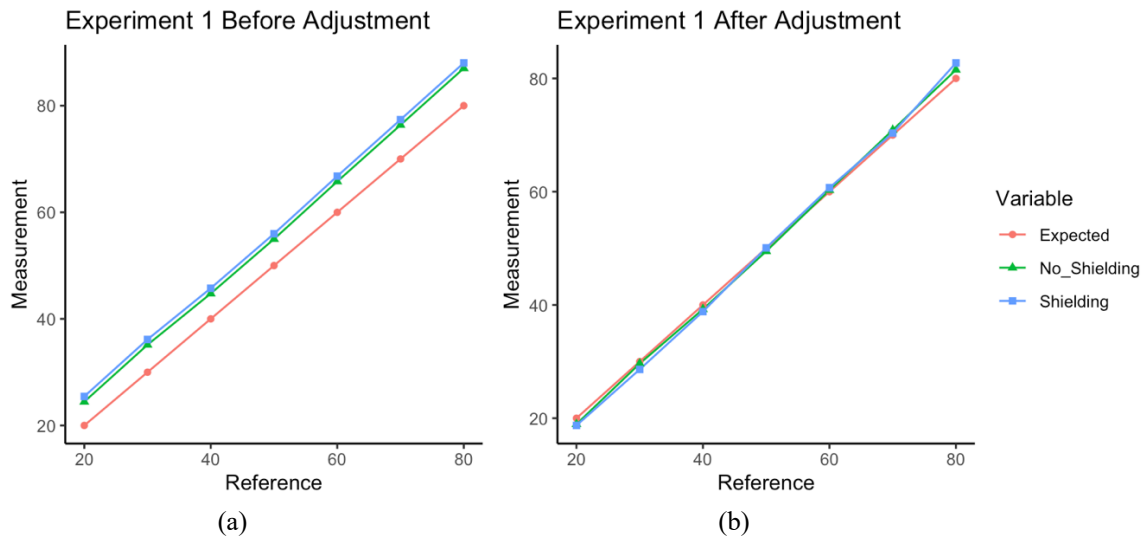


Fig. 12: both plots show both experiments compared to the expected level, it can be from (a) it is not much linear error, we only need to conduct zero adjustment. (b) shows that both methods are very close to the expected value, it is hard to determine which one is better.

However, Fig. 13 indicates that this shielding method did not improve the accuracy but obtained a worse result. We suspect that this could be an eye observation error. In Fig.11 (b), we obtained the reference reading from the top of the beaker because the beaker was covered. A better reference method should be used in future experiments.

TABLE 3: EXPERIMENT 1 ERROR COMPARISON

Not Shielding		Shielding	
Error (mm)	Error (%)	Error (mm)	Error (%)
-1.05	-1.31%	-0.71	-0.88%
-0.36	-0.46%	-0.81	-1.02%
-0.75	-0.93%	-0.60	-0.75%
-0.52	-0.65%	0.66	0.82%
0.28	0.35%	1.27	1.59%
0.88	1.10%	0.91	1.14%
1.52	1.90%	3.30	4.13%

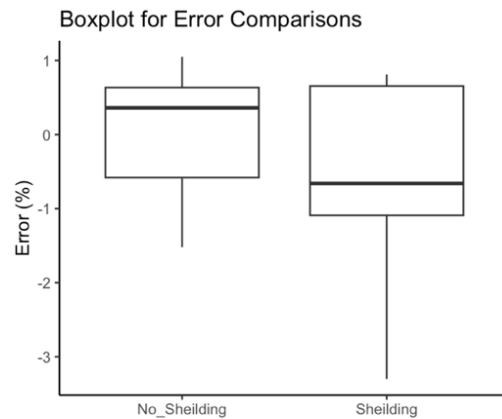


Fig. 13: The boxplot shows that no shielding method produce better result. It is suspect that may be an eye observation error, as we took the reading from top of the beaker.

B. Part II

In this part, we conducted two experiments: Experiments 2 and 3. The objective of Experiment 2 is to evaluate the performance of the sensor over a range of temperatures. To achieve this, Design A was employed, as shown in Fig. 14. Two measurements were conducted at ambient temperature (21°C) and ice point (0°C). Initially, we calibrated the sensor using the ambient temperature and then applied the same offset to the ice point measurements. The result of Experiment 2 is presented in Table 4.

The objective of Experiment 3 was to evaluate Designs A and B. If the accuracy rates of Design A and Design B are comparable, Design A will be selected because it allows for measurements below the reference level. As Experiments 2 and 3 were conducted in the same environment, we used the Design A results from Experiment 2. We conducted measurements using Design B and performed the same calibration process. The result is shown in Table 5. An overall error comparison for Part II is shown in Fig. 15.



Fig. 14: To maintain an ice point, we kept ice inside the container.

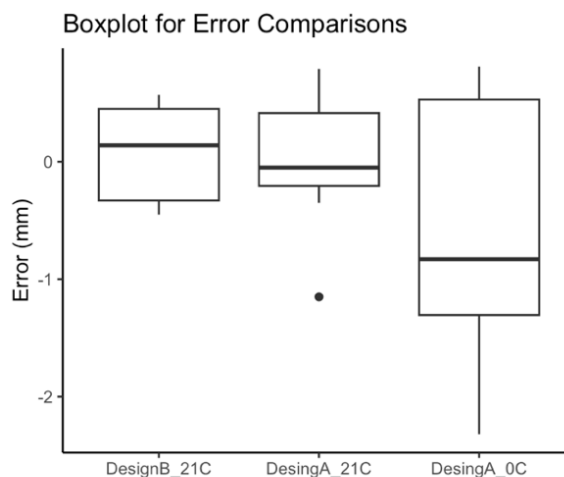


Fig. 15: The boxplot shows that both Design A and B produce good result in ambient measurement. The error expanded when the temperature decreases to 0°C.

TABLE 4: EXPERIMENT 2 RESULT

Ref Height (mm)	21°C				0°C		
	Measurement Height (mm)	Error (mm)	Adjustment made (mm)	Error on Full scale (%)	Measurement Height (mm)	Adjustment made (mm)	Error on Full scale (%)
20	31.18	11.18	19.94	-0.08%	31.97	20.73	0.91%
30	41.39	11.39	30.15	0.19%	42.05	30.81	1.02%
40	51.19	11.19	39.95	-0.07%	50.41	39.17	-1.04%
50	60.89	10.89	49.65	-0.44%	59.67	48.43	-1.96%
60	72.03	12.03	60.79	0.99%	71.57	60.33	0.42%
70	81.92	11.92	70.68	0.85%	80.20	68.96	-1.30%
80	90.09	10.09	78.85	-1.44%	88.92	77.68	-2.90%
Mean Error		11.24					

TABLE 5: EXPERIMENT 3 RESULT

Ref Height (mm)	Design B		Design A	
	Measurement Height (mm)	Error on Full scale (%)	Measurement Height (mm)	Error on Full scale (%)
20	19.61	-0.48%	19.94	-0.08%
30	30.36	0.45%	30.15	0.19%
40	40.57	0.71%	39.95	-0.07%
50	50.54	0.67%	49.65	-0.44%
60	60.14	0.18%	60.79	0.99%
70	69.55	-0.56%	70.68	0.85%
80	79.73	-0.34%	78.85	-1.44%

In Experiment 2, the accuracy of the ice point measurement was slightly lower. The error rate reach under 2.9% when measuring 80mm. This suggests that the sensor may have accumulated errors when the temperature varied from the calibration point. However, the design principle of this sensor is to maintain uncertainty within an acceptable range. For instance, if the manufacturer's specifications for a level sensor require an accuracy of $\pm 3\%$ of the full scale within 0–40°C, then this sensor would meet the requirements.

Experiment 3 showed that both designs yielded acceptable outcomes with appropriate calibrations. Except for the last reading of Design A, all errors were within 1% of the full scale or 0.8 mm. Although Design B shows a slightly higher accuracy, as shown in Fig. 17, this result indicates that the mutual capacitance in Design A does not significantly influence the measurement result. Fig. 3 indicates Design A has a mutual capacitance of 0.3pF/mm higher than Design B, however, this value could be smaller in the real design because there is an additional layer of insulation. In addition, the high sensitivity of our design may minimise the influence of such interference. Hence, Design A is considered the optimal option because it allows for continuous monitoring of water levels below the reference level in this application.

VI. CONCLUSION

In this practical, we started by utilising MATLAB and FUSION to conduct simulations to determine the various factors that could impact the measurement accuracy. Subsequently, an internal water level measurement sensor was designed using an aluminium paper and a wooden plate. The results demonstrated that the designed sensor exhibited acceptable accuracy in measuring the water levels when the relative permittivity of water was unknown. However, this design has certain limitations. First, it cannot measure corrosive or hazardous liquids. Second, the sensor itself increases the actual water level, which must be carefully considered when the measurement aims to calculate the volume of water. Third, a reliable insulation layer is necessary when constructing the sensor, because a single leak point can potentially damage the sensor entirely.

Furthermore, our results indicate that slight changes in the dimensions of the sensor and thicknesses of the insulation tapes require different calibration offsets to correct readings. Therefore, periodic calibration is required for these sensors because the material may wear out over time, particularly when submerged in water. In conclusion, this practical experiment demonstrates that external interference with environmental variations can be reduced by using mathematical models and additional reference points. Future practical experiments can employ capacitance to build temperature, humidity, and other environmental monitoring sensors.

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