Liquid level sensor based on phase-shifting of radio-frequency wave

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***Abstract*—The presence of liquid slightly changes the local properties of submerged transmission line. A dedicated sensor is presented in this paper to estimate the level of liquid, through two different determinations: measurement of the overall capacitance of a bi-wires and time of flight estimation of electromagnetic radiation. Since two measurement methods are physically independent, the proposed sensor has an intrinsic redundancy. The level of liquid is measured through phase shift: the signals are sampled at a sufficiently high frequency and then phase differences is evaluated by calculating the coefficients of the digital Fourier transform. Both measurements are performed directly in baseband without requiring frequency conversions. In contrast with typical TDR system where the end of the cable is open or short-circuited, the bi-wires fold and return to the measurement electronics. The characterization of the proposed sensor is determined experimentally for water and diesel fuel, in good agreement with simulation results. As results show, both phase-shifting measurements are linear with the liquid level, providing a resolution in the order of 0.1 mm through a compact and low-cost realization.**

***Index Terms*—Capacitance measurement; Phase measurement; Transmission line measurements; Capacitive sensors; Measurement techniques.**

I. Introduction

DEPENDING on the type of fluid, operating condition, and required accuracy, several techniques such as contact or non-contact as well as direct and indirect approaches have been proposed to precisely detect the level of a liquid. The direct methods utilize devices such as a dipstick, gauge glass, float, displacer, etc. In the float or displacer-type sensor, the change of the liquid level is proportional to the position of a float or displacer [1,2]. However, loss of motion at mechanical linkages causes error in measurement in addition to a shorter life period [3-5]. In contrast, indirect approaches measure the level in terms of parameters that varies with changes in the level of liquid such as hydrostatic pressure, attenuation of radioactive energy, or electrical properties. The capacitive-type liquid level sensor is widely used to measure the level of water or aqueous solutions in a storage tank. Despite of simple and rugged construction, the sensitivity of such sensors reduces drastically for the liquid with low dielectric constant. Duarte et al. [6] and Miranda et al. [7] have measured and analyzed the impedance of a water capacitor between two metal electrodes at different frequencies of the excitation signal. They concluded a nonlinear variation of the impedance of the water capacitor with frequency. A modified capacitance-type level sensor is proposed in [8]. In the proposed sensor, the self-inductance effect of the metallic rod electrode of a conventional capacitance-type level sensor is eliminated. Its design consists of two non-inductive, two-layer windings mounted on coaxial cylinders immersed in the liquid, which was contained in a metallic storage tank. A linear response is demonstrated for a maximum liquid level of 60 cm. In [9], a Circuit Board (PCB) electrode was designed for developing a capacitive water-level sensor to measure the rise of the water level for avoiding floods, without been affected by the chemical composition of the water. The performance of the sensor was analyzed in the range of 0-30 cm, demonstrating linear response. In [10], a level sensor based on the Differential Pressure (DP) sensing approach is proposed. The phase-sensitive demodulation of the signal is performed by a discrete Fourier transform. Despite the linear response, the performance is evaluated in the presence of turbulence and temperature variation. The obtained results show a combined uncertainty lower than 1 mm, mainly limited by sloshing conditions. To compare with existing capacitive sensors, the measurement errors due to the presence of parasitic capacitance, foam, or more generally probe contamination have been eliminated in the proposed DP sensor. Despite capacitive or pressure-based techniques, various contact-based optical sensing methods have been carried out. Generally, measurement based on optical techniques may divide in discrete (or point) [11-13] and continuous level measurement systems. As non-contact technique, laser interferometry-based approaches also presented for continuous level measurement. Self-mixing interferometry is a measurement technique where

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a laser beam is reflected from an object and back into the laser [14]. In [15], a non-contact level instrument based on the self-mixing induced in the laser diode by modulating the laser wavelength is proposed to measure the level during the industrial filling process. The resolution of 1 mm is achieved when the level is increasing slowly without high frequency stirring. In a process known as ranging, distance is measured by an observer to the target by rangefinders such as laser, lidar, radar, etc. In Time of Flight (ToF) measurement principle, distance can then be calculated as one half the measured round-trip time divided by the propagation velocity. Ultrasound sensors can measure the level of liquid without having contact with the liquid based on the ToF principle. The ultrasound sensors produce relatively high frequency in a range of 20-200 kHz acoustic waves onto the liquid surface. A low-cost ultrasonic-based sensor system for the marine environment was characterized in [16]. As results show, the temperature has a remarkable effect on the measured TOF values and limits the functional range of the ultrasonic sensor. Sending microwave beams emitted by a sensor to the surface of the liquid in a tank is a principle behind all radar level detectors. Generally, radar level measurement methods are categorized into non-contact (non-invasive) or contact (invasive) approaches. Two well-known non-invasive systems are Frequency-Modulated Continuous Wave (FMCW) and Pulsed radar. The main advantage of employing the FMCW technique for level measurement in a tank is that the transmitted signals are frequency modulated i.e. FM instead of amplitude-modulated i.e. AM signals. Since a major part of the noise in a tank fall in the AM range, it does not influence the FM signals. In the case of dealing with fluid with a very low dielectric constant, such non-invasive measurement techniques can pose problems. As an alternative to through-air radar systems, guided wave radar systems have been proposed. In such a technique, a transmission path or a cable is used as a waveguide to lead the microwave from the source to the surface of the liquid. Then, straight to the bottom of the tank.

Guided wave radar-based level systems are fundamentally Time Domain Reflectometry (TDR) systems. This technique was first suggested by Rohrig in 1931 [17] as a method to detect cable faults. For over 40 years, cable fault detection was its main area of application until it was suggested as a solution to other engineering problems. Employing TDR technique in passive distributed sensing elements like (e.g., bi-wires) to precisely detect the presence of water in large areas has been demonstrated in [18][19]. The bi-wire acts as a permanent sensing element that can be connected to the measurement instrument whenever it is necessary to check for the presence of leaks. In [20] TDR-based solution for monitoring moisture content in cement-based samples is presented. Such approach offers the possibility of continuous monitoring the actual water content profile inside structures. The TDR measurement was performed through the Hyperlabs (HL1500). The instrument generates a step-like signal with a rise time of 200 ps and with amplitude equal to 250 mV. Since the presence of water increases the dielectric constant of the medium surrounding the bi-wire, two major approaches to measure level of the liquid have been examined and compared in [21]. The first approach was based on TDR itself. The idea was to measure ToF of the signal propagating along the bi-wire. While the second method includes measuring capacitance of the bi-wires [22]. All the tests were performed on a set of four bi-wires different lengths of 5 m, 10 m, 15 m, and 20 m. ToF measurements were performed using an arbitrary waveform generator (Agilent 33220A) and reflectograms were acquired using a 350 MHz-bandwidth digital oscilloscope (LeCroy LT262). The ToF values were measured as the time intervals between the two rising edges of acquired reflectograms. On the other hand, capacitance is measured based on charging time with a DC current using a portable capacitance meter (Escort EDC-128). In addition to the sensitivity evaluation, the two methods are compared regarding the possibility of false or missed detections due to temperature variations. ToF method shows lower sensitivity to temperature with respective to capacitance as expected by theoretical prediction. Although both methods can detect the presence of water, with the ToF method, the measurement hardware must be equipped with a fast clock. Consequently, two approaches are useful to trigger an alert regarding the monitored water detection system while more accurate control can be achieved using more expensive TDR instrumentation. The purpose of the paper is to propose a continuous level measurement employing both capacitance and ToF techniques. The proposed sensor utilizes variations in both capacitance per unit length and velocity propagation in bi-wires concerning the presence of liquid in single hardware through phase shifting of the radio frequency wave. Both measurements are performed in baseband where Discrete Fourier Transform (DFT) is performed based on evaluating the Fourier coefficients. We must note that the capacitance varies linearly with the dielectric constant of the medium, while the speed of electromagnetic waves depends on the square root of the dielectric constant, therefore the two measurements are independent. The advantage of acquiring double information considering ToF measurement results in less reduction in sensitivity for fluid with lower dielectric constant (e.g., fuel). The rest of the paper is structured as follows. Section II represents the numerical computation and simulation results to evaluate capacitance and velocity propagation due to the presence of the water and diesel fuel. In section III, level measurement methods in addition to measuring circuit are explained in more detail. The experimental arrangement and measurement results are discussed in section VI. Finally, a conclusion and future works are presented in Section V.

II. THEORETICAL ANALYSIS AND NUMERICAL COMPUTATION

Depending on the design and application, different types of cable can be used as transmission lines such as coax, two pair wires, parallel plates, etc. Assuming electric fields will oscillate and attenuate in the direction of propagation while the cross-sectional profile will remain unchanged, a well-known field solution then yields specific parameters known as parameters per unit length. Like any other arbitrary waveguide able to support such Transverse Electric-Magnetic (TEM) modes, bi-wires can be described using their specific parameters known as capacitance, inductance, resistance, and conductance per unit length [23]. Figure 1 shows cross section of Unshielded Twisted Pair (UTP) simulated in COMSOL Multiphysics to evaluate capacitance and inductance per unit length. The diameter of each wire d is 0.5 mm (24 AWG wire conductor) while High-Density Polyethylene (HD-PE) with dielectric constant ~2.3 is used as insulator. The distance between the center of wires D is 0.86 mm. Table1 represents the parameters expression and their nominal values for such geometry where the c is the velocity propagation of the light in vacuum.

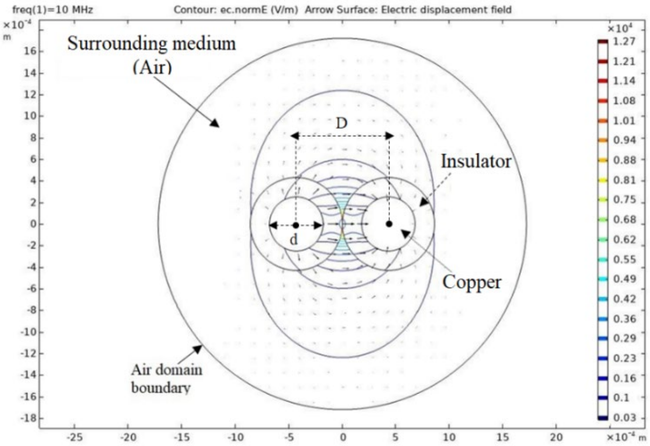

Fig. 1. Magnitude of electric field and distribution of electric displacement filed at 10 MHz for bi-wires consist of 24-AWG conductor and HD-PE dielectric surrounded by air.

As mentioned in literature, when the bi-wires are surrounded by medium other than air, useful information can be extracted by measuring the total capacitance or propagation speed of traveling electromagnetic wave in new medium. In such multi-layer systems, use of effective dielectric constant can considerably reduce the complexity of electromagnetic equation.

TABLE I
UTP CABLE'S PARAMETERS: EXPRESSION AND NOMINAL VALUES

Property	Expression	Nominal value	Unit
Capacitance	$C = \dfrac{\pi\varepsilon_0\varepsilon_r}{cosh^{-1}(D/d)}$	56×10^{-12}	F/m
Inductance	$L = \dfrac{\mu_0\mu_r}{\pi}\ cosh^{-1}(D/d)$	455×10^{-9}	H/m
Velocity	$1/\sqrt{LC}\ = 0.69\times c$	2.07×10^{8}	m/s

Therefore, the UTP cable coated by insulator with dielectric constant ε_c and surrounded by medium with dielectric constant ε_m is represented as a couple of conductors surrounded by a homogenous medium of effective dielectric constant ε_{eff}. Let us assume L length of bi-wires, which follows a symmetric round-trip path, is submerged into water while the rest is in the air as represented in figure 2(a). Here, L_d and L_w represent half of total length in the air and liquid, respectively. The effective dielectric constant associated with the dry portion of the bi-wires is represented by ε_{eff1}. While ε_{eff2} is the effective dielectric constant of the wet medium. In contrast with typical TDR system where the end of the cable is open or short-circuited, here, line folds and returns to the measurement electronics. Therefore, x is an offset in level measurement where the level of liquid is twice the wet length. In [24], an improvement in sensitivity of the TDR-based level sensor is achieved by wrapping the waveguide-pair around a cylinder. This introduces an inclination angle ϕ which increases the time-of-flight by a factor of $1/sin\phi$ and therefore the level resolution is increased by the same factor. An alternative design of the proposed sensor is shown in figure 2(b) where the bi-wires are folded and back again to the electronics as mentioned earlier.

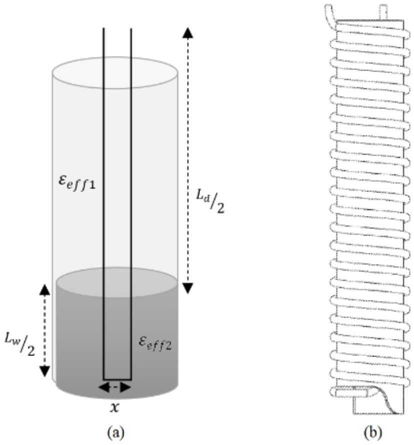

Fig. 2. Schematization of proposed level sensor; (a) Partially submerged straight bi-wires into the liquid with effective dielectric constant ε_{eff2} (ε_{eff1} is effective dielectric constant of the dry portion of wire), (b) folded and wrapped bi-wire around cylinder.

Before moving to experimental validation, let us to briefly express the variation in capacitance per unit length of bi-wires and velocity propagation in presence of the liquid. Using (1), total capacitance of generic length of L with effective dielectric constant ε_{eff} can be determined.

$$C = k.\varepsilon_0.\varepsilon_{eff}.L \tag{1}$$

where ε_0 is the absolute permittivity of vacuum and k is geometry dependent constant. Considering geometry of the bi-wires presented in figure 1, $k = \pi/\text{arccosh}(D/d)$. Following (1) and figure 2(a), the total capacitance of the partially submerged bi-wires in liquid may be written as:

$$C = k.\varepsilon_0.\varepsilon_{eff1}.L + k.\varepsilon_0.(2L_{wet} + x).(\varepsilon_{eff2} - \ \varepsilon_{eff1}) \tag{2}$$

Level of liquid l can be determined using (2) since it is twice the wet length in proposed level sensor. Further computation is necessary to obtain estimation of effective dielectric constants in both mediums. In general, dielectric constant of coating material is not declared by the manufacturer.

Considering the geometry of the UTP-CAT5, $k = \pi/\text{arccosh}(0.86/0.5) \cong 2.761$ and capacitance per unit length of conductors in vacuum equals to $C_c = 24.43$ pF/m. Since the nominal value of the capacitance per unit length C_n is 56 pF/m, its nominal dielectric constant is $\varepsilon_{eff1} = C_n/C_c \cong 2.29$ which is coherent with dielectric constant of HD-PE used as insulator in UTP-CAT5 cables. To determine an estimation of effective dielectric in presence of liquid, capacitance is computed using COMSOL Multiphysics for water and diesel fuel as surrounding liquid with relative permittivity $\varepsilon_w = 80$ and $\varepsilon_d = 4$ respectively. The computed capacitance in presence of diesel fuel is ~78 pF/m while it reaches ~205 pF/m for water. This indicates that the effective dielectric constants are ~3.2 and ~8.4 for diesel fuel and water respectively. As shown above, the effective dielectric constant varies depending on the surrounding liquid which results in different values for capacitance per unit length. However, this variation in effective dielectric constant also alters the velocity propagation of electromagnetic wave in such a multi-medium environment. Considering non-magnetic medium, the propagating wave experiences phase shift while traveling through L length of bi-wires as shown below.

$$\Delta\varphi = -\omega(L/v) \tag{3}$$

where ω is angular frequency and $v = c/\sqrt{\varepsilon_{eff}}$ represents the speed of propagation, being c the speed of the light in vacuum. Following the proposed level sensor geometry and (3), level of the liquid can be expressed by (4).

$$\Delta\varphi = \frac{-\omega}{c}\left(L.\sqrt{\varepsilon}_{eff1} + (2L_{wet} + x).\left(\sqrt{\varepsilon_{eff2}} - \sqrt{\varepsilon_{eff2}}\right)\right) \tag{4}$$

As shown earlier, the effective dielectric constant equals to 2.29 and therefore the electromagnetic wave propagates with speed of $v = 3 \times 10^8/\sqrt{2.29} \cong 1.99 \times 10^8$ m/s. According to derived values for the effective dielectric constant of diesel fuel and water, it is expected that the velocity propagation of the traveling wave through submerged bi-wires in these mediums becomes $\sim 1.677 \times 10^8$ m/s and $\sim 1.035 \times 10^8$ m/s respectively. It should be noted that the dielectric constant depends on temperature. Following (2) and (4), temperature dependency of capacitance and ToF methods can be evaluated based on sensitivity coefficients α_c and α_t, which are given by the relative variation of the measured parameter (capacitance and ToF) due to the presence of liquid. Assuming $\Delta C/C_n = \alpha_c \, \Delta l/L$ as relative capacitance variation in presence of liquid, the sensitivity coefficient α_c becomes $(\varepsilon_{eff2}/\varepsilon_{eff1}) - 1$. Since $t = \Delta\varphi/\omega$, the relative time taken by the wave to travel along the wet length can be determined as, $\Delta t/t_n = \alpha_t \, \Delta l/L$, being t_n its nominal propagating time. This resulting in a different sensitivity coefficient, which depends on the relative variation of square root of effective dielectric constant as $\alpha_t = \sqrt{\varepsilon_{eff2}/\varepsilon_{eff1}} - 1$.

In [22], the sensitivity to the temperature variation for both capacitance and ToF techniques have been studied and compared in more details. In conclusion, the level measurement based on traveling time affects less by temperature compare with measuring the capacitance. Here, the proposed sensor measures both capacitance and propagating time delay using single hardware. Therefore, the suitable technique can be selected automatically by user depending on the application without changing the hardware. It should be noted that the temperature characterization is out of the scope of this paper.

III. EXPERIMENTAL SETUP

A. Measurement methods

Generally, capacitance can be measured through several cost-effective and simple techniques such as measuring the charge time with DC current, capacitive bridge divider, relaxation oscillators or through more complex impedance metering algorithms [25]. In this paper, capacitance of bi-wires is determined through phase shift between two signals of the same frequency. Figure 3 shows a single line diagram of a transmission network that delivers the energy from source to a load through bi-wires. The network consists of an electrical source at frequencies of megahertz which supplies a sinusoidal wave with amplitude A to the network under impedance matching conditions. Source and load impedances are represented by Z_S and Z_L respectively. As shown in this figure, voltage is measured at three different points v_{o1}, v_{o2} and v_{o3}, with respect to ground.

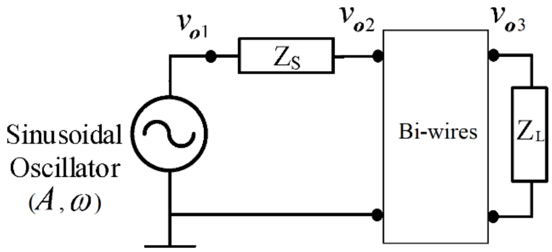

Fig. 3. Single line diagram of a transmission system based on bi-wires to deliver energy form the source to load.

If the length of bi-wires as transmission line is less than 1/10 of the wavelength λ, its parameters per unit length (e.g., resistance, capacitance, and inductance) are lumped into electrical components where only reactance can shift phase of voltage along the bi-wires. This results in substituting the bi-wire with a series RLC circuits where its capacitance varies due to presents of liquid. This is the circuit that is used for capacitance to phase angle conversion. Although drive frequency can be adjusted to keep the phase measurement in a readily measured range, one further step can improve more the sensitivity. Assuming Z_S-and Z_L purely resistive (R_s, R_L), the sensitivity with respect to the small changes in its capacitance can improve by measuring $\Delta\varphi_{31} = \angle v_{o3} - \angle v_{o1}$ instead of $\Delta\varphi_{32} = \angle v_{o3} - \angle v_{o2}$ since involving R_s simply shifts position of the pole to lower frequencies. Using (2) and considering the dielectric constant of water and insulator, this second-order system is simulated in MATLAB to estimate the variation in phase shift $\delta\Phi$ with respect to changes in level of water. The figure 4 shows the variation in phase shift for two driving frequencies 100kHz and 1MHz with and without purely resistive source impedance therefore $\delta\Phi_{31}$ and $\delta\Phi_{32}$ respectively. As shown in this figure, the resolution in water level measurement can be improved by increasing R_s in addition to the excitation frequency. If the length of bi-wires becomes greater than 1/10 of the wavelength, lumped circuit approximation is not valid anymore. In this case, its parameters per unit length are distributed contentiously and physical distance can provide phase shift.

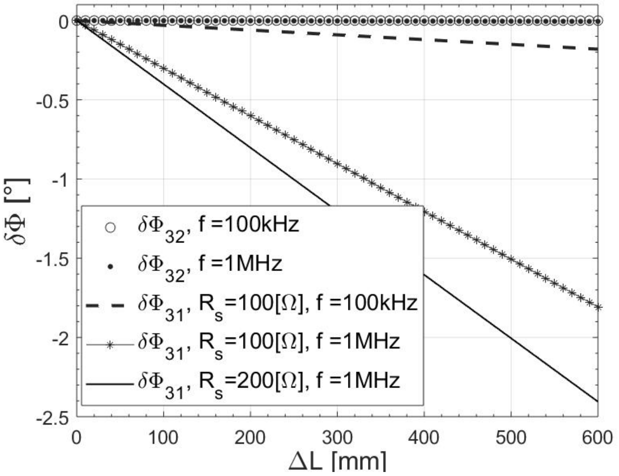

Fig. 4. Estimation on phase shift $\delta\Phi$ variation versus changes in level of water as function of excitation frequency and source resistance.

Assuming purely resistive source and load impedances, which they are placed physically close to the bi-wires, $\Delta\varphi_{21} = \angle v_{o2} - \angle v_{o1}$ is negligible, resulting $\Delta\varphi_{31} \cong \Delta\varphi_{32}$. This phase shift is proportional to traveling time for a propagating electromagnetic wave for a length of bi-wires as expressed in (4).

B. Instrumentation and Measuring Circuit

For the prototype, a UTP-CAT5 twisted pair cable is used as passive distributed sensing element in the proposed level sensor, but different types of transmission lines can be applied in the proposed sensor as passive sensing element, for example magnetic wires twisted or traces on a Printed Circuit Board (PCB). The cable folds and returns to the electronics that are mounted on top of the sensor, outside of the tank. This eliminates the potential risk of explosion in case of crash especially in relatively huge fuel tanks (e.g., airplanes). As mentioned earlier, the twisted pair can be kept straight or wrapped around a plastic cylinder. Such approach offers an alternative solution to the existing level probes where a rigid mechanical design can damage tank in case of crash, resulting in a leakage of the fuel with the risk of contact with the heated turbines and catching fire. In addition, the cost of the maintenance of such passive distributed sensing elements is very low since they can be replaced easily. Figure 5 shows the block diagram of the measuring circuit for the proposed level sensor. It consists of four units, namely signal generation unit, analog front-end, signal acquisition unit, and elaboration block. DIGILENT-Analog Discovery 2 (AD2) is a portable multi-function instrument that manages the signal generation and acquisition units. It uses clock generator PLL with integrated voltage-controlled oscillator (ADF4360-9). The AD2's Arbitrary Waveform Generation (AWG) unit uses a dual, 14-bit, 125 MS/s DAC (AD9717) to generate the wave. The AWG output voltage is limited to ±5V. To acquire the signals, a dual-channel, 14-bit, 105MS/s ADC (AD9648) is utilized. A dual channel monolithic ADC guaranties synchronization between two sampled signal sequences. Indeed, this measurement requires synchronous acquisition of signals from three different points of the circuit (v_{o1}, v_{o2} and v_{o3}). To keep the design simple and use efficiently the AD2, one ADC is shared between two measurement points which are selected using relays as multiplexer. While the second one is dedicated only to acquire signals from the third measurement point v_{o3}. Sinewave generated by AD2's DAC is a single-ended signal referred to AD2's ground. Due to limited current capability of the AWG output stage, to properly drive the bi-wires and the termination resistors, TI OPA692 high current video amplifier is used. Three voltage signals are sampled differentially with respect to their ground. TI LM6172 is used to buffer these signals from measurement points and related reference ground signal.

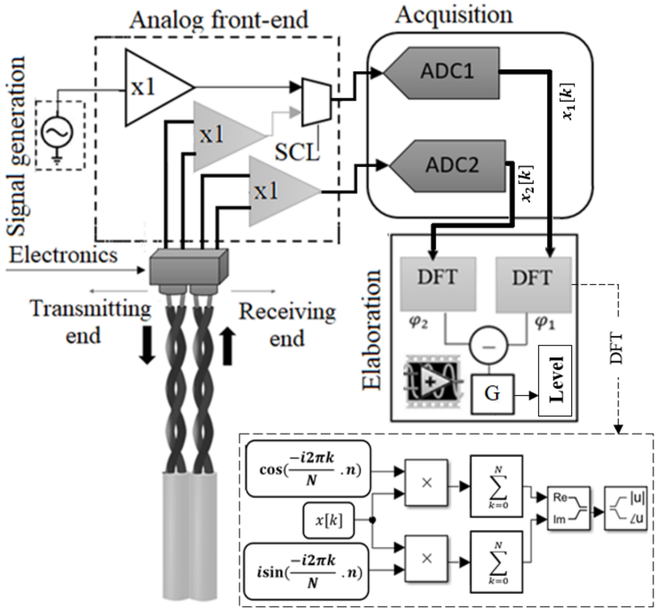

Fig. 5. Proposed level sensor with signal generation, acquisition, and processing block diagram.

In case of working at relatively low frequencies, measurement can be performed directly in baseband without requiring any frequency conversions. Therefore, sampling signal at sufficiently high frequency and then evaluating phase differences. Here, the phase and quadrature components are extracted using a digital synchronous receiver, which performs the multiplication of the sampled signal for two quadrature signals (sine and cosine at the same frequency), to then evaluate the Fourier coefficients [26] (bottom inset in figure 5). From the two phase and quadrature signals, a phase measurement is easily obtained, which becomes more accurate with the number of acquired points. The DFT is computed on 4000 samples, and it is performed on a personal computer by a program written in LabVIEW™ from National Instrument. Once the phase component for each measured signal is extracted, difference between them will fit into characterization curve of the instrument to detect the level. It should be noted that the proposed system is different from the already proposed ones, based on ToF variation [24]. The standard measurement is in time-domain [24], realized with high-cost instrumentation, and it is limited to ToF. In the present approach we have two independent measurements (ToF and capacitance) realized through low-cost electronics, at frequency limited to some megahertz (no need for expensive microwave instrumentation). This approach allows for system implementation in real field applications.

IV. EXPERIMENTAL RESULTS

Figure 6 shows the experimental arrangement to evaluate the sensitivity to the presence of the water for both capacitance and ToF methods. The level of water is increased in steps by adding water, and Keyence laser rangefinder (LK- G152) works as reference instrument during characterization and calibration processes. Considering 9 MHz of analog bandwidth for DAC and ADC, the driving frequency is limited to 7.5 MHz. This implies that the length of bi-wires should be greater than 4 m since the $\lambda = c/f = 40$ m.The UTP-CAT5 in length of 6.4 m is wrapped around 0.6 m of cylinder with thread angle of ~ 6 degree. The software manages the operating status (e.g., capacitive or ToF method) automatically by setting driving frequency, amplitude of excitation signal, and sampling frequency in addition to the relay's operation. The length of DFT vector is set for including a finite number of signal periods, to avoid problems of spectral leakage in the DFT elaboration. The time sharing between capacitance and ToF measures can be managed by user-defined acquisition counter in the software.

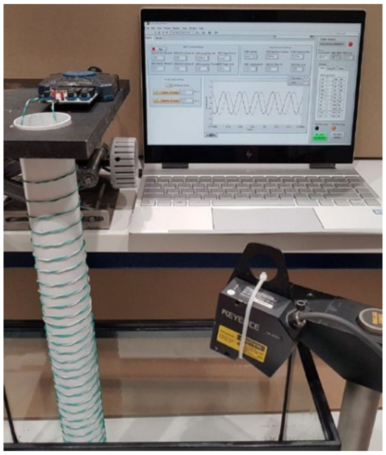

Fig. 6. Experimental setup for evaluating sensitivity of proposed level sensor with respect to the water presence including the reference instrument (LK- G152), and software.

Previously, we demonstrated that involving R_s results in improvement in sensitivity in capacitance measurement in addition to increasing driving frequency. Therefore, relays are configured to sample v_{o1} using ADC1 while v_{o3} is always sampled by ADC2. However, to verify the improvement in sensitivity practically, second characterization is performed where v_{o2} is sampled by ADC1instead of v_{o1}. Each signal is acquired at 10 MSPS for 400 µs, consequently, the DFT is computed on 4000 samples. Considering the frequency of driving signal 500 kHz and 1 MHz, system acquires exactly 200 and 400 periods respectively, avoiding problems of spectral leakage in the DFT elaboration. Figure 7 shows almost zero variation in phase shift $\delta\Phi_{32}$ with respect to the change in overall capacitance at 500kHz due to the presence of water. As expected, increasing the frequency of excitation signal to 1MHz results in more variation in phase shift with respect to small changes in capacitance. However, this sensitivity is improved further by measuring phase shift involving R_s as illustrated $\delta\Phi_{31}$ in figure 7. To measure the ToF variation as function of level of water, the frequency of the excitation signal is set to the maximum value (7.5MHz). Since $L > \lambda/10$ and the fact that sinusoidal source is located physically close to source and load resistors, the phase shift is only due to the distance traveled by wave.

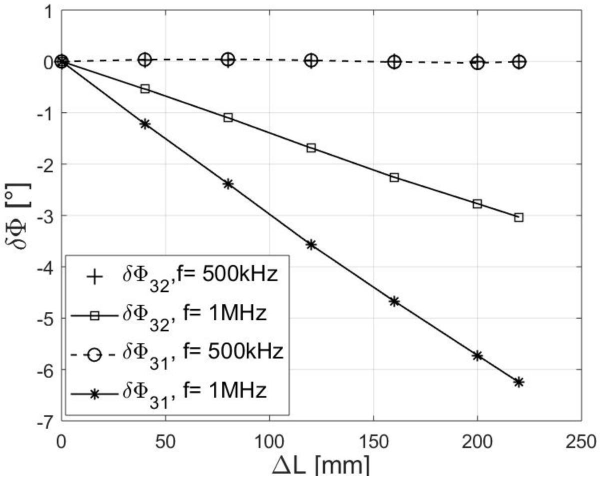

Fig. 7. Measured variation in phase shift V.S changes in level of water for driving frequency of 500kHz and 1MHz with and without source resistance ($\delta\Phi_{31}$ and $\delta\Phi_{32}$ respectively).

Therefore, the relays are configured to sample v_{o1} only using ADC1. As mentioned, ADC2 is dedicated to sample v_{o3}. Each signal is acquired at 100 MSPS for 40 µs, resulting DFT length of 4000. The sampling frequency choice depends on a trade-off between system cost and performances: 100 MSPS is about the higher frequency that we can implement with low-cost electronics. Considering that the driving signal is at 7.5 MHz, the system acquires exactly 300 periods. In figure 8, the variation in phase shift (ToF) with respect to the water is illustrated. Propagating wave needs ~9.5 ps to travel along 1 mm of UTP-Cable submerged in water. Since $9.5 \times 10^{-12}/10^{-3} = 2.(v_2 - v_1/(v_1.v_2))$, the velocity propagation in water v_2 is $\sim 1.02 \times 10^8$ m/s, being v_1 the velocity propagation in the air$\sim 2 \times 10^8$ m/s as determined numerically. This indicates the effective dielectric constant for part of UTP-Cable submerged in water $\varepsilon_{eff2} \cong 8.64$. Figure 9 shows the corresponding standard deviation curve evaluated on 100 repeated measurements for measuring the level of water using both capacitive and ToF methods: the ToF is evaluated at 7.5 MHz, sampled at 100 MSPS, while the capacitance is measured at 1 MHz, sampled at 10 MSPS. For common application of level sensing, the desired maximum allowable error is considered as ± 1 mm. Considering negligible uncertainty due to the reference instrument, the standard deviation is limited to about 0.1 mm under steady state conditions. The obtained results are adequate for different practical applications, and comparable with other standard techniques: capacitive sensors [8] shows a relative standard deviation of about $5 \cdot 10^{-4}$ over 50 cm (about 0.2 mm at 40 cm); capacitive [27] and piezoresistive [10] differential-pressure level sensors show an uncertainty value between 0.15 mm (under steady state condition) and 0.63 mm (under sloshing conditions).

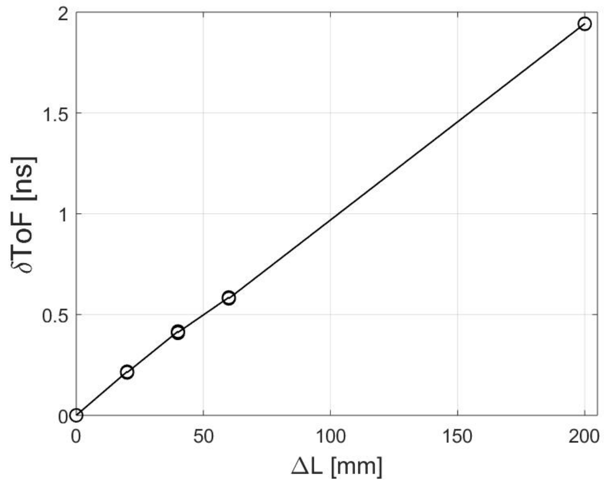

Fig. 8. Measured variation in phase shift V.S incrementing the level of water.

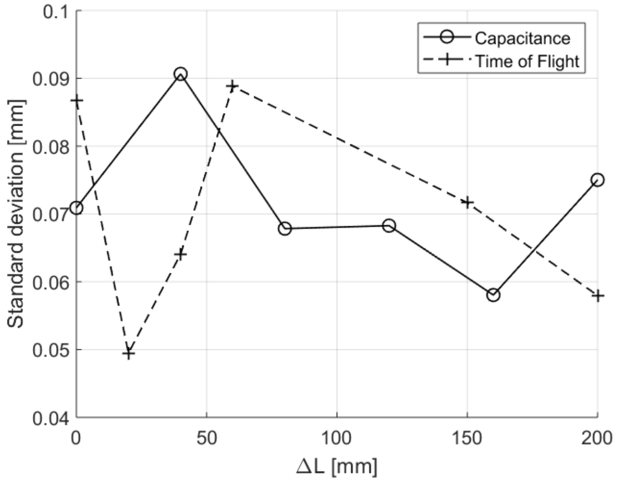

Fig. 9. Standard deviation for measuring level of water using both capacitive and ToF methods, evaluated over 100 samples.

As mentioned in literature, measuring the level of liquids with very low dielectric constant is a challenge for TDR-based system where such pulse-duration measurements with high resolution require high costs for the overall data-acquisition system. Figure 10 shows the sensitivity of proposed sensor while measuring the level of diesel fuel. As shown in this figure, the velocity of the propagation is $\sim 1.652 \times 10^8\,\mathrm{m/s}$ which results $\varepsilon_{eff2} \cong 3.4$. Therefore, the proposed sensor provides an alternative solution for measuring the level of liquid with low dielectric constant. Linear response with sufficient resolution to measure continuously the level is achieved while reducing the cost. It should be noted that:

- Choice of the UTP-Cable is not the optimum and other bi-wires in alternative geometry covered by different insulator may be selected as passive distributed sensing elements.
- Precise threat angle in wrapping of the twisted pair around the cylindrical body is out of the scope of this paper. A better realization is presented in [24] where the cylinder was printed using 3D printer with a thread angle of 0.9°.
- The proposed sensor uses a multifunctional and portable instrument (AD2) to generate and acquire the signals. Its price is two orders of magnitude lower than a portable and accurate reflectometer. There is also the possibility to implement dedicated embedded electronics, drastically reducing the system.
- DFT algorithm and elaboration of the results are managed by software developed using National Instruments LabVIEW on a PC. However, this can be implemented in a cost-effective microcontroller, as shown in [11].
- Liquid level is measured through two different methods. It allows for the measurement of other liquid parameters, by custom calibrations.
- Surface tension contribution is not considered in this characterization: for our measurement setup the liquid surface tension appears as an offset that is already included during characterization. This effect can add measurement hysteresis, depending on the liquid properties and surface treatment, that will affect the measurement accuracy.

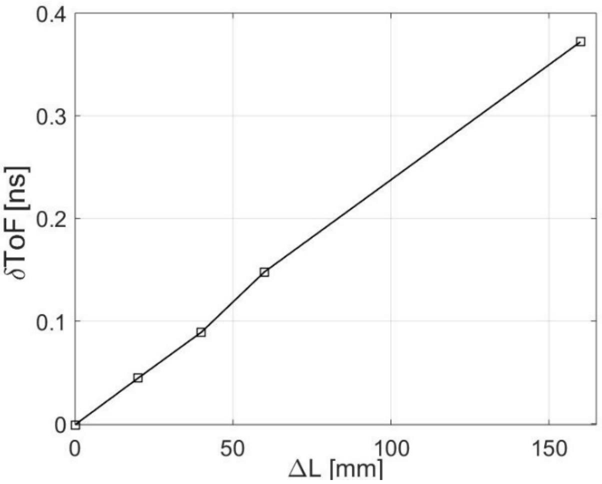

Fig. 10. Measured variation in phase shift as a function of the level of diesel fuel.

V. CONCLUSION

In this paper, a level sensor is proposed to detect the level of liquid based on phase shift measurement through two different determinations, which concern the measurement of overall capacitance of the bi-wires and propagation time of electromagnetic radiation. The behavior of twisted pair cable UTP-CAT5e as passive distributed sensing element covered by thin layer of HD-PE insulator which is partially submerged in water or diesel fuel is simulated using COMSOL Multiphysics. Simulation results show a total capacitance increasing from its nominal value 56 pF reaching to ~78 pF/m and ~205 pF/m due to presence of diesel fuel and water respectively. This results in ~3.2 and ~8.4 as the effective equivalent dielectric constant. It is also demonstrated that the propagation speed of electromagnetic wave in such multimedium environment reaches $\sim 1.677 \times 10^8\,\mathrm{m/s}$ for fuel and $\sim 1.035 \times 10^8\,\mathrm{m/s}$ for water. As result of characterization, it is experimentally demonstrated that both phase shifting measurements provide a result that varies linearly with the liquid level. The proposed level sensor consists of commercial twisted pair cable UTP-CAT5e which as passive distributed sensing element, dedicated driver circuit and a portable multi-function instrument (Analog-Discovery 2) to generate and acquire the signals. The phase measurement is obtained by calculating the coefficients of the digital Fourier transform, through multiplication by a sine vector and a cosine vector at the generated frequency. UTP-CAT5 in length of 6.4 m is wrapped around 0.6 m of cylinder with thread angle of ~6 degrees. In addition, it demonstrated that the sensitivity of the proposed sensor is improved by involving the input resistance. The frequency of the excitation sinewave is chosen 1MHz for capacitance measurement. Sample rate is 10 MSPS and the DFT is computed on 4000 samples. For 6.4 m of the twisted pair cable driven by a sinewave at 7.5MHz, the Lumped circuit assumption is not valid anymore. However, distance traveled by wave through the wire provides phase shift. Compared to the offset (x), the phase shift due to the physical position of source and load resistance or mismatch in line impedance is negligible. To measure the ToF with respect to the presence of liquid, the sampling rate is 100 MS/s and DFT is computed on 4000 samples. The ToF measurement shows the velocity propagation of $\sim 1.02 \times 10^{8}\,\mathrm{m/s}$ and $\sim 1.652 \times 10^{8}\,\mathrm{m/s}$ for water and diesel fuel which indicates a good agreement between the numerical and experimental results. The proposed sensor offers a single, compact, and cost-effective hardware to measure level of the liquid using two capacitance and ToF methods: in the proposed prototype a multifunctional and portable instrument (AD2) was employed (its cost is about 200 €), but the same principle can be implemented on low-cost embedded electronics, all driven by a microcontroller. As future works, the Analog discovery 2 will be substituted by embedded electronics to generate excitation signals, acquire, and elaborate the results independently. Further studies on the geometry and type of bi-wires are required in addition to temperature and prob contamination dependency.

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