Application Note

AN000596

PCap04

Fill Level Sensing

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Content Guide

1 Introduction

Fill level measurements can be useful in many applications. Conventional fill level sensors are often based on floating potentiometers. They are mechanically relatively complicated and therefor expensive. A capacitive sensor can give many benefits in the application. No moving parts are necessary anymore.

This application note describes how the capacitive sensing method can be used for fill level applications. This gives a basic understanding about capacitance and the most important influences. Capacitive fill level measurements can be challenging. PCap04 can provide many solutions here. How this can be done will be also part of this document.

PCap04 is a capacitance-to-digital converter (CDC) with integrated digital signal processor (DSP) for on-chip data post-processing. Its front end is based on **ams** PICOCAP principle. This conversion principle offers outstanding flexibility with respect to power consumption, resolution and speed. Further, PCap04 covers a wide capacitance input range from a few femtofarads up to several hundreds of nanofarads. It is easy to configure the PCap04 for different capacitance measurement tasks, i.e. single as well as differential sensors in both, grounded or floating connection. The on-chip DSP allows to implement sensor algorithms like linearization and temperature compensation, with data output in a digital (SPI or IIC) or analog (PDM/PWM) way.

Figure 1:
Added Value of Using PCap04

Benefits	Features
High Flexibility: Easy adaption to various applications – ultra low power, high resolution or high speed – just by configuration.	Up to 6 capacitors grounded, 3 capacitors floating. Capacitive range 1 pF to 100 nF Internal reference 1 pF to 31 pF Integrated guard driver
High resolution or high speed	Up to 8 aF at 2.5 Hz and 10 pF base capacitance Up to 50 kHz sample rate Up to 20-bit resolution
On-chip DSP for sensor algorithms, signal post-processing including linearization and temperature compensation	32-bit DSP 3 k ROM code, 1 k NVRAM 96 x 32 bit RAM SPI/IIC interface PDM/PWM outputs, GPIO

Benefits	Features
On-chip and external temperature measurement capability	Supply voltage 2.1/3.0 V to 3.6 V Operating current down to 3 µA PCap04-Bxxx -40 °C to 85 °C PCap04-Axxx -40 °C to 125 °C QFN24 or die (1.588 mm x 1.46 mm)

2 Ordering Information

Figure 2:
Ordering Information

Ordering Code	Package	Marking	Delivery Form	Delivery Quantity
PCap04-AQFT-24	QFN24	PCAP04 AQF V1 YYWWXZZ	13” Tape & Reel in dry pack	6000 pcs/reel
PCap04-AQFM-24			7” Tape & Reel in dry pack	1000 pcs/reel
PCap04-BQFT-24	QFN24	PCAP04 BQF V1 YYWWXZZ	13” Tape & Reel in dry pack	6000 pcs/reel
PCap04-BQFM-24			7” Tape & Reel in dry pack	1000 pcs/reel
PCap04-ASWB	n.a	n.a	Sorted wafer in box	1 wafer = ~ 10000 die
PCap04-ASDF	n.a	n.a	Sorted wafer on blue foil	1 wafer = ~ 10000 die
PCap04-BSWB	n.a	n.a	Sorted wafer in box	1 wafer = ~ 10000 die

Eval Kit Ordering Code	Description
PCAP04-EVA-KIT	PCap04 Eval Kit Standard Board

3 Capacitance Basics

Figure 3:
Parallel Plate Capacitor Model

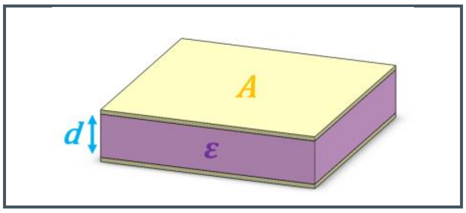


Figure 4:
Parallel Plate Capacitor Equation

$$C = \varepsilon \frac{A}{d}$$

$$\varepsilon = \varepsilon_r \varepsilon_0$$

A = capacitator surface area
d = distance between plates
ε_r = relative permittivity (~1 for air)
ε_0 = permittivity of vacuum $8{,}854 * 10^{-12}$ As/Vm

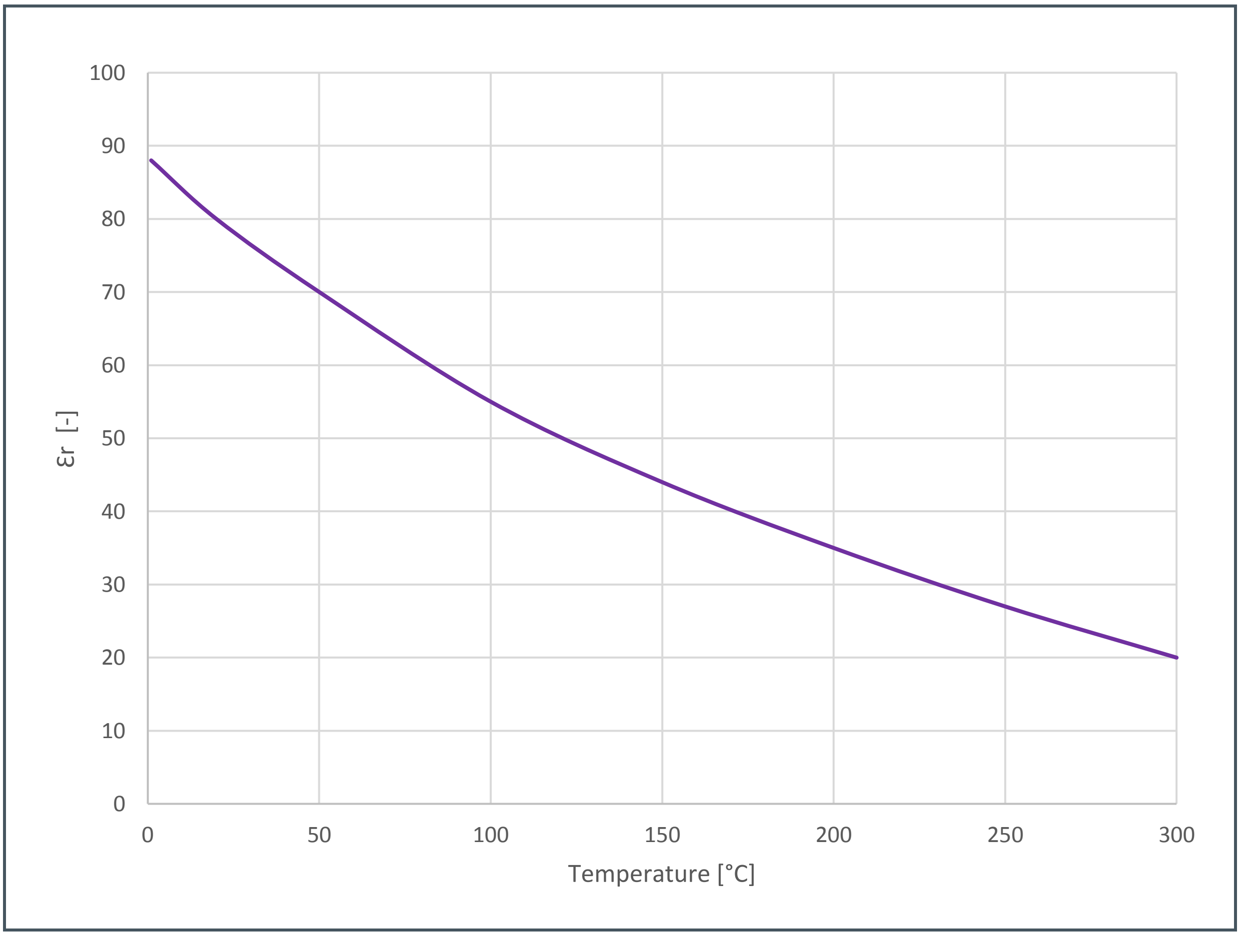
The simplest model of a capacitor consists of two thin parallel conductive plates each with an area of *A* separated by a uniform gap of thickness *d*. *d* is filled with a dielectric. This dielectric material has a characteristic permittivity ε. ε consists of the constant permittivity of vacuum ε_0 and the relative permittivity ε_r. Most materials has their unique permittivity at a certain temperature. There are some examples of materials with their properties shown in Figure 5.

Figure 5:
Relative Permittivities of Some Materials vs Temperature

Material	Relative Permittivity εr	Temperature [°C]
Air	1	25
Ammonia	26, 22, 20, 17	−80, −40, 0, 20
Methanol	30	25
Ethylene glycol	37	25
Water	88, 80, 55.3, 34.5	0, 20, 100, 200

Material properties have an effect on the permittivity. In addition, the actual temperature of the material can also have a strong impact. Figure 6 shows how temperature vs permittivity are corresponding to water.

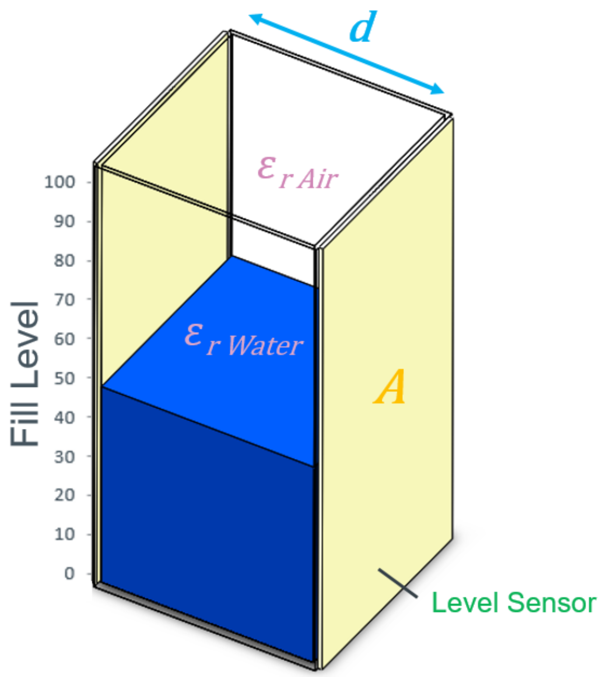
Figure 6:
Relative Permittivity of Water vs Temperature



4 Liquid Fill Level Sensing

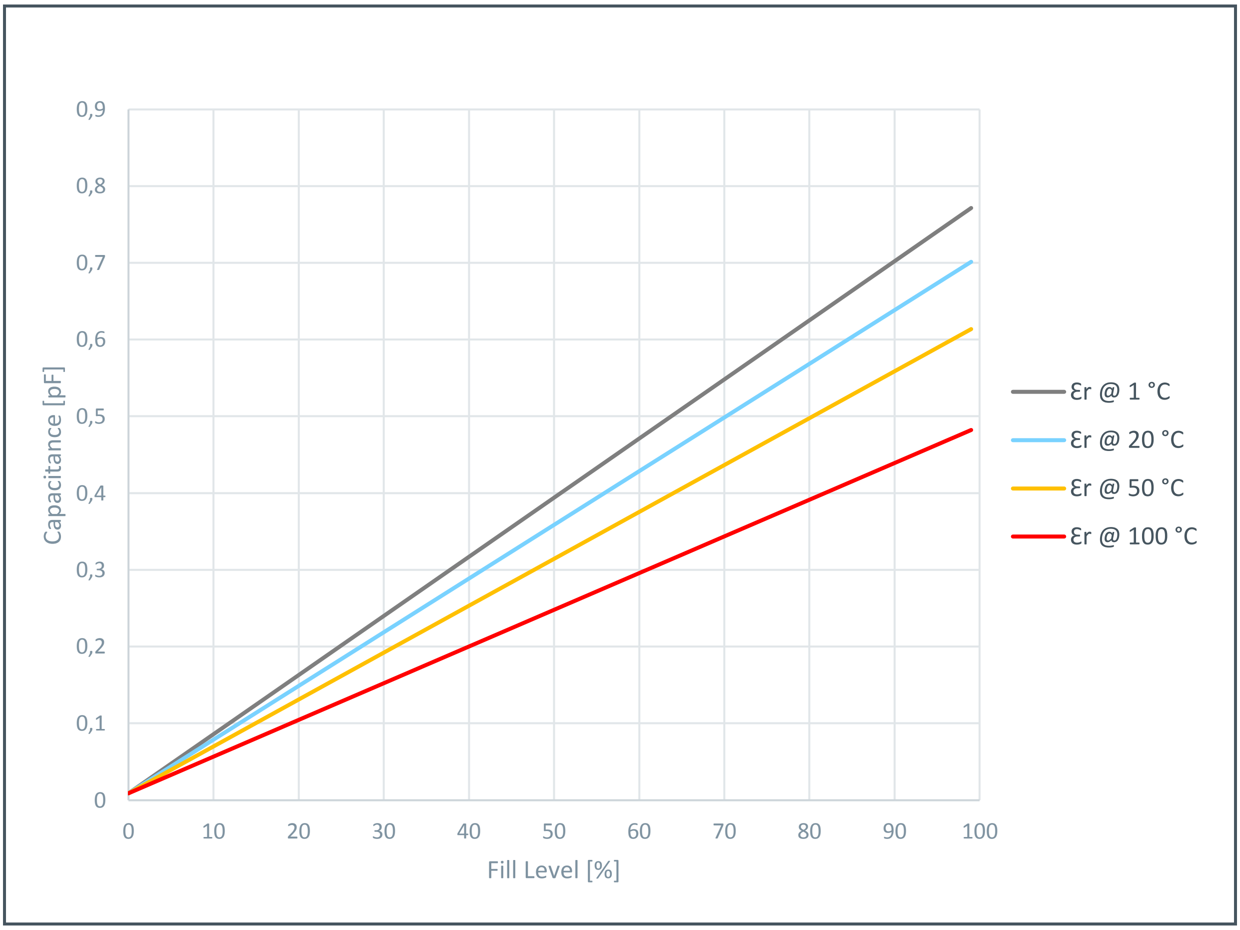
Now let´s focus on how capacitive fill level measurement can be done. The goal is to measure the level of a medium. Assuming an application for fill level measurements of water. This can be done by a simple sensor configuration based on a parallel plate capacitor. Figure 7 shows a container with two sides covered by conductive plates. As capacitive measurements cannot be done through conductive materials, the container has to be made of non-conductive materials. The distance (*d*) between those plates and the surface area (*A*) are constant. The permittivity will change and this is mainly determined by the level of water inside the container.

Figure 7:
Fill Level Sensor for Water



Due to the material properties of air and water, an empty container would have the relative permittivity of air (ε_r=1). A container full of water at 20 °C would have a relative permittivity of 80 and 40 for a half-full container. The measured capacitance would directly represent the fill level of the container. The capacitance increases near linearly as the liquid level increases. Figure 8 represents the relation between capacitance and fill level between 1 °C and 100 °C. (Simulation based on d = 1 cm, A = 2 cm²)

Figure 8:
Capacitance vs Fill Level of Water Between 1 °C and 100 °C



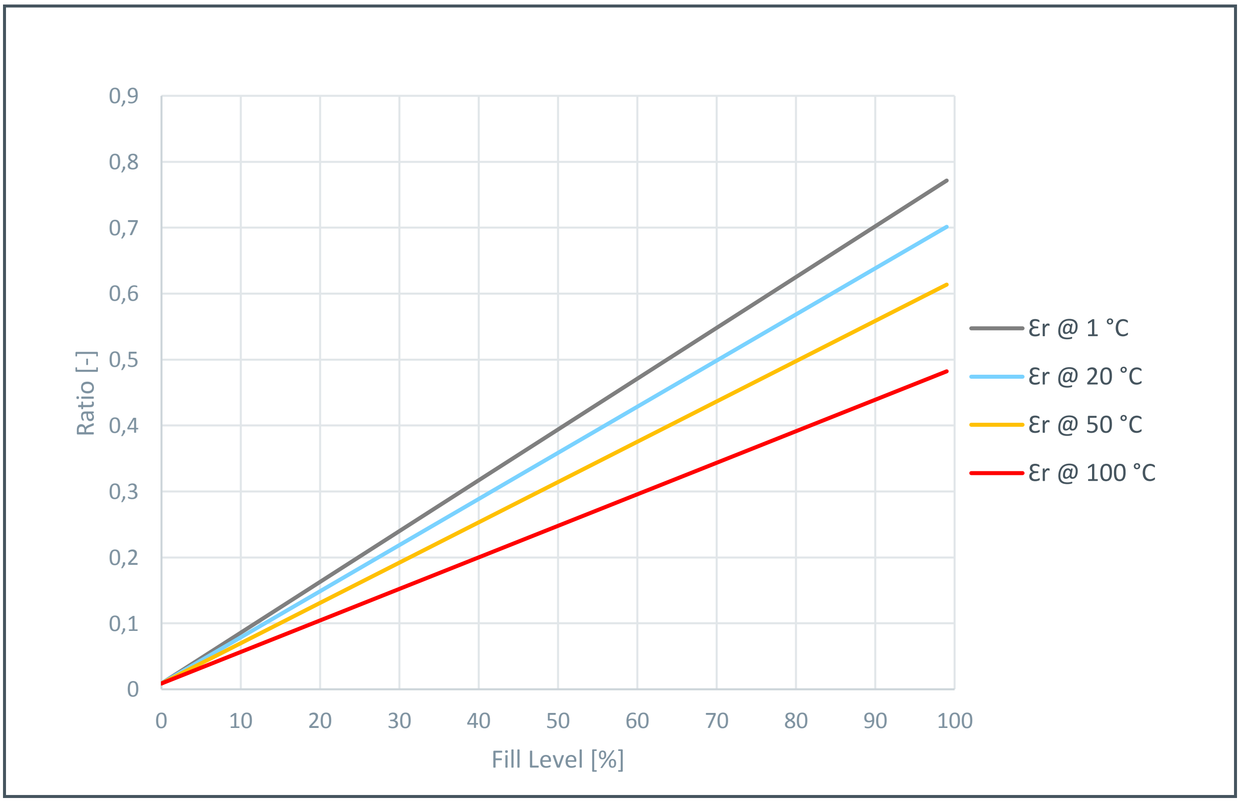
5 Application Topics and Challenges

This chapter is focusing on the most relevant applications for capacitive fill level sensing. Each of them has its own challenges. It is a guideline on how to design sensor plates and what parameters might affect the measurement.

5.1 Temperature Dependency

As already mentioned in chapter3, the permittivity of water varies over temperature Figure 8 shows the relation between fill level and absolute capacitance values. To get absolute capacitance values, a calibrated measurement system is required. A low cost alternative to calibrated systems is the PCap04. It measures the capacitance ratio of a known internal or external reference and the variable sensor capacitance. As can be seen in Figure 9, the gradient and linearity corresponds to the results of Figure 8. This method can be useful if liquid material and temperature is known.

Figure 9:
Ratio vs Fill Level of Water between 1 °C and 100 °C

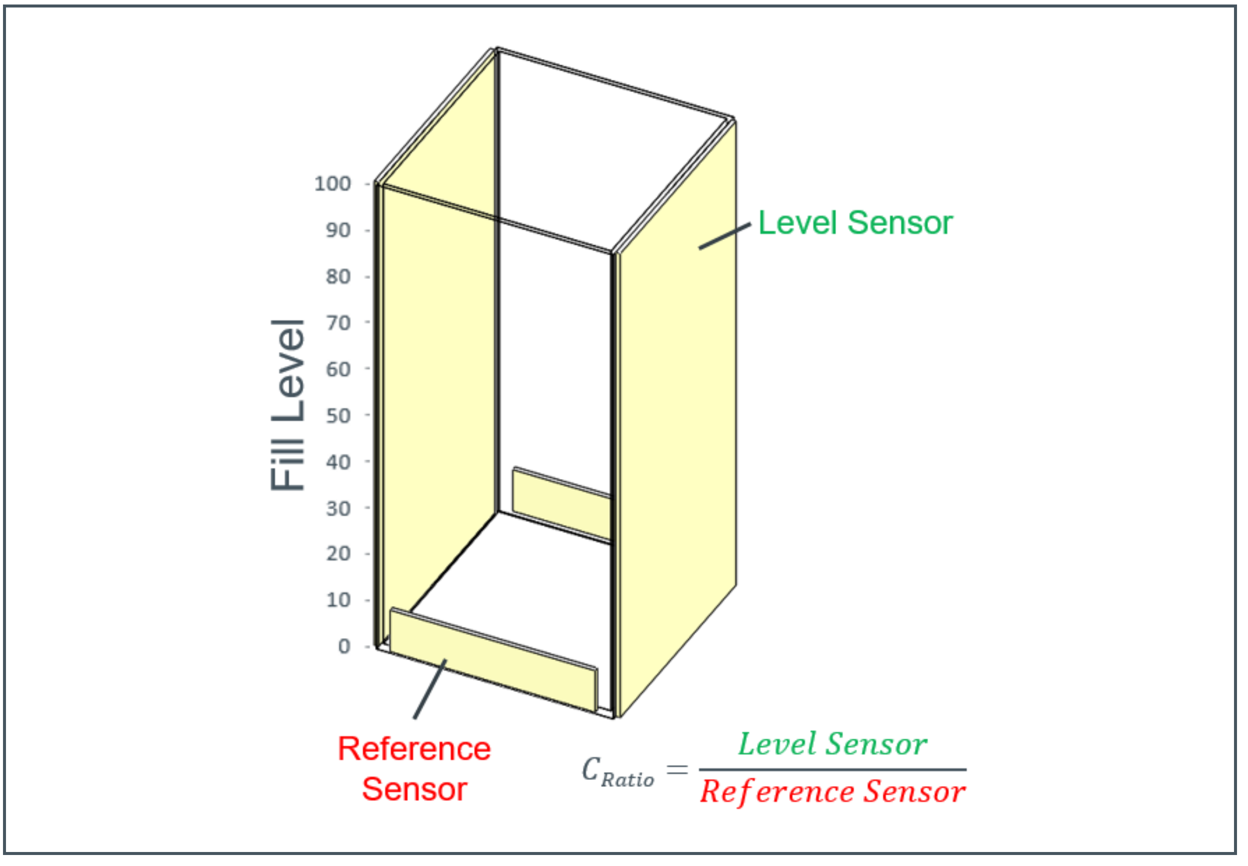


5.1.1 Ratiometric Measurements

In case permittivity and temperature are unknown, a reference sensor can be used to replace the reference capacitance. Figure 10 shows an example of a container with two sensor plates and a reference sensor at the bottom. This is to make sure, the reference is measuring the liquid even with a low fill level.

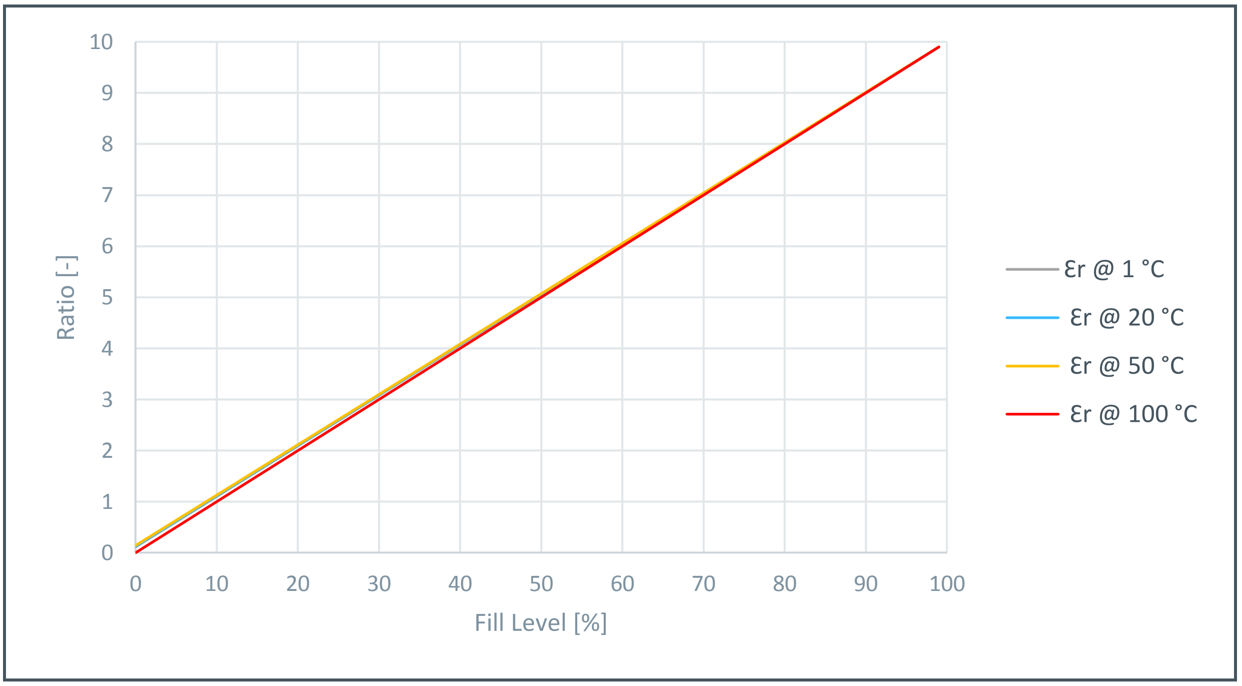
This configuration produces ratiometric measurements. This means the ratio between level sensor and reference sensor will be always the same independent of material properties or temperature. In this configuration, both parameters will affect both sensors and therefor balances itself amongst them.

Figure 10:
Ratiometric Fill Level Setup



As seen in Figure 11, the Ratiometric setup can compensate the temperature spread seen in Figure 9.

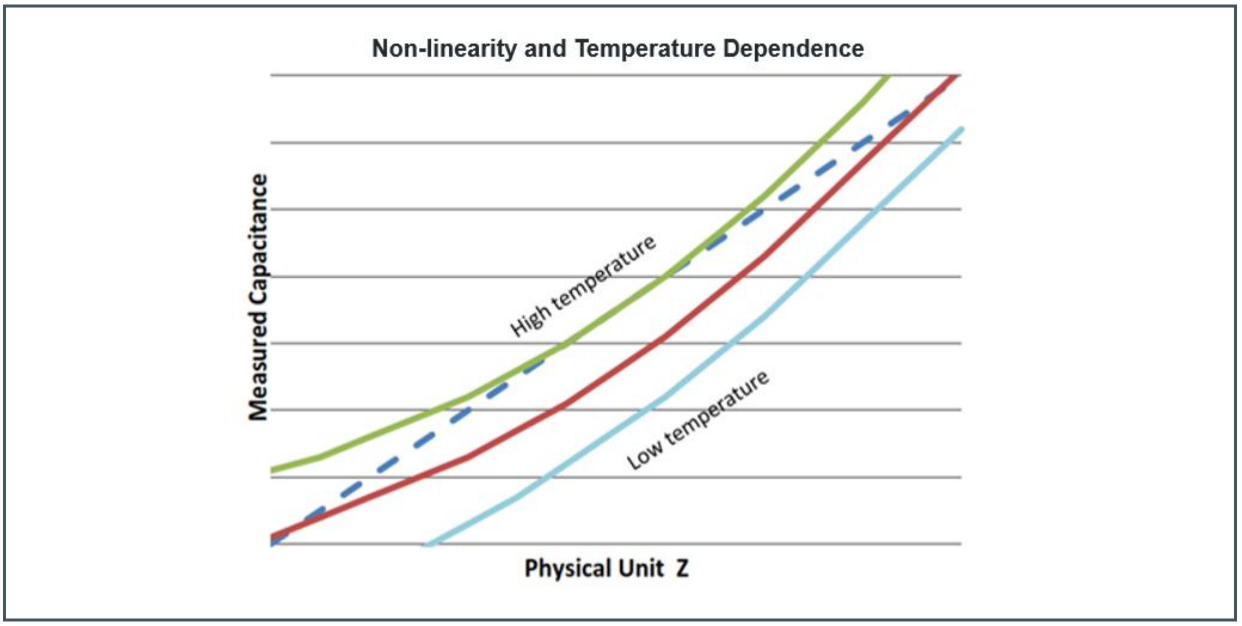
Figure 11:
Ratiometric Fill Level Sensing



In Figure 11 the ratio metric setup appears to have a linear behavior. As this figure is based on simulations only, a nonlinear behavior is to be expected from a real-world measurement. This is due to mechanical tolerances and additional parasitic capacitances influencing the measurement. Therefore, additional linearization is highly recommended. It can be accomplished with the linearized firmware as described in the next chapter

5.1.2 Linearization with PCap04

Figure 12:
PCap04 In-Build Linearization

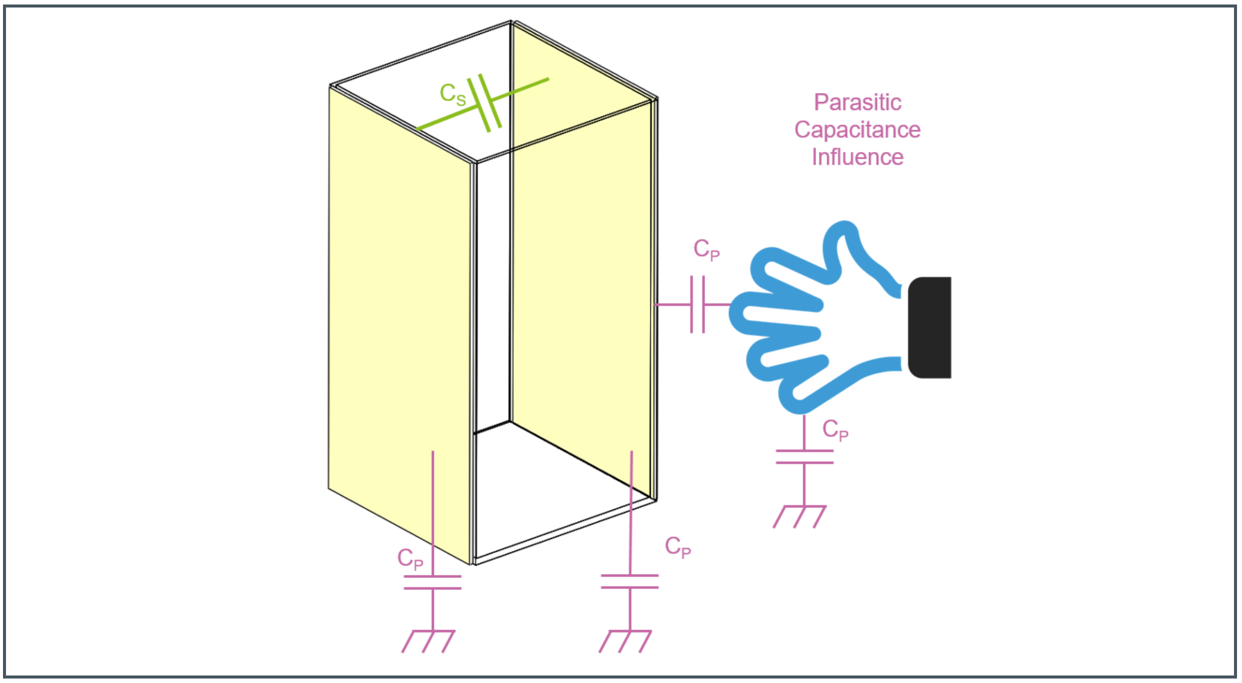


ams provides a ready-made linearize firmware that performs a linearization via polynomial of third degree and temperature compensation via polynomial of second degree. Many functional blocks for the linearization firmware are implemented as ROM code. This way, the main firmware can be very compact and can fit into the 1 k NVRAM. How this can be done with the PCap04 eval kit is described in a separate application note “Linearization with PCap04”

5.2 Parasitic Influence

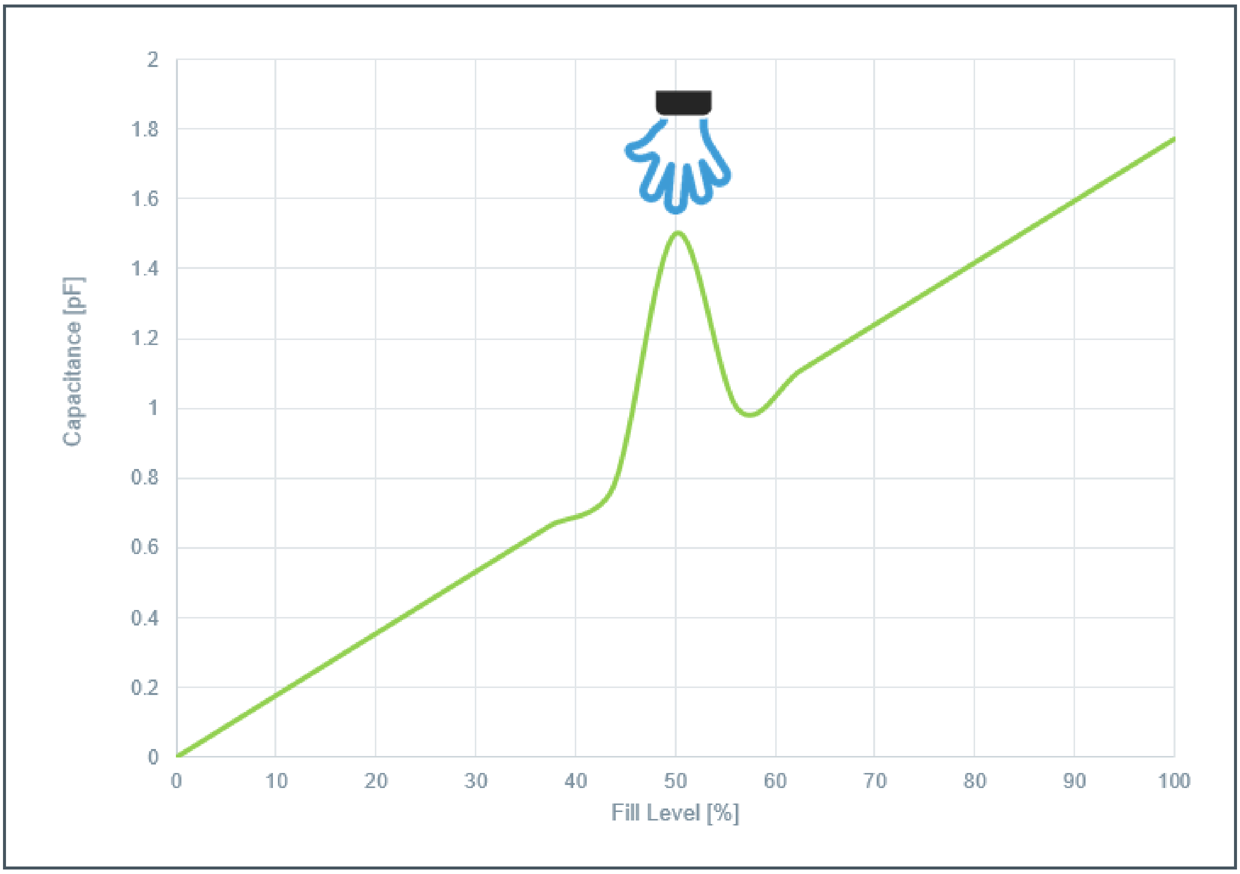
Many external factors could have an impact on the capacitive sensor elements. The human body itself can introduce a lot of parasitic capacitances and therefore disturb the measurements.

Figure 13:
Parasitic Influence



The high content of water in the human body causes a potential difference between the sensor plates and therefor influences the measurement. This additional parasitic capacitance will be measured and would bring a distortion to the fill level relation, as can be seen in the simulation in Figure 14.

Figure 14:
Distortion by Human Hand

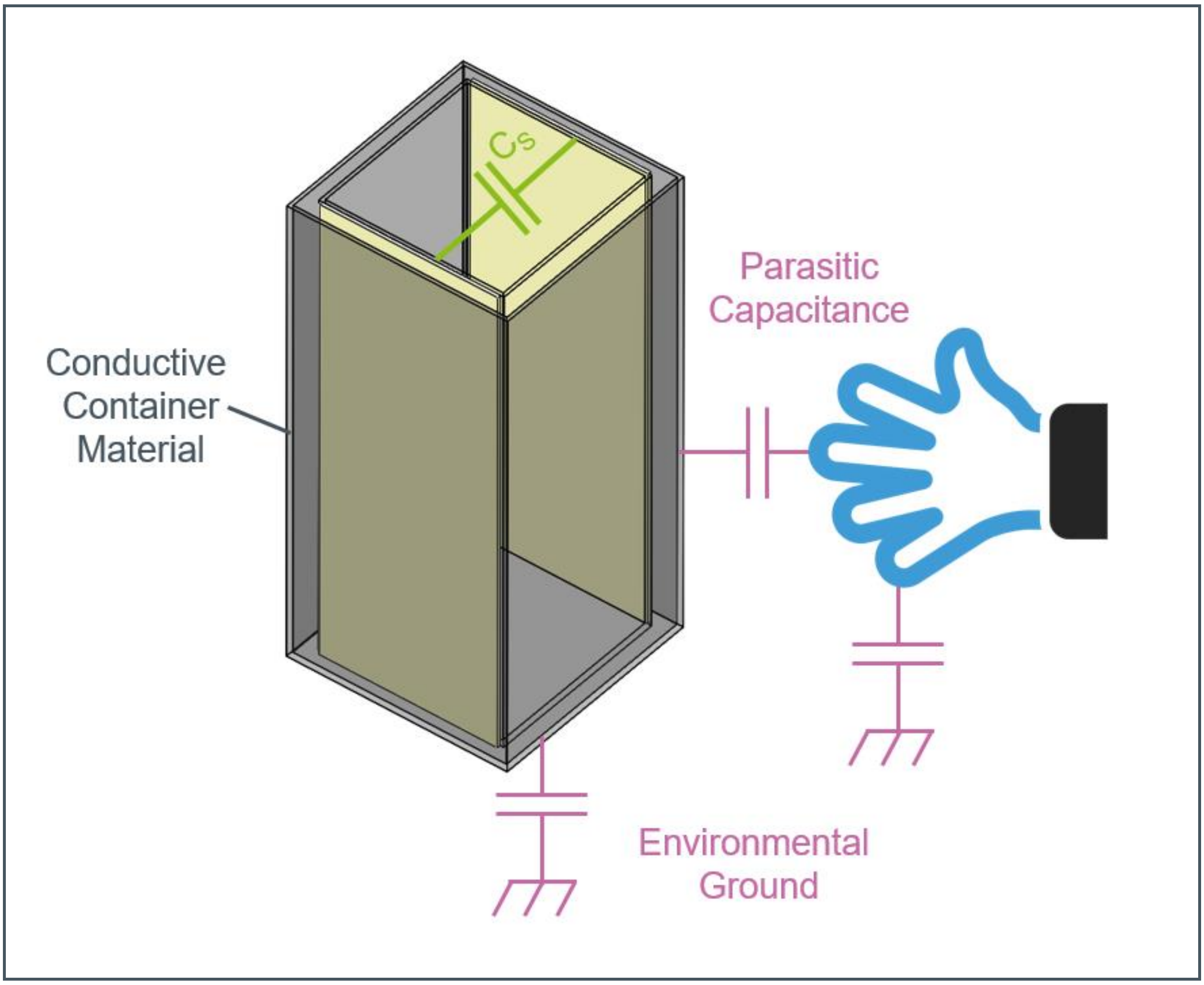


5.2.1 Shielding with Conductive Container

One way to reduce external parasitic influences is to build up a shielding around the level sensor, as shown in Figure 15. An additional conductive container, that is not connected to the sensor ground acts as a shield against parasitic capacitances coming from outside.

It is important to keep the sensor ground and the container isolated from each other to have the measurement system isolated from the environmental ground.

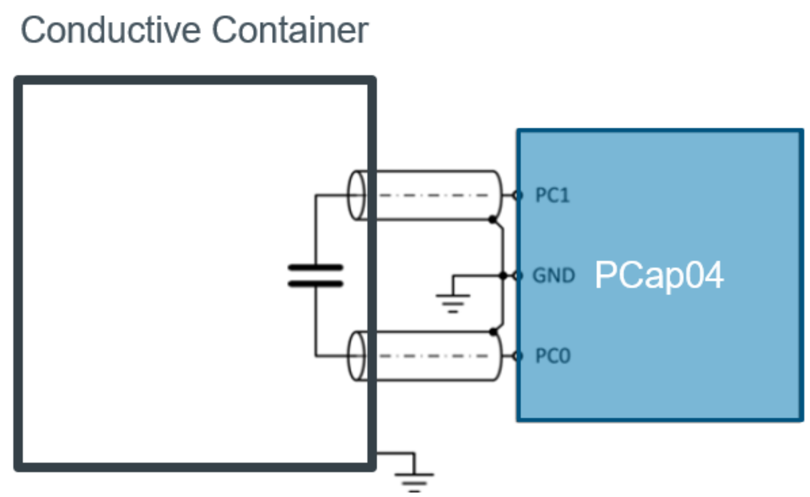
Figure 15:
Shielding vs Parasitic Influence



5.2.2 Compensate Parasitic Influences with PCap04

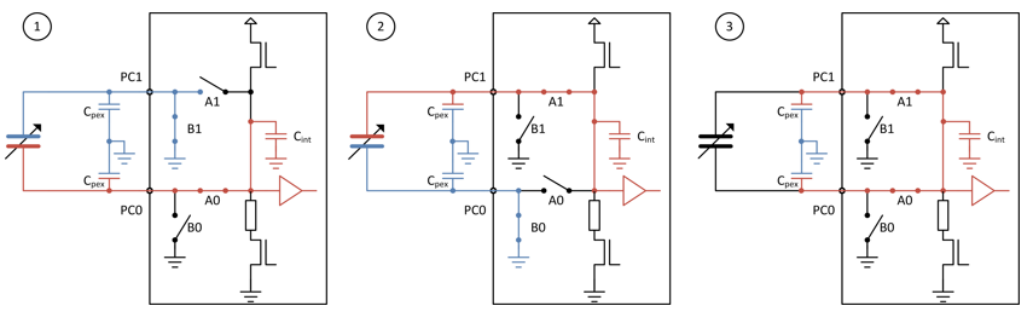
With floating capacitors, PCap04 has the additional option to compensate external parasitic influences against ground. On the PCB, the wire capacitance typically refers to ground. For long wires, it is recommended to use shields which should be grounded to the conductive container and PCB side as can be seen in Figure 16.

Figure 16:
Shielding Container and Cables Against External Parasitic Influence



Three measurements are necessary for each capacitor in case of floating sensors. This is shown in the Figure 17. First, the electrode at PC0 is loaded to VDD18. The discharge time is defined by the sensor capacitance, the parasitic capacitance of the connection, including the chip pad, and the internal capacitance. Second, the same measurement is done for the electrode at PC1. Third, both electrodes are set at VDD18. Therefore the field across the sensor is zero and has no impact. The discharge time includes only the connection and pad capacitance as well as the internal capacitance. Now it is possible to correct mathematically for the parasitic capacitance. This correction is covered by the **ams** firmware

Figure 17:
PCap04 External Parasitic Compensation



Additional information on the parasitic compensation can be found in the PCap04 datasheet under section “External Compensation”

5.3 Removable Container

In some applications, removable containers are necessary. Practically, sensors cannot be applied directly on a removable container. A good idea is to place the sensor plates outside on the container mount as shown in Figure 18. The removable container has to be made of a nonconductive material. Field lines between parallel plates follow a direct path.

Figure 18:
Removable Container

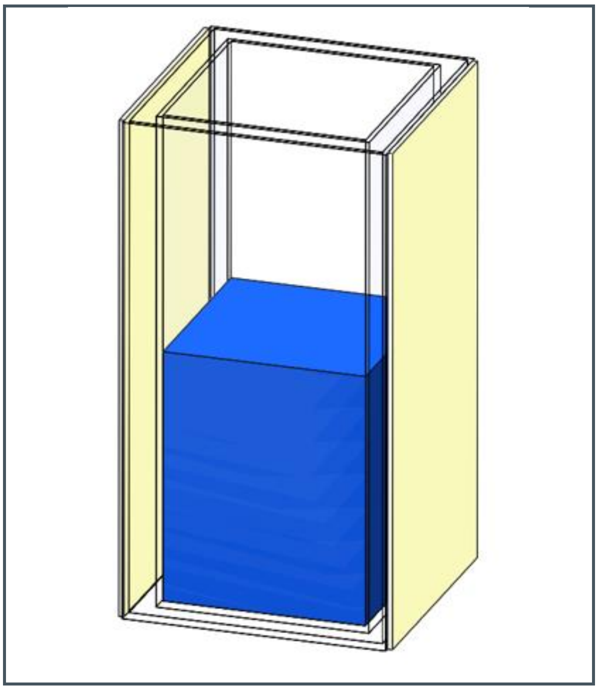
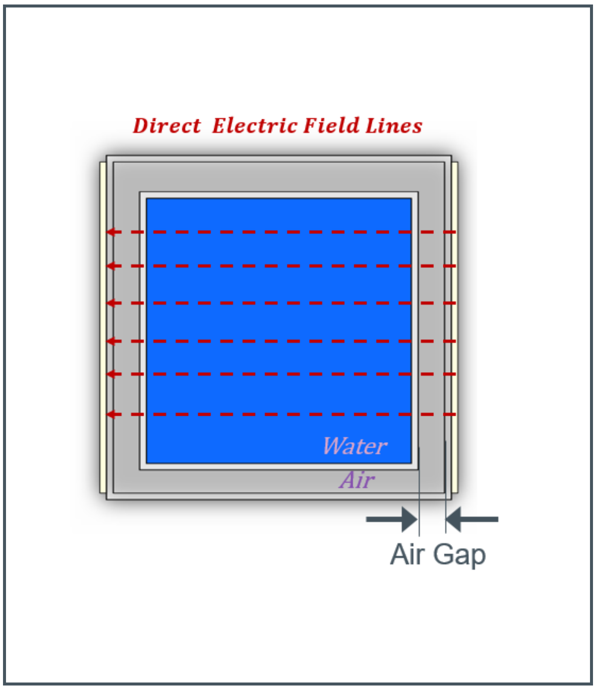


Figure 19:
Air & Water



Air gap variations between the containers do not have an effect on the measurement result, as the total amount of air and water is always the same between the parallel plates. No matter how the removable container is moving inside the container holder.

Information

Permittivity of the materials are ignored in these illustrations.

5.4 Coplanar Sensor Plates

In some applications it is more practical to build up coplanar sensor plates instead of parallel plates. This configuration has to be applied on only one side of the container. The reference sensor can be placed on the opposite side on the bottom of the container as shown in Figure 20. The equation behind this coplanar sensor setup is for sure different and more complicated. However, at the end only the ratio between level sensor and reference sensor will be measured.

Figure 20:
Coplanar Sensor Plates

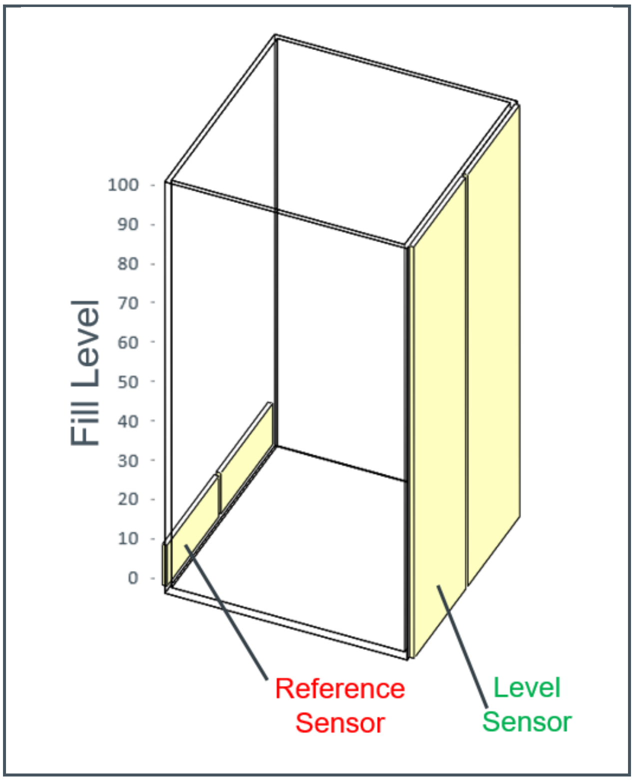
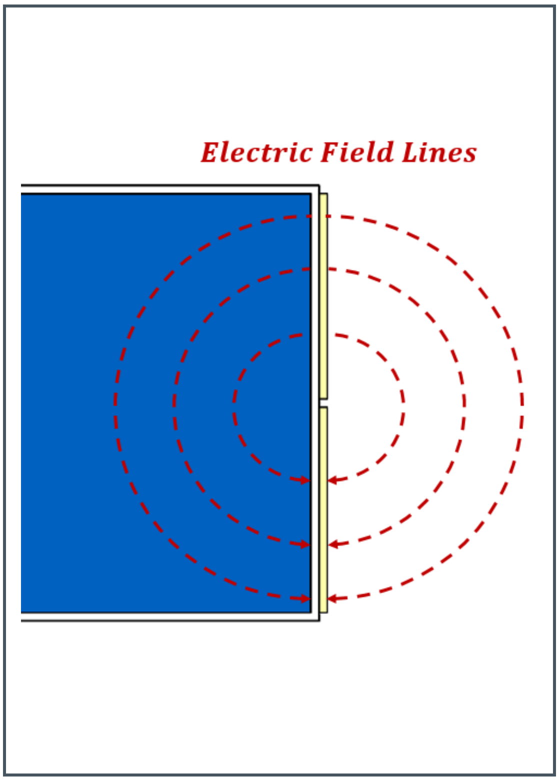


Figure 21:
Electric Field Lines



6 Revision Information

Changes from previous version to current revision v1-00	Page
Initial Version	

- Page and figure numbers for the previous version may differ from page and figure numbers in the current revision.
- Correction of typographical errors is not explicitly mentioned.

7 Legal Information

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