

Capacitive Sensing: Out-of-Phase Liquid Level Technique

David Wang

ABSTRACT

Various methods have been used to determine the level height in liquid tanks or containers. Recently, capacitive sensing has gained popularity due to the accuracy and resolution of the measurements as well as the simplicity, flexibility, and low cost of the sensor design. The sensors in a capacitive-based sensing system can be either in direct contact with the container (placed on its outside) or can be remote (a few cm away). The system design is also independent from environmental conditions such as temperature and humidity and can be made robust against external interferences. The conventional liquid level technique does have limitations with robustness since any external interference (for example – a human hand) causes capacitance drifts. An alternative approach to the conventional liquid level technique provides the necessary barrier to minimize any interference to maximum the signal-to-noise ratio and overall robustness of the system. This approach is referred to as the Out-of-Phase (OoP) technique. The OoP technique relies on a symmetrical sensor layout as well as using the shield drivers in a unique way to stabilize measurements. This application note discusses the use of TI's FDC1004 capacitive-to-digital converter with the OoP technique and how it can be implemented in various liquid level applications to improve performance versus the conventional approach.

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1 Conventional Liquid Level Sensing Approach

Liquid level sensing is based on the theory of a ratiometric measurement, using three sensors as shown in Figure 1:

1. LEVEL – The capacitance of the LEVEL electrode is proportional to the liquid height (h_w). It has to be as high as the maximum (MAX) allowed liquid level.
2. REFERENCE LIQUID (RL) – The REFERENCE liquid electrode accounts for the interval unit measurements of the LEVEL electrode. The liquid level has to be higher than the RL height in order to have a liquid and temperature independent measurement system.
3. REFERENCE ENVIRONMENT (RE) – A second (optional) reference electrode accounts for container properties. It has to be placed above the maximum (MAX) allowed level of liquid to track environmental factors and not the primary target (the liquid in the container).

A key aspect of this approach is that all three sensors are driven with the same excitation signal. Changes in the excitation signal due to changing capacitance are measured and used to calculate the corresponding liquid level.

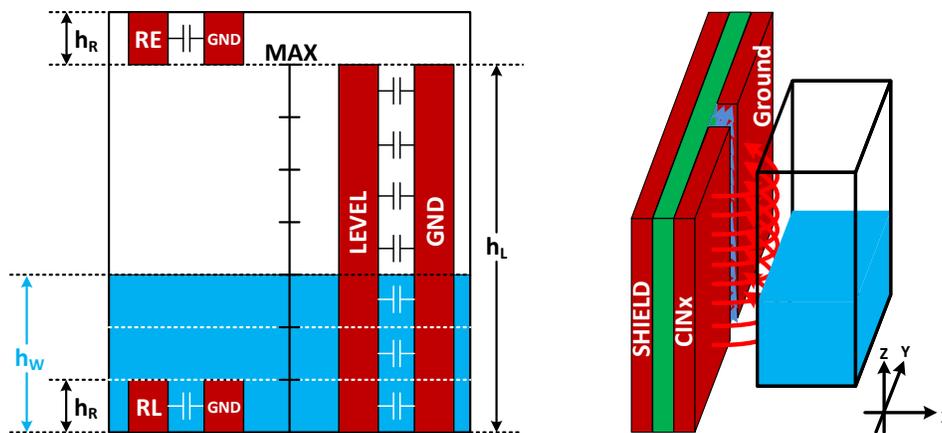


Figure 1. Ratiometric Measurement Setup

The working principle of the liquid level sensing involves measuring the fringing capacitance between the primary LEVEL electrode (CINx) and a ground (GND) electrode in the parallel fingers topology. The fringing capacitance becomes a function of the dielectric variation in the x-axis direction, and proportional to the liquid height, as given by Equation 1:

$$C_{\text{meas}} \propto h_w \epsilon_w + (h_L - h_w) \epsilon_a \quad (1)$$

Where:

- h_L = maximum height of the liquid
- h_w = height of liquid
- ϵ_w = dielectric of liquid
- ϵ_a = dielectric of air

To calculate the level of the liquid at any interval height, use Equation 2:

$$\text{Level} = h_{\text{RL}} \frac{C_{\text{level}} - C_{\text{level}}(0)}{C_{\text{RL}} - C_{\text{RE}}} \quad (2)$$

Where:

- h_{RL} = the unit height of the reference liquid sensor (often 1)
- C_{level} = capacitance of the LEVEL sensor
- $C_{\text{level}}(0)$ = capacitance of the LEVEL sensor when no liquid is present (empty)
- C_{RL} = capacitance of the REFERENCE liquid sensor
- C_{RE} = capacitance of the reference environmental sensor

NOTE: If RE is not used in the system, replace C_{RE} with $C_{\text{RL}}(0)$ in Equation 2.

Figure 1 also illustrates the use of a shield behind both electrodes, which focuses the sensing direction toward the liquid target and provides a barrier from any interference affecting the measurements from the backside. The FDC1004 features two dedicated shield drivers which can drive up to 400-pF capacitance each. The shield is driven with the same excitation signal as the other sensors. Because it is charged to the same potential as the other sensors, there is no electric field on the shield side of the sensors, so the only active field is in the direction of the liquid. The sensor size of RE should be the same size as RL so the measurements can be subtracted from one another. If the sensor sizes are not matched, a differential measurement cannot be performed since fringing capacitance is not linear/proportional to area size (unlike the parallel plate form).

Figure 2 illustrates an example of the capacitance of the LEVEL and REFERENCE electrodes based on the liquid level height. The capacitance of the LEVEL electrode (green line) increases linearly as the liquid level increases. Once the liquid level is above the h_R height, the RL capacitance saturates and becomes constant (blue line). The reference empty (red line) shows the behavior of the RE electrode and any change from environmental factors with this electrode can be used to eliminate the change seen on the level and RL electrode.

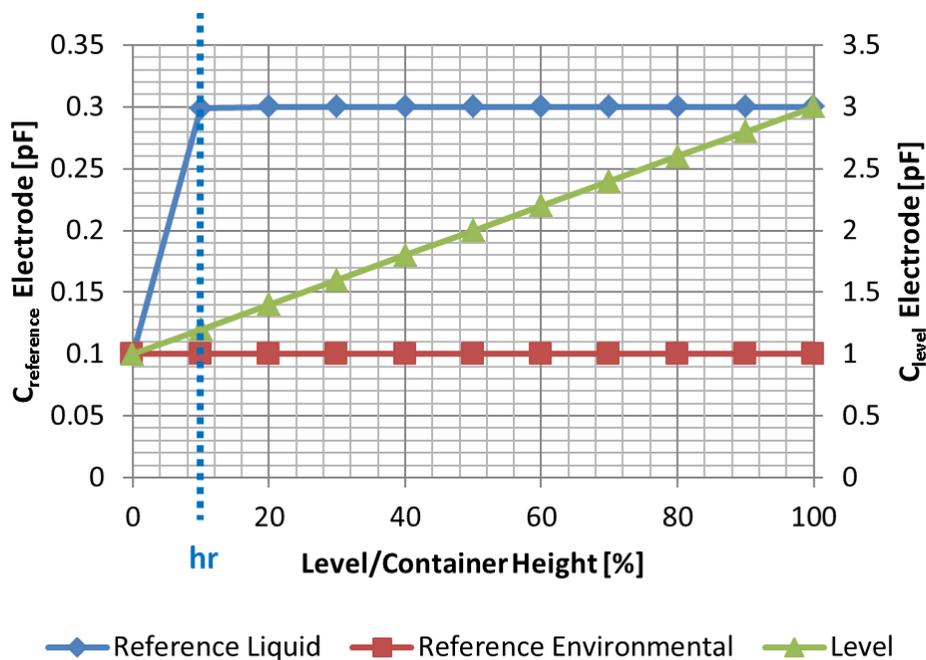


Figure 2. Capacitance Measurements for LEVEL, RL, and RE Electrodes

1.1 Gain and Offset Compensation

Even though the capacitance measurements are proportional to the liquid level height, the calculated level compared to the actual liquid level can vary dramatically. This is due to variations in the LEVEL, RL, and RE electrode capacitances for each liquid level interval. Gain and offset compensation, typical for the system-under-measure, is necessary in order to match the actual with the measured levels. A first-order linear correction algorithm (Equation 3) can be applied to compensation for the variations:

$$\text{Level}' = \text{Level} \times \text{Gain} + \text{Offset} \tag{3}$$

The FDC1004 allows gain and offset compensation-per-measurement and can be changed in real-time to adjust for system-environment conditions.

2 Problems with the Conventional Approach

The conventional approach of driving all the sensors and shield with the same excitation signal works well when the system is isolated from any external noise or interference, but any grounded interference or EMI causes significant deviations in capacitance measurements. These large changes caused by interference cannot be distinguished from small or large changes in liquid level, ultimately compromising the accuracy and reliability of the system.

The electrical model of the liquid level system contains the capacitance/resistance of the water and the capacitance of the container (shown in Figure 3) from the CINx (LEVEL) electrode to the GND electrode. The measured capacitance as liquid level increases should be linear. Once the human body presence (human hand) is in close proximity to the liquid source, an additional parasitic capacitance is introduced into the model and causes the potential difference due to the liquid to change relative to the absence of the hand. This potential difference corresponds to disturbances (as shown in the graph on the right in Figure 3) along the linear data plot. An alternative approach to mitigate this additional parasitic capacitance is the Out-of-Phase (OoP) technique.

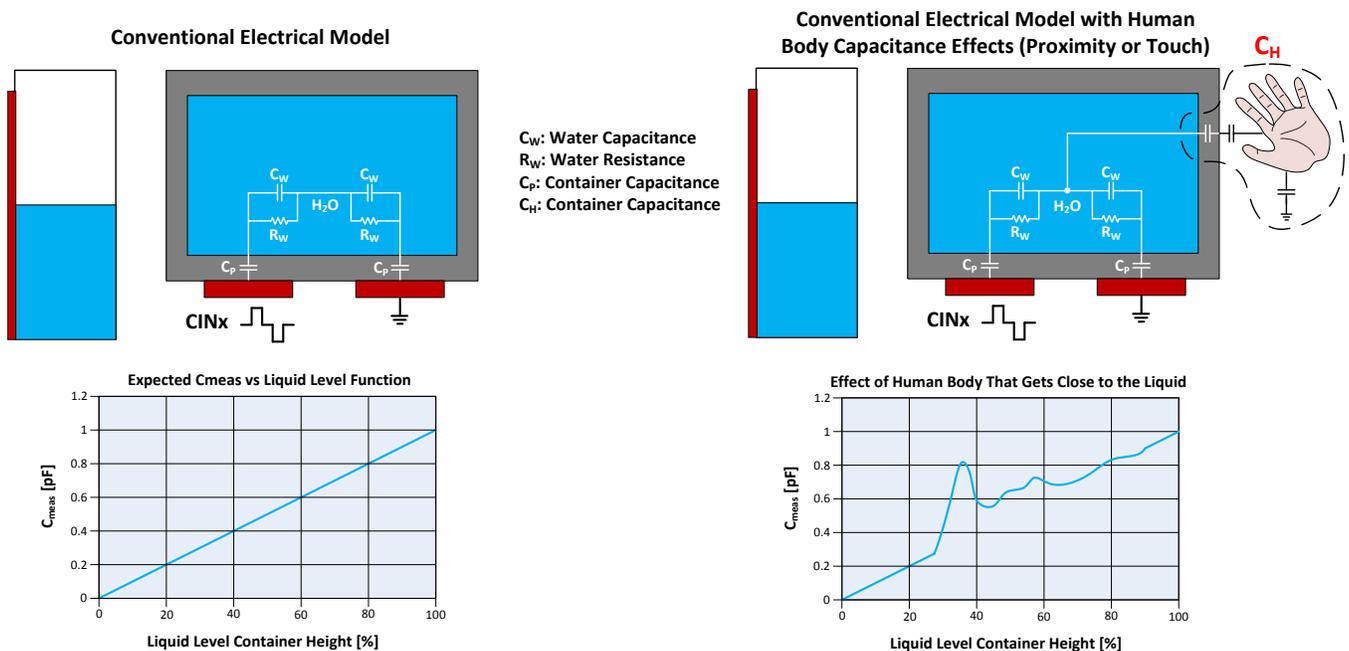


Figure 3. Comparison of the Conventional Electrical Model With and Without Human Body Presence

3 The Out-of-Phase Liquid Level Approach

3.1 Theory

The OoP technique relies on a symmetrical sensor layout as well as using the shield drivers in a unique way to counteract the effects of the human body capacitance and stabilize measurements. In the conventional approach, the liquid experiences a voltage potential difference to GND. In the OoP technique, the liquid potential is kept constant during the excitation/drive phases by using a differential capacitive measurement, thus eliminating the human body capacitance effects from the measurements.

Figure 4 shows the comparison of the conventional and OoP electrical model. The OoP technique takes advantage of the unique features of the FDC1004 to drive a CINx electrode and a SHLDy electrode in differential mode to make the voltage potential at node C_H fixed. The SHLDy electrode takes the place of the GND electrode and is actively driven. Specifically, the FDC1004 is configured for differential mode (CINx–CINy), for example CIN1–CIN4, in this case. By default, SHLD1 is in-phase with CIN1 and SHLD2 is in-phase with CIN4. Because CIN1 and CIN4 are 180 degrees out of phase with respect to each other, node CH is maintained at a constant potential. See the FDC1004 datasheet ([SNOSCY5](#)) for more information about differential mode configurations and how the shields are paired with the channels.

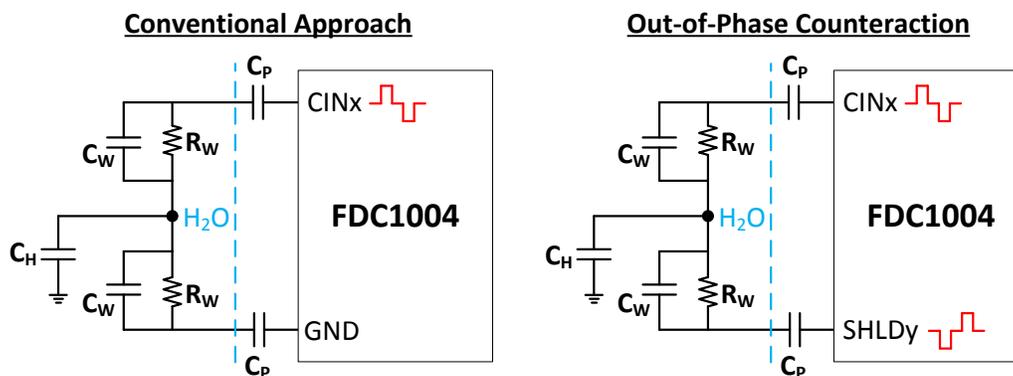


Figure 4. Comparison of Conventional Approach and OoP Electrical Model

3.2 Sensor Layout

The OoP technique is effective because the capacitance towards the liquid seen by the in-phase and the out-of-phase excitation/driver signal is the same. This approach relies heavily on symmetry of the channel and shield electrodes. If there is any mismatch, the liquid will not be at a constant potential. *Symmetry* is the key. Figure 5 shows the sensor layout that incorporates shield barriers on the backside of the electrodes. OoP works because the FDC1004 can be configured for differential mode. Most other capacitive-to-digital converters cannot be configured this way.

To implement the OoP method of liquid level sensing using the FDC1004, the following sensor assignments can be used:

- CIN1 – LEVEL electrode
- CIN2 – REFERENCE LIQUID electrode (RL)
- CIN4 – Floating, no electrode attached

FDC1004 measurements are configured as follows:

- Meas1 = CIN1 (CHA) – CIN4 (CHB). CIN1 is set as the positive input channel, and CIN4 is set as the negative input channel.
- Meas2 = CIN2 (CHA) – CIN4 (CHB). CIN2 is set as the positive input channel, and CIN4 is set as the negative input channel.

With Meas1 and Meas2 in differential mode, CIN1/2 is in-phase with SHLD1 and CIN4 is in-phase with SHLD2. CIN1/2 and CIN4 are out-of-phase by 180 degrees. The SHLD2 electrode adjacent to CHx needs to be shielded by another SHLD2 electrode adjacent to SHLD1 to match in-phase and out-of-phase excitation/drive symmetry, shown in Figure 5.

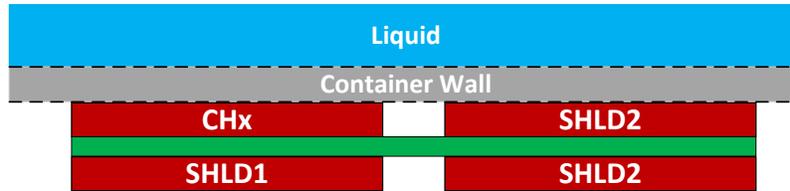


Figure 5. OoP Technique Sensor Layout for LEVEL and REF Sections

To allow further symmetry, SHLD1 and SHLD2 (furthest away from the liquid) are exactly the same size as the SHLDs for the LEVEL electrode (shown in Figure 6). SHLD1 and SHLD2 are shared between LEVEL and RL. Because the FDC1004 samples the capacitance channels sequentially, when it reads the capacitance for the LEVEL measurement, the RL electrode is floating but the SHLD1 and SHLD2 paired with the RL section are connected during the LEVEL measurement. Creating symmetry between the LEVEL and RL sections is as important as symmetry within each measurement section.

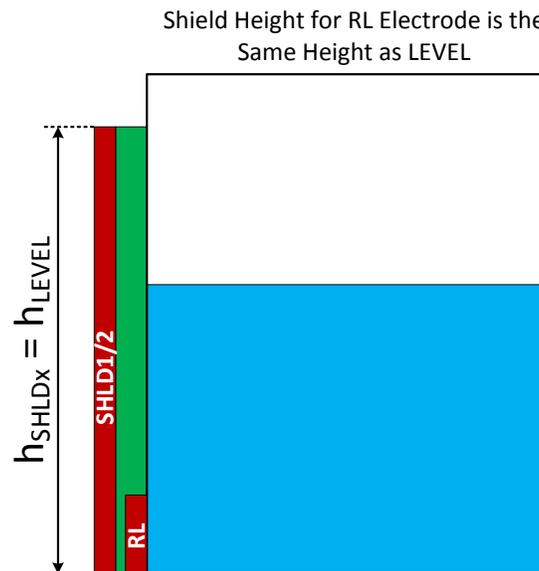


Figure 6. Side View of SHLD Electrode Height Compared to RL Electrode Height

4 Experimental Comparison

4.1 Test Setup

Two liquid level setups were compared experimentally: the conventional and OoP approach. The main focus of this experiment was to determine how much the human hand (in proximity or in contact with the container with liquid) affected capacitance measurements for the two methods. Both sensor layouts were attached to separate plastic rectangular containers (Figure 7 shows container used for the OoP method). The FDC1004 measurements were collected using the FDC1004EVM and EVM GUI. At specific liquid level heights, measurements were taken from the baseline condition (no hand interference). The measurements were then repeated by placing a hand at fixed distances away from the container, including touching the container. Both the LEVEL and RL (also referred to as REF) measurements were collected and the calculated level height and error from baseline conditions were computed (see Appendix A for measurement analysis). Water was used as the liquid to obtain the measurements.

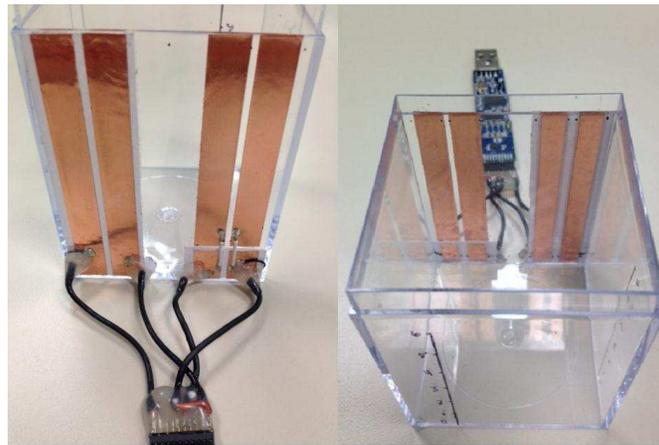


Figure 7. Test Setup for the OoP Technique

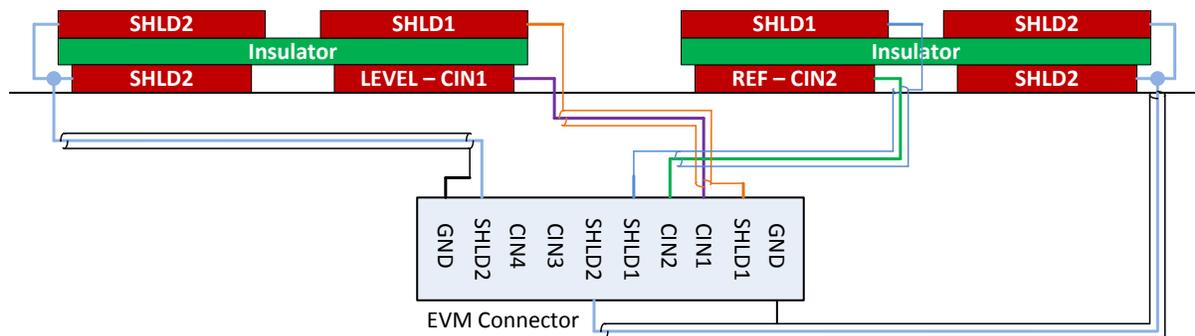


Figure 8. Sensor Layout and Connections to FDC1004EVM

4.2 FDC1004EVM GUI Setup

The FDC1004EVM was used to obtain the capacitance measurements to calculate the height of the liquid level. MEAS1 and MEAS2 were setup for differential mode (MEAS1 = CH1 – CH4, MEAS2 = CH2 – CH4).

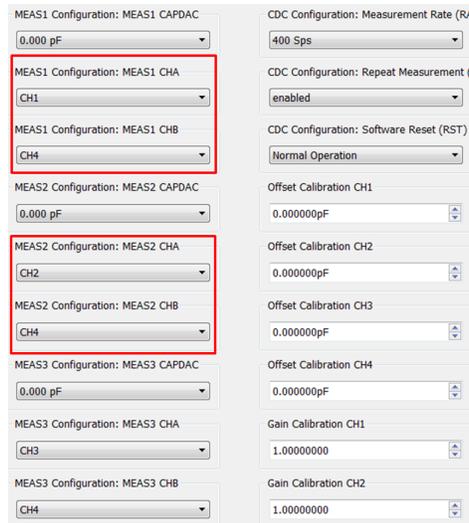


Figure 9. FDC1004EVM GUI Configuration Settings

NOTE: CDC configuration measurement rate and uC sampling rate can be changed based on the system requirements.

4.3 Results

4.3.1 Liquid Level Data

From the capacitance measurements seen in Table 2, the level height of the water was calculated using the level equation in Section 1. Figure 10 illustrates the difference in calculated levels from the actual levels. As the water level increases, the error in the calculated level gets significantly worse due to variations in LEVEL and REF capacitance for each level interval. A first-order linear correction algorithm was applied with a gain and offset setting of 1.23 and -0.6 , respectively. The green and blue plot in Figure 10 illustrates that the corrected levels matches the actual levels fairly well, compared to the original calculated level.

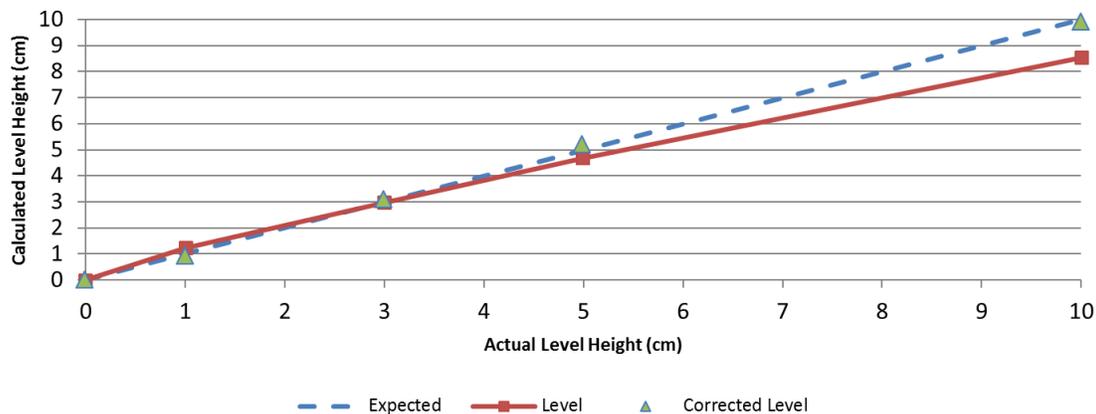


Figure 10. Level Calculation Comparison

4.3.2 Parasitic Capacitance Interference

The conventional method exhibited a maximum error of $\approx 11\%$ whereas the OoP method showed a maximum error of only $\approx 0.5\%$, which occurred when the water level was maximum. Table 1 shows the LEVEL measurements for the water level at 10 cm. The parasitic capacitance introduced by the human hand was reduced significantly.

Table 1. OoP and Conventional Liquid Level Technique Comparison

	Hand Distance (cm)	Change in Cap From Baseline (fF)		Calculated Level Error (%)	
		Conventional	OoP	Conventional	OoP
10-cm Water Level	5	157.5	0.7	-2.51	0.03
	4	180.3	0.8	-2.75	0.14
	3	218.5	1.7	-3.28	0.09
	2	275.7	1.3	-4.06	0.15
	1	380.0	1.6	-5.13	0.20
	0	1000.5	-1.3	10.34	0.50

4.3.3 System Considerations

Since the experimental setup was constructed using manually cut copper tape, it is possible to further reduce the error using more precise PCB layout rather than copper tape. Another variation from this setup that caused deviations in calculated level measurements compared to the expected level was matching the actual liquid level height to the expected level height when pouring the liquid into the container. The FDC1004 can detect changes in capacitance less than 1mm of height, so any variations above or below a level will be detected. A syringe can be used to accurately dispense the appropriate volume of water based on specific height intervals for experimental setup consistency.

NOTE: Water is the liquid used in this experiment. Liquids that cannot be used for liquid-level sensing include oil-based liquids, soap, or a liquid with a sticky or slick residue.

5 Conclusion

From the experimental data, the OoP method has a significant robustness advantage compared to the conventional method. With approximately 0.5% calculated error measurements from the OoP method, liquid level sensing applications are able to accurately determine the height of the liquid at a high resolution and confidence. Keeping the potential of the liquid constant allows the capacitance measurements to be undisturbed from external interference. The conventional approach is still a valid implementation if the system is isolated from any interference, but for most liquid level sensing applications, the OoP method is the optimal solution.

Liquid Level Approach

Table 2. Conventional Approach Experimental Result

		Conventional Liquid Level Approach							
		LEVEL MEAS			REF MEAS			Calculated Level (cm)	Error (%)
Water Level (cm)	Hand Distance	Capacitance (pF)	Change in Cap From Baseline (fF)	Error From Hand Based on Change in Water Level (%)	Capacitance (pF)	Change in Cap From Baseline (fF)	Error From Hand Based on Change in Water Level (%)		
0	Baseline	2.1712			1.0016				
	5cm	2.1781	6.9		1.0052	3.6			
	4cm	2.1797	8.5		1.0059	4.3			
	3cm	2.1807	9.5		1.0068	5.2			
	2cm	2.1823	11.1		1.0072	5.6			
	1cm	2.1843	13.1		1.0081	6.5			
	Touch	2.1898	18.6		1.0098	8.2			
1	Baseline	2.7135			1.3944			1.3806	0
	5cm	2.7424	28.9	5.3292	1.4152	20.8	5.2953	1.381	0.03
	4cm	2.7478	34.3	6.3249	1.419	24.6	6.2627	1.3814	0.06
	3cm	2.7537	40.2	7.4129	1.4232	28.8	7.332	1.3816	0.08
	2cm	2.7624	48.9	9.0171	1.4301	35.7	9.0886	1.3797	-0.07
	1cm	2.7784	64.9	11.9675	1.4421	47.7	12.1436	1.3784	-0.16
	Touch	2.8235	110	20.284	1.4777	83.3	21.2067	1.3701	-0.76
3	Baseline	3.5097			1.3987			3.3707	0
	5cm	3.5667	57	4.2585	1.4216	22.9	5.7668	3.3226	-1.43
	4cm	3.5768	67.1	5.0131	1.4254	26.7	6.7237	3.3167	-1.6
	3cm	3.5906	80.9	6.0441	1.4312	32.5	8.1843	3.304	-1.98
	2cm	3.6157	106	7.9193	1.441	42.3	10.6522	3.2874	-2.47
	1cm	3.6456	135.9	10.1532	1.453	54.3	13.6741	3.2663	-3.1
	Touch	3.8275	317.8	23.743	1.5279	129.2	32.5359	3.1471	-6.63
5	Baseline	4.2265			1.3878			5.3219	0
	5cm	4.3096	83.1	4.0432	1.4109	23.1	5.9814	5.2245	-1.83
	4cm	4.3271	100.6	4.8947	1.4155	27.7	7.1724	5.2087	-2.13
	3cm	4.3544	127.9	6.2229	1.4233	35.5	9.1921	5.1771	-2.72
	2cm	4.3873	160.8	7.8237	1.4326	44.8	11.6002	5.1418	-3.38
	1cm	4.4574	230.9	11.2344	1.452	64.2	16.6235	5.0759	-4.62
	Touch	4.7699	543.4	26.439	1.5381	150.3	38.9177	4.8438	-8.98
10	Baseline	5.9343			1.3859			9.7921	0
	5cm	6.0918	157.5	4.1854	1.4123	26.4	6.8696	9.5461	-2.51
	4cm	6.1146	180.3	4.7913	1.4157	29.8	7.7544	9.5228	-2.75
	3cm	6.1528	218.5	5.8064	1.422	36.1	9.3937	9.471	-3.28
	2cm	6.21	275.7	7.3264	1.4315	45.6	11.8657	9.3947	-4.06
	1cm	6.3143	380	10.0981	1.4476	61.7	16.0552	9.2895	-5.13
	Touch	6.9348	1000.5	26.5871	1.5442	158.3	41.1918	8.7792	-10.34

Table 3. OoP Approach Experimental Results

		OoP Liquid Level Approach							
		LEVEL MEAS			REF MEAS			Calculated Level (cm)	Error (%)
Water Level (cm)	Hand Distance	Capacitance (pF)	Change in Cap From Baseline (fF)	Error From Hand Based on Change in Water Level (%)	Capacitance (pF)	Change in Cap From Baseline (fF)	Error From Hand Based on Change in Water Level (%)		
0	Baseline	2.1615			0.625				
	5cm	2.1619	0.4		0.6251	0.1			
	4cm	2.1623	0.8		0.6252	0.2			
	3cm	2.1627	1.2		0.6256	0.6			
	2cm	2.1631	1.6		0.6257	0.7			
	1cm	2.1633	1.8		0.6259	0.9			
	Touch	2.1639	2.4		0.6263	1.3			
1	Baseline	2.7554			1.1113			1.2213	0
	5cm	2.7555	0.1	0.0168	1.1116	0.3	0.0617	1.2207	-0.04
	4cm	2.7558	0.4	0.0674	1.1123	1	0.2056	1.2196	-0.14
	3cm	2.7561	0.7	0.1179	1.1119	0.6	0.1234	1.2212	-0.01
	2cm	2.7564	1	0.1684	1.1119	0.6	0.1234	1.2218	0.04
	1cm	2.7564	1	0.1684	1.1123	1	0.2056	1.2208	-0.04
	Touch	2.7576	2.2	0.3704	1.1141	2.8	0.5758	1.2188	-0.2
3	Baseline	3.9345			1.2198			2.9808	0
	5cm	3.9344	-0.1	-0.0056	1.2201	0.3	0.0504	2.9792	-0.06
	4cm	3.9354	0.9	0.0508	1.2198	0	0	2.9823	0.05
	3cm	3.9364	1.9	0.1072	1.22	0.2	0.0336	2.983	0.07
	2cm	3.9363	1.8	0.1015	1.2201	0.3	0.0504	2.9824	0.05
	1cm	3.9373	2.8	0.1579	1.2206	0.8	0.1345	2.9815	0.02
	Touch	3.9393	4.8	0.2707	1.2208	1	0.1681	2.9839	0.1
5	Baseline	5.0393			1.24			4.6793	0
	5cm	5.0394	0.1	0.0035	1.2399	-0.1	-0.0163	4.6803	0.02
	4cm	5.0403	1	0.0347	1.2397	-0.3	-0.0488	4.6833	0.08
	3cm	5.0408	1.5	0.0521	1.2404	0.4	0.065	4.6787	-0.01
	2cm	5.0401	0.8	0.0278	1.2403	0.3	0.0488	4.6784	-0.02
	1cm	5.0409	1.6	0.0556	1.2394	-0.6	-0.0976	4.6865	0.15
	Touch	5.0417	2.4	0.0834	1.2386	-1.4	-0.2276	4.6939	0.31
10	Baseline	7.7165			1.2761			8.5317	0
	5cm	7.7172	0.7	0.0126	1.276	-0.1	-0.0154	8.5341	0.03
	4cm	7.7173	0.8	0.0144	1.2753	-0.8	-0.1229	8.5434	0.14
	3cm	7.7182	1.7	0.0306	1.2757	-0.4	-0.0614	8.5396	0.09
	2cm	7.7178	1.3	0.0234	1.2753	-0.8	-0.1229	8.5442	0.15
	1cm	7.7181	1.6	0.0288	1.275	-1.1	-0.1689	8.5486	0.2
	Touch	7.7152	-1.3	-0.0234	1.2727	-3.4	-0.5222	8.5745	0.5

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