

## Research Article

# Design and Implementation of SOC-Based Noncontact-Type Level Sensing for Conductive and Nonconductive Liquids

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In contrast to the existing electromechanical systems, the noncontact-type capacitive measurement allows for a chemically and mechanically isolated, continuous, and inherently wear-free measurement. Integration of the sensor directly into the container's wall offers considerable savings potential because of miniaturization and installation efforts. This paper presents the implementation of noncontact (NC)-type level sensing techniques utilizing the Programmable System on Chip (PSoC). The hardware system developed based on the PSoC microcontroller is interfaced with capacitive-based printed circuit board (PCB) strip. The designer has the choice of placing the sensors directly on the container or close to it. This sensor technology can measure both the conductive and nonconductive liquids with equal accuracy.

## 1. Introduction

Nowadays, all automotive vehicles are fitted with a fuel-level sensor. It measures the quantity of fuel left in the fuel tank. A fuel-level sensor is present in the fuel tank for a prolonged period and exposed to fuel, fuel additives, corrosive sulphur, methanol, and ethanol. So, manufacturers in the automobile industry need novel solutions for the longevity of fuel-level sensors. The novel solutions should also reduce cost, space, and weight and enhance the reliability of fuel sensors. The fuel-level sensor can sense numerous liquid in the automobile industry such as cooling water, windshield cleaning engine oil, and power steering fluid. The noninductive, capacitance-based sensor is capable of estimating the level of conducting as well as nonconducting fluids. The level sensor checks the fluid level in tanks. Level sensors quantify the fluid level at straight and bent states of fuel tanks. Recently, capacitive sensors have been used in many applications such as touch sensing, proximity detection systems, brake fluid

measurement, fuel-level measurement, engine oil measurement, and cooling water level. Capacitive sensor's advantages are higher sensitivity, lower mechanical stress, higher reliability, and lower impact on the temperature coefficients. Several methods are available to convert the capacitance into analog voltages. The popular techniques used in capacitance-to-analog voltage converters are transimpedance amplifier and an alternating current (AC) bridge with voltage amplifier. The limitations of these techniques are low sensitivity and nonidealities of the sensor. The low sensitivity in the interfacing circuit is due to ignoring the minimum change in the capacitance. The nonidealities are temperature, induced frequency, and switch noise. This paper discusses the current in the noncontact-type level measuring technique using System on Chip (SoC)-based approach.

The paper [1] discusses a noncontact fluid level measurement method. The resources used in the level sensor were enameled copper winding wire, acrylic bar, acrylic

pipes, and acrylic sheet. In paper [2], noncontact capacitance-type level sensors for conductive fluids are discussed. The paper [3] discusses the capacitive-based level sensor which is used in ingestion water circulation systems. The aquatic level sensor has been intended by multilayer pipes and is equivalent to a commercially existing ultrasound aquatic level sensor. The limitation is that it is a contact sensor. The paper [4] discusses the water level computation using the capacitive sensor with the printed circuit board (PCB). The paper [5] discusses the capacitive touch systems with styli consisting of the touch sensor, analog frontend integrated circuit, and microcontroller unit. The limitation is the degradation of the signal to noise ratio as the touch sensor is located far from the finger. The paper [6] presents an extensive review of the various types of sensors used in automobiles. The paper [7] discusses the multifunctional parallel-plate capacitor sensor with four electrodes. The level of the fluid is determined by sensing the values of the capacitance. Furthermore, the permittivity and angle of the fluid container are also estimated. The paper [8] presents a liquid-level sensor based on etched fiber Bragg grating (FBG). In this, an edge-emitting light emitting diode (LED) feeds aFBG which is partially in air and partially immersed in the liquid. The difference in the absorption spectra is used to measure the liquid level.

The paper [9] presents a liquid-level measurement system based on a remote grounded capacitive sensor. The sensor comes in direct contact with the liquid whose level is being measured, thus making it prone to degradation. The paper [10] discusses the development of a capacitive sensor for minute liquid droplet detection. It works on the principle of a change in dielectric constant between the plates of a parallel-plate capacitor driven by an AC voltage. However, the intended use of this sensor is in liquid dispensing systems. The paper [11] presents a measurement system that has been developed using a single-tube capacitive sensor to determine the fluid level in vehicular fuel tanks which addresses the effect of fuel sloshing due to vehicle acceleration. In our earlier article [12–16], high-performance reconfigurable architectures were proposed. The architecture discussed does not discuss the concept of SoC computing. The paper [17] discusses the development of a PCB-based capacitive pressure sensing system. The paper [18] presents a fiber optic liquid-level sensor based on a Mach-Zender optical interferometer. A major disadvantage of this system is that it works best at a temperature range of 20–40°C.

The paper [19] discusses the electrical model intended for noncontact capacitance-based liquid sensors to define liquid-level dependence. In paper [20], the authors designed a noncontact uniform circular cylinder-based capacitance-type level sensor for a conducting fluid made of insulating material. An improved linear operational amplifier with adjustable bridge sensitivity measures the variation in capacitance due to variation in the liquid level. The paper [21] discusses the signal conditioning circuit minimum parasitic capacitance for translating capacitance variation into frequency. The limitation of the transformer is that the circuit is not complementary metal-oxide-semiconductor (CMOS) compatible. The paper [22] discusses the method of

computing the error of fluid oxygen level-to-capacitance translation. In paper [23], the authors designed and fabricated a fluid level measurement structure created on a beached tubular capacitive sensor for conductive fluids. The structure is not capable to shield the potential of the extensive computing choice and high linearity. The paper [24] discusses the features of a paired spiral capacitance sensor for the quantity of the fluid theft in flat lubricant-aquatic dual-stage drift. The limitation of the paper is that it does not consider the edge protecting conductors to decrease the current. The paper [25] discusses a method established on a modest linear capacitor array, and it is capable of resolving differences of the solid fraction. The paper [26] presents a modified version of a noncontact capacitance level transducer for a conducting liquid explained in paper [7]. The paper [27] discusses the interfacing of a capacitive sensor with the common microcontroller Arduino. The paper [28] discusses the possibilities of using common off-the-shelf ultrasonic sensors for fuel-level sensing applications.

The paper [29] presents a noninvasive portable capacitive transducer for measuring fuel level of portable engines. Although the sensor itself is not in direct contact with the fuel, the measurement unit consists of three coated copper electrodes which are inside the fuel tank. The paper [30] discusses the optical fiber sensor established on silica spout configuration. The paper [31] discusses the optical fiber sensor for an instantaneous measure of fluid level and temperature. The sensor is designed by incorporating a no-core fiber and fiber Bragg raucous. The paper [32] discusses the capacitive sensor with an array of electrodes resembling to comb structure for fluid level measurement. The paper [33] discusses the Helmholtz resonance process to design a fluid level gauge using liquid hydrogen. The paper [34] discusses the fluid level measurement structure founded on energetic pipe pressure conventional for high-temperature corrosive molten salts. The paper [35] discusses the fluid level structure based on discrete wavelet packet multiresolution proportional integral (PI) controller.

In paper [36], the authors discuss the flexible liquid-level optical fiber sensing to measure the liquid level. In paper [37], the authors discuss the light guide plate-based optical liquid-level sensor. The paper [38] discusses the development of the capacitive fuel measurement sensor. The sensor comprises of two copper plates acting like a parallel-plate capacitor. The system detects a change in fluid level based on the change in capacitance. In paper [39], the authors designed an instrument for determining the liquid level. The instrument uses a multisensory model comprising a capacitive level sensor, ultrasonic level sensor, and capacitance pressure sensor to measure the liquid. The paper [40] discusses a fuel-level measurement model based on a single-tube cross-capacitance sensor. The disadvantage is that it is an immersible-type sensor, making it prone to quicker degradation. From the above literature review, it is evident that the implemented methodologies are predominantly contact-type sensing techniques. The limitations are that the liquid is to be immersed in the tube and a separate structure is needed to know the liquid level.

In this paper, we describe the development of a distant capacitive-type level sensor. The proposed sensor is fabricated using an easily available multilayer PCB. The sensor comprises a PCB configured with two coplanar probes. This paper focuses on the brake fluid level measurement in four-wheelers. The proposed methodology in this paper overcomes the limitation discussed in the literature. The flex PCB structure is to be mounted on the container wall. The capacitive-type fluid level measurement using a capacitive sensor is easy to assemble, costs less, more robust, high repeatability, high resolution, and easy to install. Using this methodology lowers the development cost of the sensor and related interfacing electronic circuits. This paper is organized as follows. Section 2 presents the proposed methodology and design resources. The capacitance modeling and analysis are presented in Section 3. Section 4 presents the design and implementation of capacitance liquid-level sensing. Section 5 presents the results and discussion. Finally, Section 6 presents the conclusion.

## 2. Proposed Methodology

This section discusses the methodology and hardware-software design resources for noncontact-type level sensing and their feasibility. The capacitor structural sensor is proposed in this paper. Fluid level is a significant parameter in the industrial evolutions. A noticeable substitute in the industrial automation is the capacitive level measurement in relative to mechanical structures. Capacitive fluid level sensors are conductive pads or dash pads placed on a nonconductive material such as plastic or glass or PCB. The intrinsic capacitance of the PCB dash pads is the parasitic capacitance ( $C_p$ ). Once the fluid moves towards the sensor, a small fluid capacitance ( $C_L$ ) is added to  $C_p$ . This is illustrated in Figure 1. Liquid-level sensing implies calculating the increased capacitance while water exists near the sensor.

The Programmable System on Chip (PSoC) 4 CapSense Element given in the PSoC Creator Integrated Development Environment (IDE) processes the capacitance through introducing a current into the sensor through a current Digital to Analog Converter (IDAC). A timer measures how long it takes the IDAC to charge the sensor's voltage to a reference voltage using a comparator.

**2.1. Parasitic Capacitance.** The parasitic capacitance ( $C_p$ ) is the undesirable capacitance present between chunks of an electronic circuit purely because they are located close to each other. The CapSense Element processes the total capacitance and addition of parasitic and fluid capacitance ( $C_{TOTAL} = C_p + C_L$ ) restricted by dynamic range. The bigger the  $C_p$ , the lesser the fluid slice of the entire signal. It reduces the system sensitivity in the presence of liquid hence increases the total system accuracy. The main components of parasitic capacitance in CapSense designs are sensor capacitance and dash capacitance. The sensor dimensions are increased by increasing the in-dash measurement and reducing the annular gap. However, it leads to more  $C_p$  value. The technique that decreases the  $C_p$  value and declines the

noise immunity is to broaden the gap between the sensor and the ground.

**2.2. Mechanical Variations.** Mechanical variations within the system can take many forms to change the sensor's  $C_p$ . There are two types of mechanical variations.

- (1) Motionless disparity is usually generated through developed tolerances in the sensor assembly, PCB, and sensor arrangement towards the fluid container. Static variations, if understood and controlled, are compensated during manufacturing with the baseline calibration operation.
- (2) Dynamic variation is caused during operation. These changes often manifest themselves as changes to  $C_p$  by changing the sensor's capacitor dimensions. Unlike temperature changes, dynamic variation is difficult to compensate. It is the best to design the system to minimize dynamic-mechanical variation effects on the sensors.

The most common mechanical variation encountered is a change in the distance between capacitor plates, where the first plate is the sensor and the second plate is the liquid surface. It is triggered through air-bubbles present in the adhesive. The adhesive attaches the sensors to the container—the air-bubbles propagate and shrink through air pressure. Another cause is when the sensors are not directly attached to the liquid container allowing a changing air gap between the sensor substrate and the container wall. These effects are reduced by eliminating air-bubbles; hence, the mechanical design is adequate to sustain precise sensor arrangement.

**2.3. Temperature Effects.** Temperature variations during maneuvers have a substantial effect on performance. Compensation for temperature deviation is addressed through augmented sensor designs. A small isolating air gap should exist between the fluid basin and the sensor substrate.

**2.4. Capacitive Level Measurement.** Even though capacitive level sensing is a familiar technique, it is not used in automotive applications because of its sensitivity to the conductivity of the fluid and variations in dielectric constant. Contemporary development in capacitive level sensing such as smart capacitive organization with reparation of the side effects and emergent processor power in the sensors makes use in automobile applications.

**2.5. Capacitive Sensor Section.** The capacitive sensor section consists of the fixed capacitor on a typical PCB intended to measure the fuel level. The design arrangement of the capacitive sensors is distinct. The inclination of the fluid is determined using differential capacitive measurement. PSoC 4200 is used as the target device to implement the non-contact-type level sensing. The PSoC-4 device with CapSense circuitry (CY8CKIT-042) is interfaced with capacitive sensors. It senses the deviation in the capacitance in the

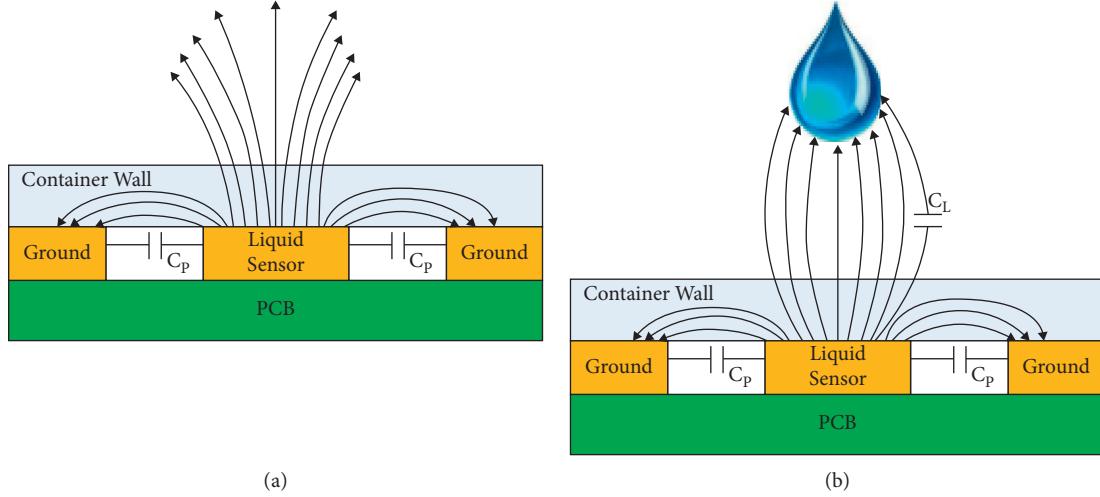


FIGURE 1: (a) Capacitive level sensor. (b) Extra capacitance once fluid approaches the sensor.

container. It also calculates the liquid level based on the capacitance variations of the sensors in the CapSense block shown in Figure 2. Figure 3 shows the system-level diagram.

### 3. Capacitance Modeling

This section describes the implementation of a five-segment capacitance linear slider. The linear capacitance sensor debugs data and positions the slider on a PC using the CapSense embedded tuner Graphical User Interface (GUI) via I<sub>2</sub>C communication. The CapSense tuner provides a quick and easy method for monitoring and updating capacitance linear slider parameters.

**3.1. CapSense Component.** This section demonstrates the functionality of the CapSense component. Figure 4 shows the PSoC top design and pins mapping diagram of the capacitive linear slider. The capacitive linear slider uses CapSense and EZI2C Slave modules.

**3.2. Firmware.** After building and installing the project in CY8CKIT-042, launch the Tuner Graphical User Interface (GUI) and then right-click the CapSense Component and select launch tuner in the menu to configure it as an analog channel. The analog channel gets the raw count of the capacitance shown in Figure 5. Figures 6 and 7 show the firmware flowchart and the circuit diagram of CapSense block.

The proposed work uses the smart sense (Full Auto-Tune) tuning method to implement a linear slider. The EZI2C slave is used to display the sensor information and slider touch position statistics on a PC using the CapSense tuner in the PSoC Creator IDE via Inter-Integrated Circuit (I<sub>2</sub>C).

The current through the resistor is measured and converted to equivalent voltage using a current to voltage rectifier. The capacitance of the sensor is incremented when the touch is recognized. The increments in capacitance of the

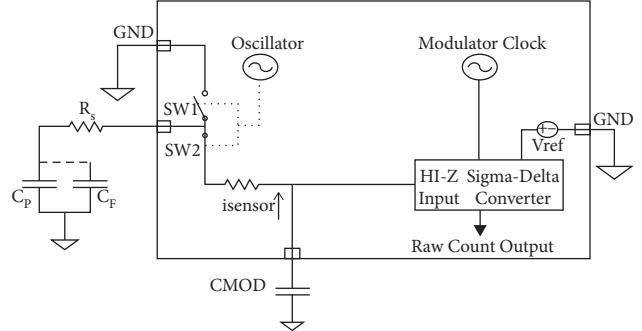


FIGURE 2: CapSense block diagram.

sensor also increment the current through the resistor. The CapSense block adjusts by controlling the modulation and frequency of the oscillator which results in an increase in voltage between the resistors.

### 4. Design and Implementation

This section presents the design and demonstration of capacitance liquid-level sensing. The linear sensor capacitance debugs and positions the data and liquid using the inbuilt CapSense tuner on a PC as a friendly GUI via universal asynchronous receiver-transmitter (UART) communication. This CapSense tuner GUI gives the observer a predictive method for validating and calibration of capacitance parameters.

**4.1. Design.** The design spark schematic tool draws the logical design and drives the PCB design. However, the PCB drawing tool is used without importing the layout schematic. The PCB design produces the productional data and the final assembled PCB. Design Spark generates the Geber files, and generated Geber files are directly sent to the manufacturer. From this Gerber data, the EMS providers can produce the final physical PCBs. A capacitive sensor built utilizing distinctive materials relies upon the prerequisite and

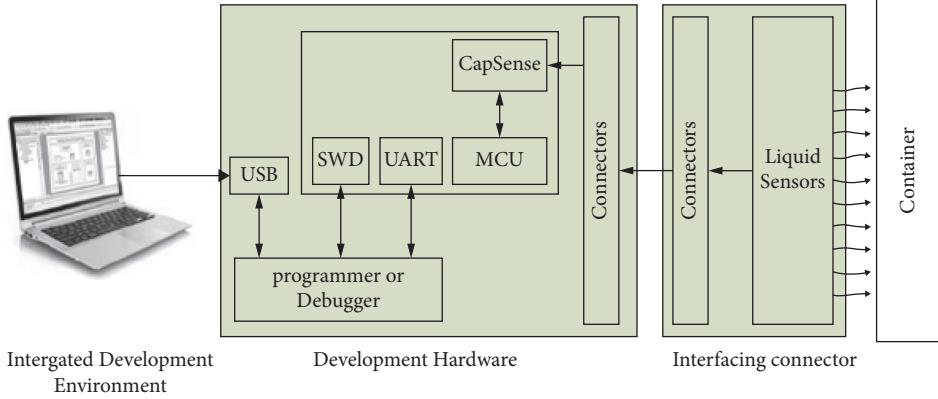
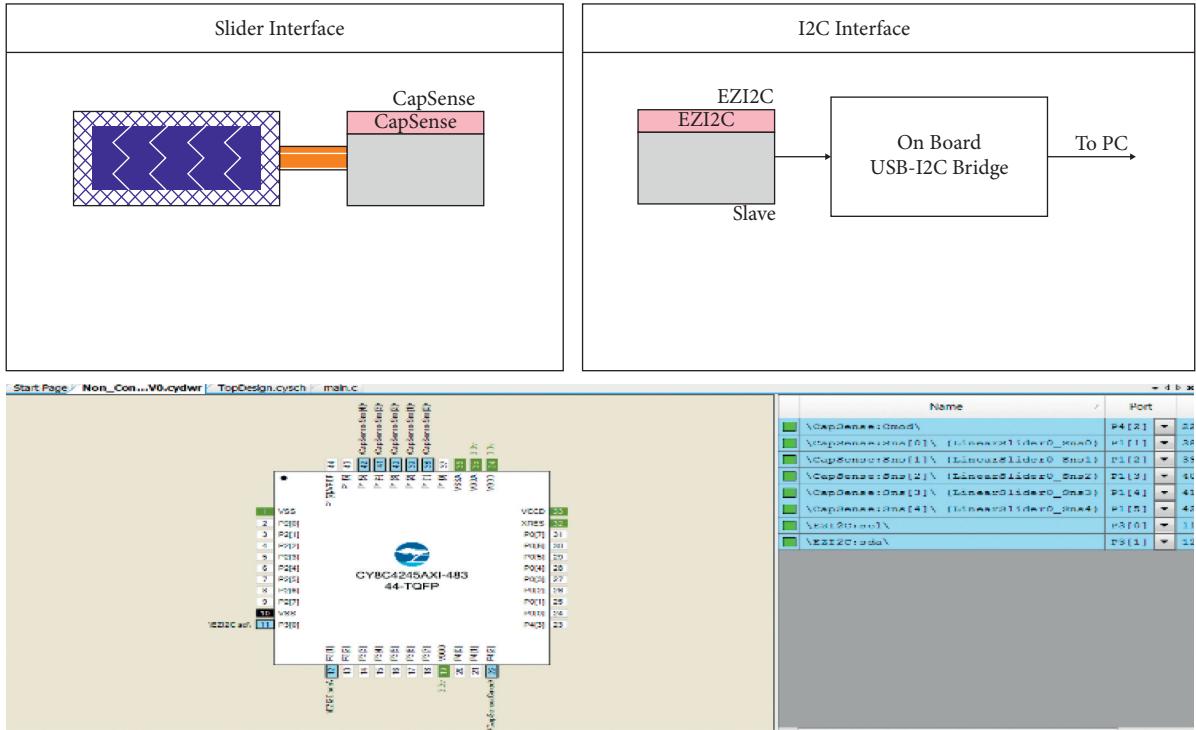


FIGURE 3: System-level diagram.



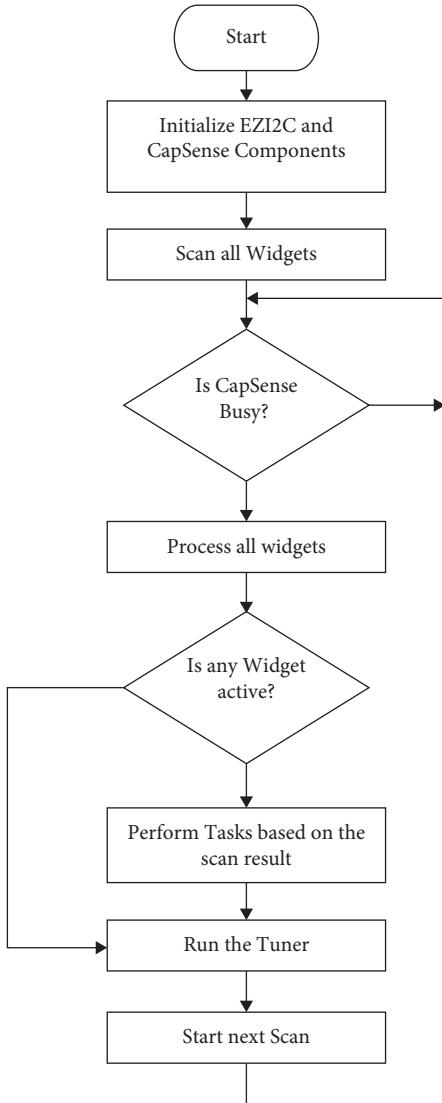


FIGURE 6: Firmware flowchart.

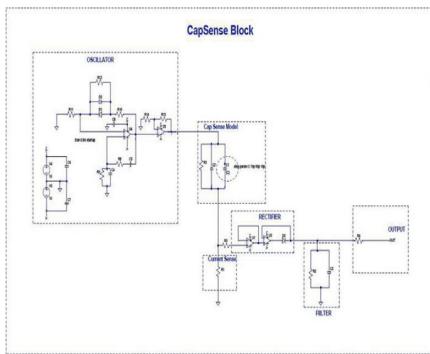


FIGURE 7: Circuit diagram of CapSense block.

Table 1. Materials with dielectric steady somewhere in the range of 2.0 and 8.0 are appropriate for capacitive detecting applications. The conductive material cannot be fit as an overlay substrate due to its impedance. Consequently, we should not utilize paints that contain metal particles in the

TABLE 1: Dielectric constants of insulation materials.

Material	Dielectric constant
Air	1.0
Formica	4.6–4.9
Glass (standard)	7.6–8.0
Glass (ceramic)	6.0
Pet film (mylar)	3.2
Polycarbonate (lexan)	2.9–3.0
Acrylic (plexiglass)	2.8
ABS	2.4–4.1
Wood table	1.2–2.5
Gypsum	2.5–6.0

overlay. Sensitivity is reciprocally dependent on the thickness of overlay material, as illustrated in Figure 8. Overlay materials should have reasonable mechanical contact to the PCB sensor. This can be accomplished utilizing a 3M type nonconductive sort adhesive film. This increases the sensitivity of the system by taking out any air gaps in the middle of the overlay and the sensor pads.

**4.3. Sensor PCB Design.** The sensor terminals have been planned with geometrical parameters chosen for a sufficient sensitivity. The PCB is structured utilizing Design Spark. Figures 9 and 10 show the sensor PCB and sensor pattern, respectively. The PCB is manufactured by an external vendor, with the parameters shown in Table 2. Figure 11 shows the fabricated PCB. The designed sensor is further fabricated and tested by using the high precision LCR meter. The designed PCBs have a parasitic capacitance of  $\sim 37$  pF (with overlay). The capacitance can change depending on the medium and can go up to  $\sim 200$  pF considering the human hand as a reference to determine the max effective capacitance. Each PCB exhibits different capacitance based on their properties and overlay materials. So, it is required to determine the capacitance thresholds of the designed sensor. Initially, it is measured using a high-resolution LCR meter. The maximum capacitance is determined by having a human hand placed proximity to the sensor. The measurement desk appears in Figure 12. The designed sensor is interfaced to Cypress PSoC4 dev kit using the interfacing card. The interfaced card has the impedance matching resistors of 560 ohms in each sensor lines. The connector pin layout is made that can be easy to interface. Figure 13 shows the connector layout of the sensor. The designed sensor is interfaced with Cypress PSoC 4 dev kit using the interfacing card. The connector pin layout is made that can be easy to interface.

**4.4. Measurement and Calibration.** The noncontact-type fluid level system arrangement consists of four segments. Figure 14 shows the diagram of a fluid level system. The device under-test (DUT) consists of a sensor, interfacing card, and PSoC 4. The sensor input is directly integrated into the container's wall that offers a considerable savings potential in terms of miniaturization and installation efforts. The output is taken from PSoC 4. The PSoC 4 is a

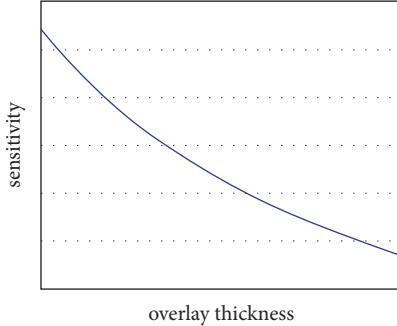


FIGURE 8: Sensitivity vs. overlay thickness.



FIGURE 9: Sensor PCB.

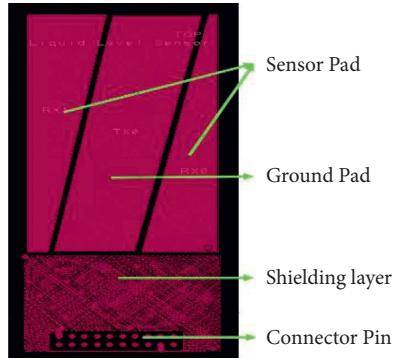


FIGURE 10: Sensor pattern.

TABLE 2: Dielectric constants of insulation materials.

PCB material	FR4
Thickness	0.4 mm
Type of pouring	Copper
Dimensions	100 * 50 mm
Connector type	Berg stick

programmable embedded system on chip, integrating custom analog and digital peripheral functions, memory, and an Arm Cortex-M0 microcontroller on a single chip. Figure 15 demonstrates the usage procedure and estimation. The personal computer (PC) is associated with the PSoC development board, PSoC creator 4.1, and Tera Term Terminal. The PC with the PSoC 4 microcontroller (PSoC 4200M) dev platform uses the PSoC debugger connected to USB interface. The test code is transferred to the microcontroller unit (MCU) by the PSoC Creator 4.1. The information from the MCU is displayed in Tera Term window at serial communication (COM2) port. The sensor is placed on a nonconductive surface in association with the PSoC 4200M

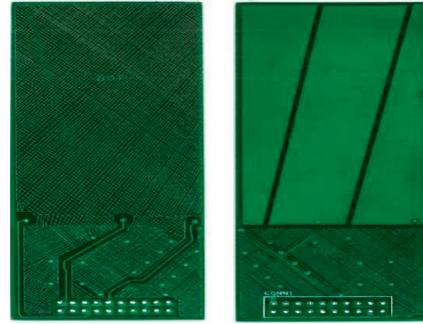


FIGURE 11: Fabricated PCB.

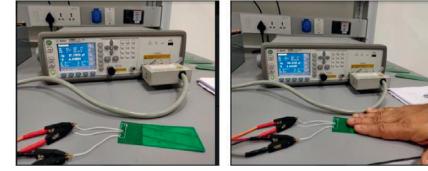


FIGURE 12: Capacitance measurement by the LCR meter.

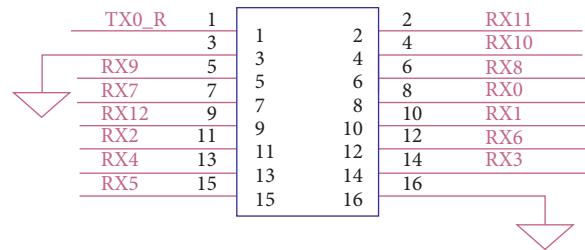


FIGURE 13: Connector layout of sensor.

development board, which utilizes a berg stick connector on another small interfacing board. The estimation results perused at various levels of the Department of Transportation (DOT4) type brake liquid segment from the base: zero levels with the base unfilled, 10 mm (similar tallness of the reflected light (RL) sensor), 15 mm, and 20 mm. The dimension is estimated at most extreme 70 mm.

## 5. Result and Discussion

The oscillator block provides the reference frequency for capacitance detection. Figures 16 and 17 show the tuner widget view and tuner graph, respectively. A simulation is carried out to sense the capacitance ranging from 10 pF to 50 pF in the step size of 10 pF. Figure 18 shows the oscillator frequency. Figures 19–21 show the CapSense-simulation. As the frequency varies with capacitance, the current across the sense resistor also varies. Figure 19 shows the current sense-capacitance variation from 10 pF to 50 pF. The sensed current is fed to the sigma-delta converter of PSoC. The behavior of capacitance vs. current is analyzed implementing a hardware rectifier and filter. It will rectify the frequency output of the current sense to the direct current

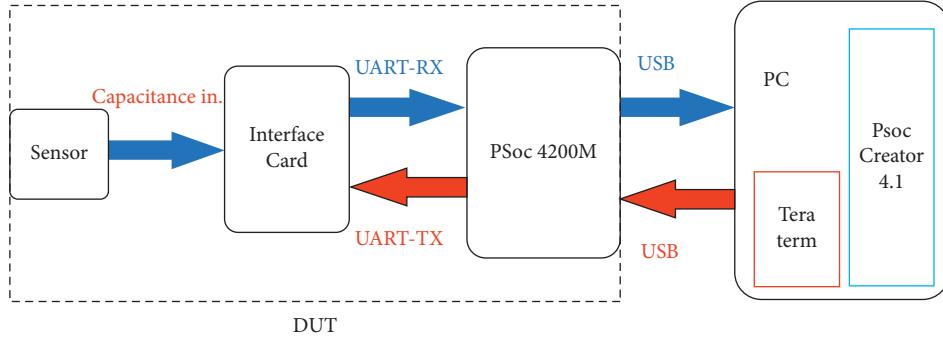


FIGURE 14: Measurement diagram for the fluid level system.

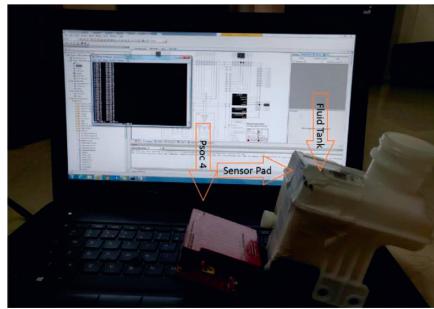


FIGURE 15: Device under-test-measurement setup.

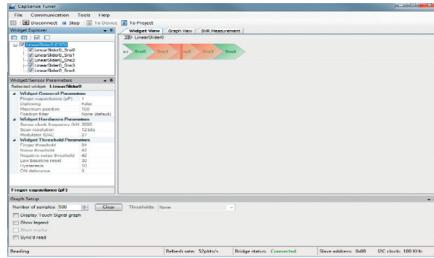


FIGURE 16: Tuner widget view.

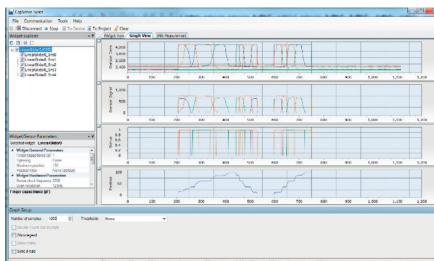


FIGURE 17: Tuner graph view.

(DC) component. Figure 20 shows the output voltage after rectification of the concerned current. This voltage values can be directly fed to any microcontroller using analog-to-digital converters (ADCs) of higher resolution. Figure 21 shows the rectification based on the peak voltage.

The PSoC 4 development board is configured for capacitance measurement. The measured capacitance values are read directly from the PSoC 4 board by using the Tera

Term Terminal. The PSoC development board measures the difference in capacitance between the two sensor pads as raw counts. The change in parasitic capacitance of the sensor is avoided through proper shielding employed on the sensor. Figure 22 shows the linearity of the sensor. The measured capacitance values are read directly from the PSoC 4 board by using Tera Term terminal. The level capacitance is increased with the increase in the fluid level from bottom of the

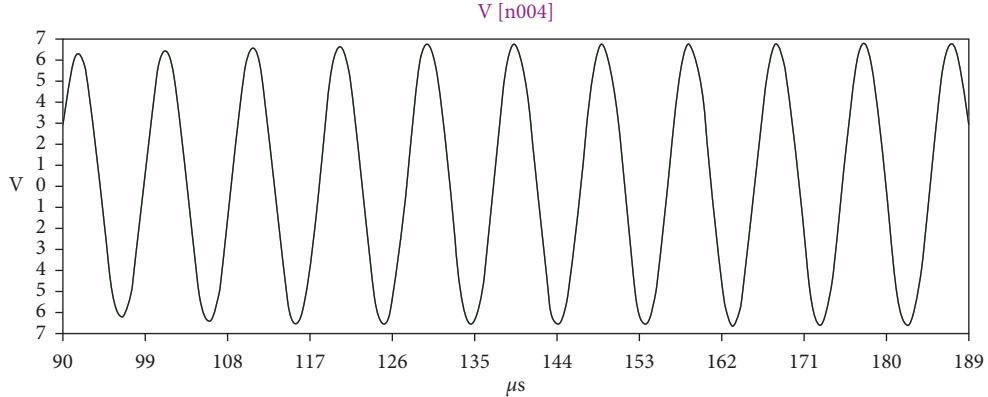


FIGURE 18: Oscillator frequency output-100 kHz.

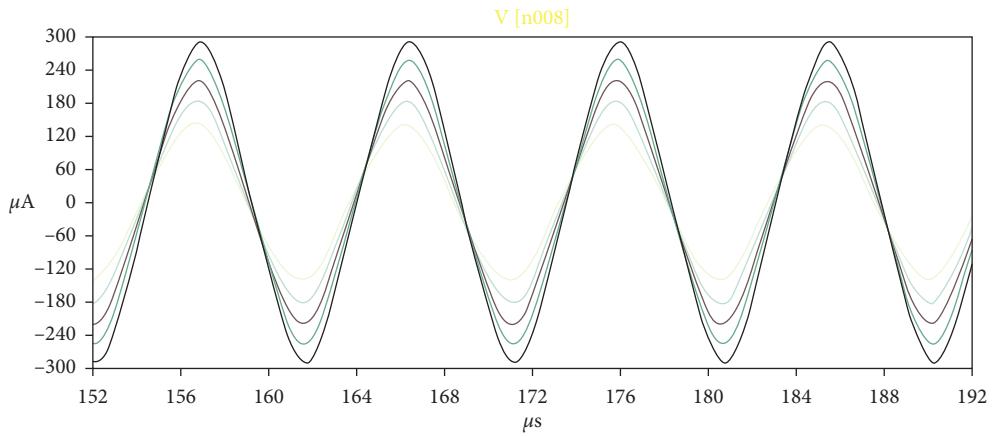


FIGURE 19: Current sense-capacitance varied from 10 pF to 50 pF.

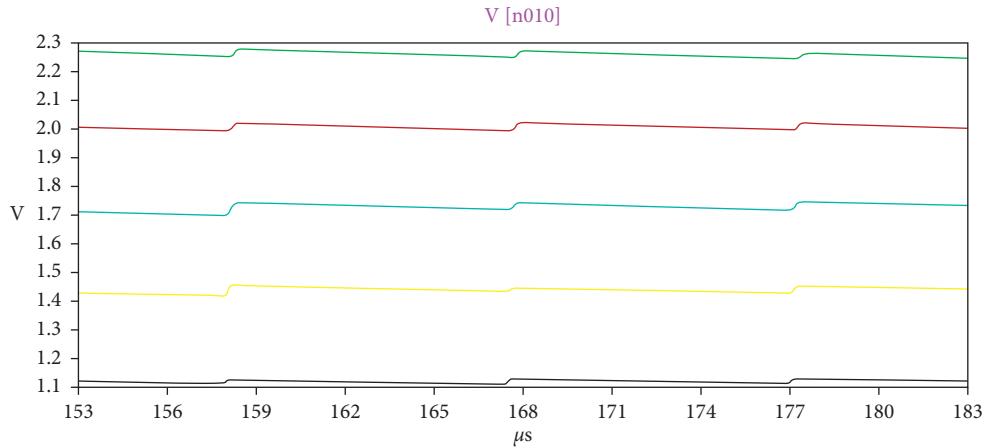


FIGURE 20: Current to rectified voltage output.

tank. The prominent change in parasitic capacitance of the sensor is eliminated by having proper shielding employed on the sensor. The solution for reducing the temperature effects on the capacitance is attained by designing the sensor based on Flexi PCB and maintains minimum connection length as possible. Level sensors are spearheaded in checking the fluid level in tanks and are utilized in numerous applications. The development model of a distant capacitive-type level sensor

is a low cost measurement method and can be deployed with different types of liquids. The model is used for both conductive and nonconductive liquid-level measurement. The model may be used in several applications because of its structure strategy and process approach. The applications are proximity detection, touch buttons, irrigation, biomedical area, pharmaceutical industry, and automation application. The proposed capacitive sort sensor is

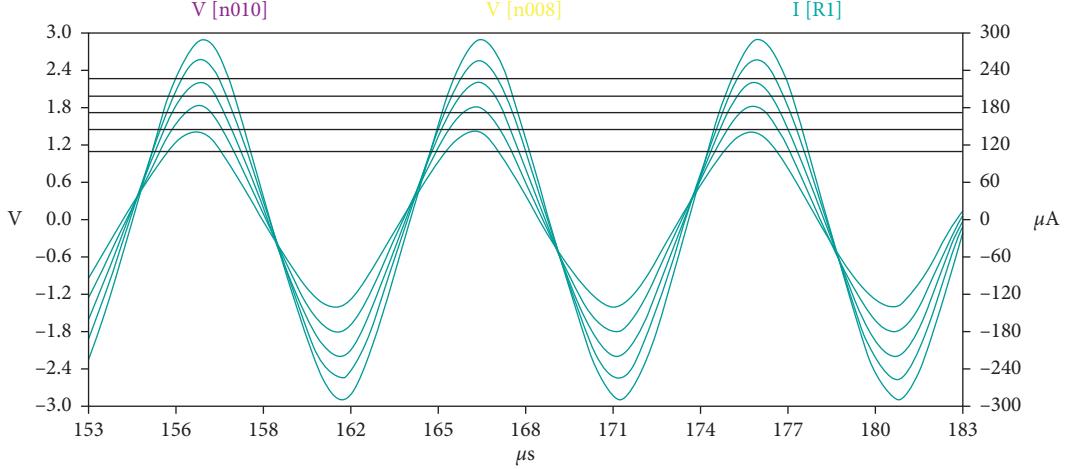


FIGURE 21: Rectification based on the peak voltage.

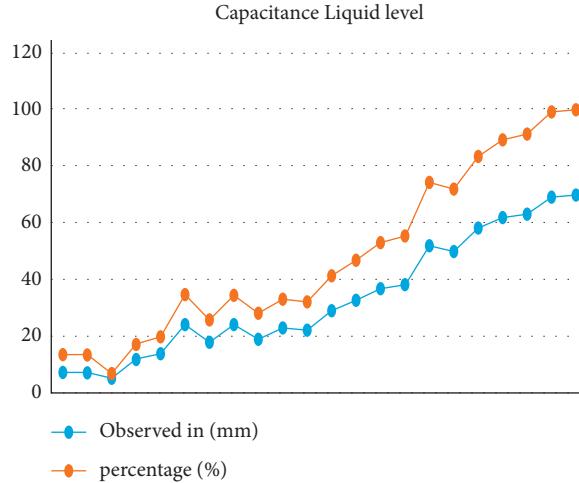


FIGURE 22: Sensor linearity.

TABLE 3: Measurements at various temperatures.

Temperature in degree	Fluid level (brake fluid)			
	Observed (mm) @40 mm	Observed (mm) @50 mm	Observed (mm) @60 mm	Observed (mm) @70 mm
0	0	27.8	27.8	13.9
5	13.7	41.7	55.6	55.6
10	27.8	48.6	62.5	62.5
20	34.7	48.6	62.5	76.4
22.81	34.7	48.6	62.5	76.4
30	34.7	48.6	62.5	76.4

manufactured utilizing generally accessible multilayer PCB. In this manner, the generation cost and the related interfacing electronic circuits are nearly less.

**5.1. Temperature Tests.** One of the main complexities for designing the sensor is to compensate for the temperature and humidity effects. The sensor is made using two coplanar

sensor pads and a ground pad in between and to take the resultant capacitance difference. So, the sensor ability is verified through the temperature tests performed (0°C to 60°C—limitation in temperature due to the development board thresholds), and the results are shown in Table 3. Figure 23 shows the temperature and fluid level. As the temperature increased, the fluid level increased, and above 20°C, the fluid level gets saturated with respect to

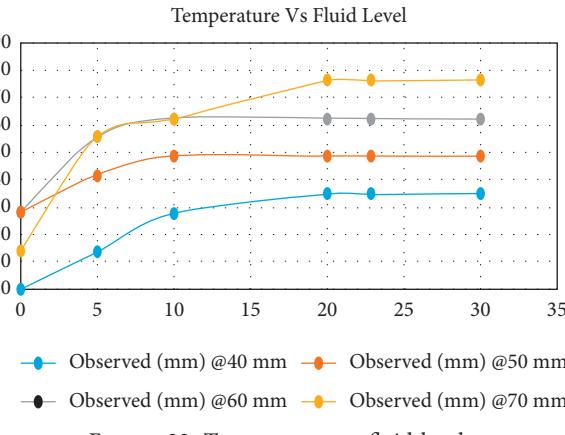


FIGURE 23: Temperature vs. fluid level.

temperature. The solution to reduce the temperature effects on the capacitance is by designing the sensor based on flexi PCB and maintaining minimum connection length as possible.

## 6. Conclusion

Capacitive-type sensors are essential for monitoring the level of the liquid. In this paper, development of a capacitive-type linear slider and a capacitive-type touch and noncontact sensor has been demonstrated using PSoC development kit which has inbuilt CapSense component for capacitance measurement and EZI2C/UART for communication to PC. The performance of the capacitive sensor design improves the reliability. The reliability is enhanced due to the decrease in corrosion of metallic electrodes due to noncontact with the fluid. The performance of the proposed sensor on the development board for touch and proximity has been experimentally evaluated. The proposed methodology includes liquid-level sensor development, interfacing the sensor to a digital data-acquisition system and testing.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that there are no conflicts of interest.

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