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MEDICAL LIQUID-LEVEL APPLICATIONS WITH ENHANCED CAPACITIVE SENSOR TECHNOLOGY

Accurate, Automatic Point Level Detection

White Paper

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Executive Summary

This document identifies key issues experienced by manufacturers of medical/biotechnology equipment regarding handling and detection of liquids with capacitive proximity sensors in particular. It examines concrete sensing/monitoring methods that will improve processes while guaranteeing reliable and dependable non-invasive liquid level detection.

The trend towards more sophisticated lab automation instruments, which are expected to handle increasingly complex tasks, requires the most proven, repeatable and reliable sensing technologies available. The potential for end-product contamination as well as safety regulations such as exposure of personnel to potential biohazards or toxic agents must be carefully considered. All of these factors make it especially difficult for machine/instrument builders to acquire essential real-time information about the machine or instrument's state in a non-invasive manner. In most applications, it's virtually impossible to place sensing devices directly in the fluid pathway.

Challenging areas of liquid level detection and monitoring in medical, biotechnology, or pharmaceutical applications today are as follows:

- **MIN-Level indication in ampules and vials**
  Non-invasive detection regardless of color or changing liquid composition
- **Overflow protection of liquid waste reservoirs and container**
  Disposable and interchangeable containers require non-invasive sensing methodology
- **Level monitoring of chemical or cleaning agent supply container**
  Assuring that an operator receives timely warning before the supply ends
- **Liquid monitoring of blood and other bodily fluids in vacuum collection instruments**
  Prevents overflow and protects vacuum pumps from contamination
- **Leakage monitoring and alarm response**
  Detection of liquid contamination in the instrument
- **Sensor operation monitoring**
  Make your sensors fail-safe by knowing their actual state of operation and monitor proper functionality in real time

Machine designers and builders - especially in the medical industry - must deliver safe, reliable products in the face of steadily increasing costs, industry competitiveness, and more stringent federal regulations.

Other important factors which affect the total cost of ownership for liquid level sensors are:

- **Time for assembly and setup**
  Time allocated to install and configure each individual sensor
- **Engineering effort for application**
  The time it takes to make the individual sensor solution function
- **Long-term reliability and impact on field service**
  Using worst case scenario can only simulate the real world application circumstances to a certain degree; sensors require conservative specifications and adaptive technologies to account for operational imbalances or imperfections
- **Confined Mounting Space**
  Limits the sensor housing and technology options

In addition to application specific challenges and external general requirements for sensors, traditional capacitive technology itself imposes pitfalls for robust and long-term stable operation.

- False positive triggering
  A result of material buildup, condensation or other prior unaccounted operational influences
- Changing material compositions
  The target or container material might require frequent sensor recalibration

Balluff, a worldwide manufacturer of automation solutions, developed a patented new approach to capacitive sensing technology to address these challenges in capacitive sensing technology. This paper will describe non-invasive capacitive sensing technologies and their application in medical and pharmaceutical related applications.

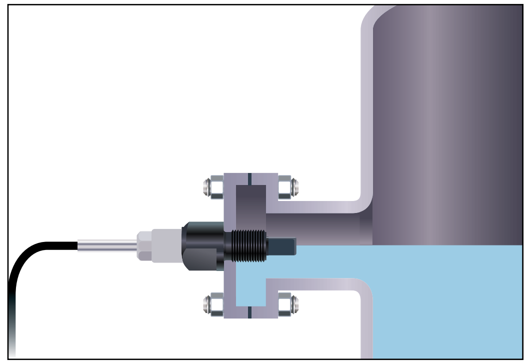


Figure 1: Invasive sensing mount

Capacitive Sensors In Liquid Level Detection Applications

Capacitive sensors are commonly used for remote presence detection of a wide range of non-conductive and conductive non-metallic objects and liquids.

In level sensing applications, capacitive sensors can be mounted in two different ways, depending on the target and container wall material.

Containers made of stainless steel or very thick non-metallic tank walls (more than 1") almost exclusively require invasive capacitive sensor mounting (Figure 1), although by-pass tubes or glass view ports in conjunction with a non-invasive sensor mount can also be used (Figure 2). With the invasive sensing approach, the sensor is placed in direct contact with the target material in order to indicate if the target level rises above or falls below the sensor location. This method might simplify sensor selection and setup since the sensor has to focus only on the core target material properties. Nonetheless, this approach imposes certain drawbacks, such as hidden costs for mounting and sealing the sensor as well as the need to carefully consider the material compatibility. Corrosive acids, for example, might require more expensive housing materials.

Figure 2: Non-invasive sensing mount

Table 1.1: Chemical Compatibility Chart

	Acids	Alkaline	Solvents	Alcohol	Fuel
PBT - Polybutyleneterephtalate	P	P	E	G	G
PVC - Polyvinylchloride	G	G	P	F	P
POM - Polyoxymethylene	P	P	E	F	G
PTFE - Polytetrafluoroethylene	E	E	E	E	G
PP - Polypropylene	G	E	P	G	F
PSU - Polysulphone	E	E	G	G	P

E = Excellent G = Good F = Fair P = Poor

A more preferred approach is to mount a capacitive sensor flush against a non-metallic wall to detect the target material non-invasively through the container wall (Figure 2).

The advantages for this approach are clear – the container wall does not have to be penetrated, which leaves the level sensor flexible and interchangeable in the application. Avoiding direct contact with the target material also reduces the chances of product contamination, leaks and other sources of risk to personnel and the environment.

The target material also has certain relevance in the sensor selection process. Medical applications involve mostly water-based reagents, process fluids, and various bodily fluids. Fortunately, high conductivity levels and therefore high relative dielectric constants are common characteristics among all these liquids. This is why the primary advantages of capacitive sensors lies in non-invasive liquid level detection, namely by creating a large measurement delta between the low dielectric container walls (see relative dielectric constants in table 1.2) and target material with high dielectric properties.

At the same time, highly conductive liquids could impose a threat to the application. This is because smaller physical amounts of material have a larger impact on the capacitive sensor with increasing conductivity values, thus increasing the risk of false triggering on foam or adherence to the inside or outside wall.

Table 1.2: Selected Dielectric Constants

Material	Dielectric Constant	Material	Dielectric Constant
Air	1.0	Glass	3.1 - 10
Oil	4 - 5	Polyamide	2.5
Water	48 - 88	Polycarbonate	2.9
Aqueous Solutions	50 - 80	Polypropylene	2.3
		Polyvinyl Chloride	3.1
Acetone	19.5	PTFE	2.0
Alcohol, Isopropyl	18.3	Rubber	2.5 - 35
Ethanol	24		
Glycerin	47		
Hydrochloric Acid	4.6		
Hydrogen Peroxide	86		
Chlorine, liquid	2.0		

In order to see the full capability of capacitive sensors in liquid level applications, one has to understand the basic underlying sensing principle.

Standard Capacitive Sensing Technology

Capacitive sensors exhibit a change in capacitance in response to a physical stimulus, such as material type, composition or distance. The general formula to calculate the capacitance of a *parallel-plate* capacitor:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

The capacitance can be calculated if the geometry of the conductors and the dielectric properties of the insulator between the conductors are known. For example, the capacitance of a parallel-plate capacitor constructed of two parallel plates both of area (A) separated by a distance (d) is approximately equal to the following, in SI units:

C is the capacitance, in farads;

A is the area of overlap of the two plates, in square meters;

$\boldsymbol{\varepsilon_r}$ is the relative static permittivity (sometimes called the dielectric constant) of the material between the plates (for a vacuum, $\varepsilon_r = 1$);

$\boldsymbol{\varepsilon_0}$ is the electric constant ($\varepsilon_0 \approx 8.854\times10{-}12$ F m–1); and

d is the separation between the plates, in meters.

By keeping the area (A), which is the active sensing surface of the sensor, constant, a standard industrial capacitive sensor will respond to changes of the target material (here: ε_r) or distance to it.

The active sensing area of a capacitive sensor is comparable to the open electrodes of a capacitor. Both electrodes are in the feedback loop of an oscillator, arranged to provide a harmonic balance (Figure 3). The amplitude of the oscillator does not change unless material is introduced into the high-frequency electro-static field (ranging from 800 kHz to 1MHz) formed between the two electrodes. The target material causes a change proportional to its dielectric factor, distance and coverage in the coupling capacitance which causes the oscillator amplitude to rise. Signal evaluation circuitry activates the discrete output at a user-adjusted sensitivity (here: amplitude) threshold level (Figure 4).

In order to get reliable and dependable sensing results, the user is required to manually adjust the sensor's sensitivity (here: amplitude threshold) by means of a trim potentiometer or a semi-automated teach-in process according to the specific application requirements. Generally speaking, for a non-invasive level detection application, a capacitive sensor would be adjusted to the point where it ignores the container wall but reliably detects the capacitance change caused by the changing level of the target material.

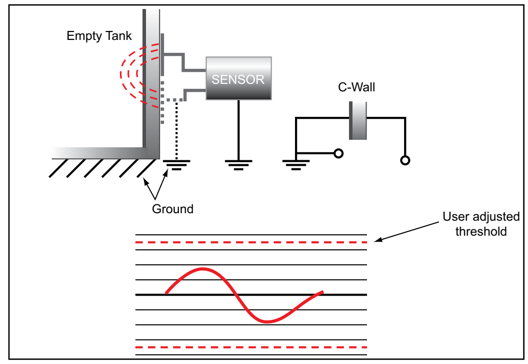


Figure 3: Standard capacitive sensor oscillator output below switching condition.

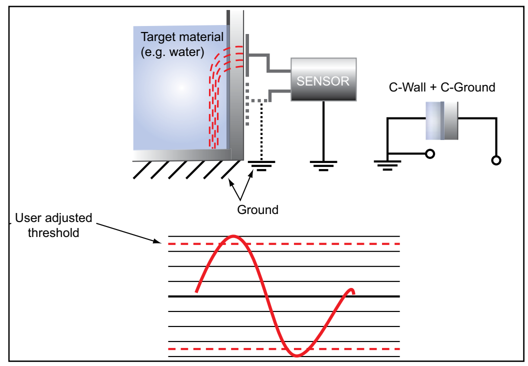


Figure 4: Standard capacitive sensor oscillator output above switching condition.

Potential Sources Of Failure With Standard Capacitive Sensors

Capacitive sensors detect any changes in their electro-static sensing field. This includes not only the target material itself, but also application-induced influences like condensation, foam or temporary or permanent material build-up. High viscosity fluids can cause extensive delays in the accurate point-level recognition or cause complete failure due to the inability of a capacitive sensor to compensate for material adhering to the container walls. In cases with low conductivity fluids (e.g. water) and relatively thin container walls (< 20% of maximum sensor sensing range), the user might be able to compensate for these sources of failure. Potential material build-up or condensation can be compensated for by adjusting the sensitivity levels or employing additional mechanical measures such as using a hydrophobic PTFE tank material or by installing in-tank covers.

This strategy works only if the fluid conductivity stays low and no other additional influencing factors like temperature or mechanical slag challenge the sensor.

Cleaning fluids like sodium hydrochloride, chemical reagents or saline solutions have very high electrical conductivity values, which cause standard capacitive sensors to false trigger on even the thinnest films or adherence. The same applies for body fluids such as blood, or concentrated acids or alkaline.

The obvious problems in this type of application are not so obvious for an untrained observer. This is especially true when the sensors performed well in the initial design phase but fail in the field for no clear reason. Difficult and time consuming setup procedures and unstable applications requiring frequent readjustment are the primary reasons why capacitive level sensors have been historically avoided in certain applications.

Enhanced Capacitive Technology

A perfect capacitive sensor for non-invasive level detection applications would not require any user interaction during the setup process – it would detect any type of target material through any type of tank wall while automatically compensating for material build-up, changing tank materials, condensation, and foam.

The laws of physics cannot be ignored, but they can certainly be stretched.
Now enhanced capacitive sensing technology helps the sensors to discriminate effectively between true liquid levels and possible interferences caused by condensation, material build-up or foaming fluids. These enhanced sensors still detect the relative change in capacitance caused by the target object but use additional factors to evaluate the validity of the measurement taken before changing state.

These sensors are intrinsically insensitive to any non-conductive material like plastic or glass, which allows them to be placed without the necessity of adjustment in non-invasive level applications. This characteristic is at the same time their only limitation: these enhanced capacitive sensors require electrically conductive fluids or target materials with dipole characteristic such as water (also: deionized) to operate properly.
Please review the last section in this paper to gain a deeper knowledge about this technology.

Medical, Biotechnology and Manufacturing Advantages

Enhanced capacitive sensing technology brings a considerable advantage to the area of liquid level detection, not only offering alternative machine designs but also reduced assembly time for the machine builder as well as drastically reduced field service liability.

Machine designers now have the flexibility to non-invasively detect almost any type of liquid through plastic, glass tubes or other non-metallic container walls, while reducing mechanical adaption effort and fabrication costs. Discrete indication tasks like fluid presence detection in reagent supply lines, reagent bottle level feedback, and waste container overfill prevention or leakage detection now become a distinct competence for capacitive sensors. Reagents and waste liquids are composed of different formulas that vary from customer to customer and sometimes even the end user. The sensing technology has to be versatile enough to compensate automatically for changing environmental or target conditions within high tolerance limits.

Applications which require precision and an extraordinary amount of reliability, such as blood presence detection in cardiovascular instruments or haemodialysis instruments, can now rely on capacitive sensing technology. Foam and body fluid residue will not lead to unexpected false positive signals.

Smart Level enhanced capacitive sensors from Balluff can offer all the reliability and effectiveness medical and pharmaceutical machine builders demand for critical applications:

Smart Level solves more level detection applications

- Compensates automatically for humidity, foam, and material build-up
- Senses liquids through glass or plastic walls up to 12mm thick
- Detects aqueous and highly-conductive liquids reliably

Reduces costs

- Eliminates routine cleaning maintenance
- Self-adjusts to most applications for faster, easier setup
- Simplifies mounting and installation efforts

Background on Smart Level Technology

Smart Level enhanced capacitive sensors work with a high-frequency oscillator, in which their amplitude is directly correlated with the capacitance change between the two independently acting sensing electrodes. Each electrode independently tries to force itself into a balanced state. This is the reason why the sensor independently measures (contrary to standard capacitive sensors) the capacitance of the container wall without ground reference and the capacitance of the conductivity of the liquid with ground reference.

Without having target material introduced into the sensor's field, the amplitude of the oscillator is at a nominal state (Figure 5). Once an empty container wall creates a capacitance change, the amplitude rises above the nominal level (Figure 6) but will never lead to a valid switching condition unlike a standard capacitive sensor. A conductive liquid which rises in the container will create a second, much higher capacitance with respect to ground. This second capacitance, being significantly higher than that of the container wall, affects the oscillation inversely to the capacitive effect of the wall and pulls the amplitude down to 0V, triggering the sensor's output (Figure 7).

The key advancement is that SMARTLevel sensors compensate for differing conditions by working at a field frequency of 6.5 MHz, which is approximately seven-times higher than that of an ordinary capacitive sensor. This high AC frequency reduces the reactance segment of the impedance between the active sensor surface and the material build-up, allowing the sensor to detect true levels without interference.

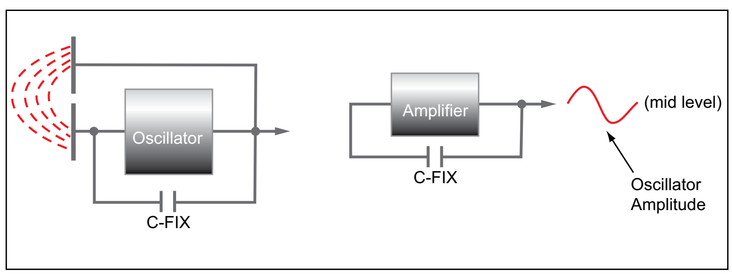


Figure 5: Enhanced capacitive sensor detection schematics – no target present

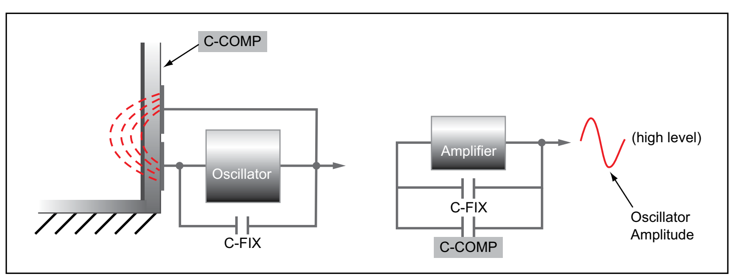


Figure 6: Enhanced capacitive sensor detection schematics – automatic tank wall compensation

Smart Level sensors provide cost-effective, reliable point-level monitoring for a wide array of medical, biotechnology, life sciences and manufacturing processes and procedures. Balluff offers this technology exclusively in a wide array of sensor configurations, all aimed at accommodating the full breadth of science and industry's most stringent application-specific level monitoring requirements.

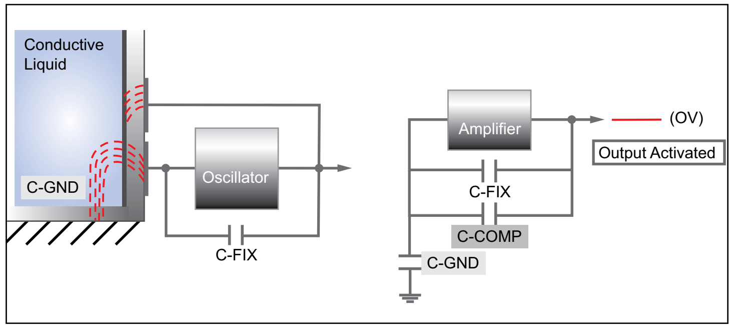


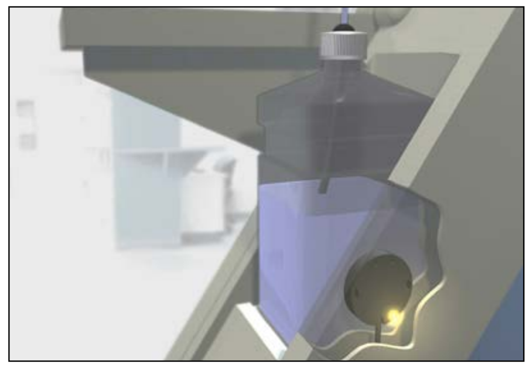
Figure 7: Enhanced capacitive sensor detection schematics – liquid level presence detection

Case Studies

Case Study #1

A well-known manufacturer of automated laboratory sample preparation instruments uses several liquids for rinsing and sample processing. One of several challenges the company faced in providing reliable liquid level feedback was avoiding any potential for cross contamination between interchangeable liquid containers. Additionally, the company couldn't completely predict the exact liquid composition a technician might use to conduct the analytical process, creating a risk for unreliable test data and the potential for added operating costs.

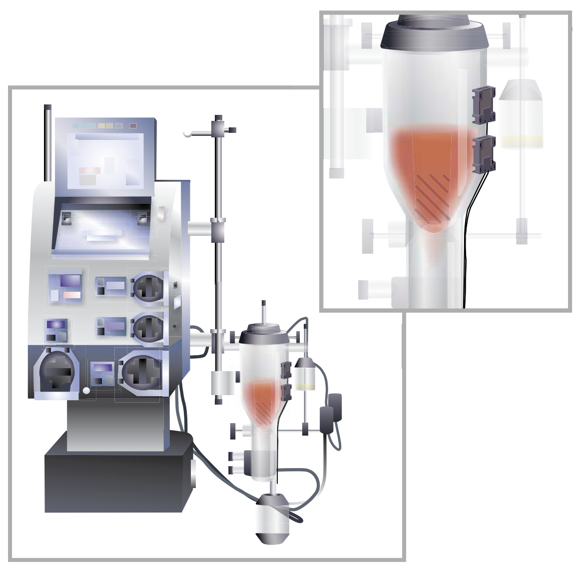
By integrating Balluff's Smart Level enhanced capacitive sensors into the process, several goals could be achieved simultaneously. This unique capacitive technology allowed them to sense liquids non-invasively through the plastic container walls while providing an added benefit of allowing strategic placement of these compact sensors beneath a plastic molded instrument panel. It also created streamlined instrument aesthetics by sensing through two separate plastic walls at once. Smart Level technology provided them with the required level of confidence that the sensor will repeatedly compensate and adjust automatically, regardless of liquid compositions, all while ignoring any potential residue accumulation on the sensing device itself. The result: essentially maintenance-free instrument operation.



Balluff's Smart Level allows for essentially maintenance-free instrument operation.

Case Study #2

Blood level detection in a cardiovascular instrument containment vessel or oxygenator is one of the most difficult challenges in today's medical liquid level sensing arena. Blood and other body fluids possess high conductivity properties and tend to foam. These fluids also possess a propensity for accumulation on vessel walls, which can "fool" traditional sensing technologies, resulting in bothersome false alarms. After extensive testing, a well known manufacturer of cardiovascular surgical equipment concluded that Balluff's Smart Level enhanced capacitive sensing technology was the device of choice for monitoring blood levels in a disposable blood collection container. This enhanced sensing technology now allows the manufacturer to reliably and repeatedly implement non-invasive (no breeching of the containment vessel wall) liquid level feedback that isn't distorted by false triggers due to residual material build-up or foaming phenomena. Smart Level technology assures that the sensors automatically adjust and compensate for these interferences.



Balluff's Smart Level technology was the device of choice for monitoring blood levels in a disposable blood collection container.

Written by Bjoern Schaefer
Product Specialist, Capacitive Sensors
Balluff, Inc.

Balluff has a long, proven history of providing dependable, robust sensing technologies for the most challenging applications found in science and industry. This is reflected in the development and release of Smart level enhanced capacitive sensing technology, these sensors' high resistance to electro-magnetic interference and noise found in today's surgical suites and laboratories also makes FDA approval processes easy and predictable.

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