Research Article

Design, development and application of a real-time capacitive sensor for automatically measuring liquid level

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Abstract

In the present study a real-time capacitive sensor based on a capacitance step method is designed, developed and applied on measuring the liquid level by immersion. The capacitive sensor consists of two electrodes from copper plated phenolite plates separated by a gap distance and mounted inside a non-conductive storage tank. Water is used as the dielectric material. The analyzed sensor behavior with liquid level variation is semi-linear and obtained in function of the output voltage variation by using proper signal conditioning circuit. For converting the voltage variation into level variation, a parallel R–C circuit is used instead of conventional bridge circuit. Under suitable parameter settings it provided good reading accuracy. The experimental results demonstrate the high efficiency of the proposed model, which confirm the satisfactory performance of the capacitive sensor for liquid level measurement. The sensor presents an excellent ease of construction and installation, linked to the good measurements precision and high autonomy of system operation. The behavior experiments under different salt concentrations show that the water chemical composition does not interfere on the sensor operation. The proposed model exhibits a promising employment in several applications, such as control equipment for irrigation, biomedical area—in the interaction between antibody–antigen or protein-DNA, aerospace and pharmaceutical industry, gas sensors, and automation solutions.

Keywords Real-time capacitive sensor · Capacitance step method · Liquid level · Parallel R–C circuit · High autonomy

1 Introduction

Capacitors are electrical components applied to store electrical charges in an electric field, accumulating an internal electric charge imbalance [1, 2]. Capacitance (C) is their property of interfacial charge storage in the form of an electrostatic field [3], and it can be calculated by the quotient of the stored charge quantity (Q) and the potential difference between the plates (ΔV), according to Eq. 1:

$$C = \frac{Q}{\Delta V} \tag{1}$$

A capacitor generally consists of two metal conductive plates, denominated electrodes, charged by a voltage source and separated by thin layers of an insulating medium, a dielectric substance, in which the charges are stored on the plates surface by means of their polarization, at the boundary with the dielectric [1]. The capacitors allow the electrical energy to be stored during a certain charging period, which may be fast or slow depending on the RC constant associated therewith, and then released as needed under controlled conditions. The storage mechanisms can be classified as non-Faradaic, pseudo-capacitive (Faradaic) or Nernstian capacitive, each with electrochemical properties of the electrodes and characteristic cyclic voltammograms [4]. Figure 1 shows the graphical representations of the main proposed storage mechanisms. Akinwolemiwa and Chen [5] attest that the Faradaic

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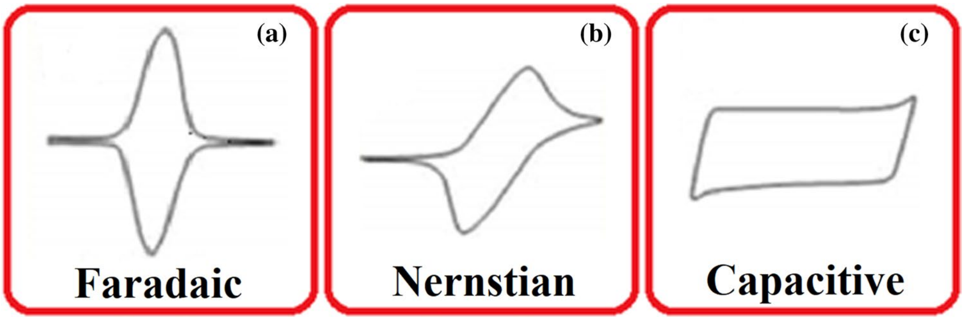
Fig. 1 Graphical representations of the voltammetric characteristics of the load storage mechanisms Faradaic (**a**), Nernstian (**b**), and capacitive (**c**)



process results from the transfer of valence electrons from ions at the electrode–electrolyte, and it is governed by the Nernst equation (Eq. 2).

$$E = E^0 + \frac{nF}{RT}\ln\left(\frac{1-x}{x}\right) \tag{2}$$

Capacitors are employed in different applications, being commercially available in the following basic technologies: ceramic, aluminum electrolytic, tantalum electrolytic, polymer films, paper or mica films, double layer chemical capacitor (DLC), and multilayer capacitors—high dielectric constant inorganic coatings (TiO_2; $ZrTiO_3$; $CaTiO_3$) constructed with interleaving electrodes in a multilayer configuration using molecular beam epitaxy [1, 6].

Several studies have been carried out around the use of capacitors in the manufacture of chemical sensors based on the field effect, searching more compact dimensional characteristics and more precise experimental resources [7–9]. Murugarajan and Samuel [10] used a high-resolution capacitive sensor for mesoscale dimensional characterization. A miniaturized experimental setup was developed using the high precision capacitive sensor and XYZ linear stage to perform the measurement. The authors proposed an algorithm based on the gain of sensor output voltage during the channel resource scanning in order to optimize the dimensional resources. Zhao et al. [11] designed a side-coupled optic-fiber liquid level sensor to achieve intrinsically safe measurement to liquid level in flammable environments. The results indicated problems in this sensor, such as the narrow measuring range (200 mm) and susceptibility to the dip of liquid. For real-time detection, Berggren et al. [12] developed a data acquisition system for direct capacitance measurement. The instrumentation has been successfully applied for the direct detection of several target analytes.

Liquid level is an important variable on the measurement and control of industrial processes. It can be detected by various methods, such as the float, ultrasonic, differential pressure optical, and capacitive methods [8, 9]. For any control system using a control loop, a sensor is required to measure the variable process and generate feedback. There are some sensors capable of converting data into an electrical signal, transmitting it from a distance—e.g. the liquid level. Each sensor has its advantages and disadvantages according to its application [13–15].

The liquid level measurement can be used from the characteristic of the liquid itself; such as permissiveness, permeability and conductivity [16, 17]. Among several techniques for sensing liquid level, the capacitive sensor has been widely highlighted due to its high linearity low power consumption, low cost, and simple to use. Its operating mechanism acts by measuring the capacitance variation of the capacitor formed by an electrode—of positive charges—immersed in the liquid that functions as a dielectric, and the tank wall, with negative charges. Figure 2 demonstrate the operating scheme of the capacitive sensor.

An attractive alternative in the industrial automation area is the capacitive detection in relation to mechanical systems. Currently, it is possible to notice a technological tendency for the use of capacitors in the industrial and consumer sectors, mainly due to the absence of mechanical parts in capacitive detection, which results in greater

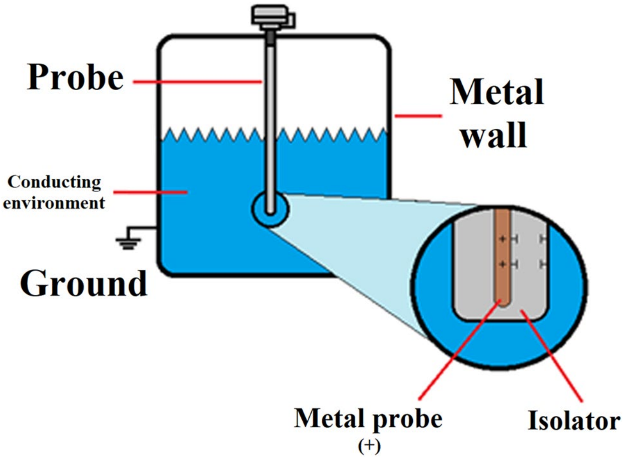


Fig. 2 Demonstrative schematic of the capacitive sensor actuation mechanism for measuring liquid level

durability and reduction of mechanical hysteresis. The capacitive sensor for works by immersion in liquids acts like a probe, getting a part dipped in the fluid that is stored there in the reservoir. It can still function as a simple cylindrical metal rod, the outer cylinder being the storage tank itself. Chetpattananondh et al. [18] developed a low-cost interdigital capacitive sensor for water level measurement. The experimental results confirm that the sensor has high sensitivity of linear character. Qurthobi et al. [19] manufactured a high impedance capacitive sensor for detecting the water level. The experiments results demonstrated a non-ideal condition effect because the sensitivity values were not constant.

In this way, the present paper describes the development of both hardware and software of a low-cost real-time capacitive sensor for liquid level measurement and monitoring. The system presents a simple setup and easy to install, and consists of two electrodes from copper plated phenolite plates which are separated by a gap distance. Water has been used as dielectric medium of the capacitor. The liquid level variation has been converted into voltage variation using parallel R–C circuit. Experimental simulations were performed to evaluate the repeatability, linearity and resolution of the proposed model. The developed model, besides presenting a measurement method and low-cost of development, can contribute to the most several applications types, due to its construction design and operation mode, such as control equipment for irrigation, biomedical area—in the interaction between antibody–antigen or protein-DNA, aerospace and pharmaceutical industry, gas sensors, and automation solutions by artificial neural network, and can be employed with different types of liquids.

2 Experimental methodology

2.1 Real-time capacitive sensor design and fabrication

Figure 3 illustrates the system composition of the designed liquid-level sensor. The capacitive sensor is formed by two PCB conductive plates of thickness 1.5 mm, with configuration of interpenetrating comb electrodes. The designed sensor has 300 mm long and 80 mm wide, and a gap between plates of 10 mm. Both plates present the capacity to store electrical charges, and the distance between plates as well the electrode dimensions can vary the capacitance range of the sensor. The PVC tank inner diameter and thickness are 200 mm and 3 mm respectively. However, these parameters have no specific limits. Besides that, the possibility of using such materials and dimensions allows a significant reduction of prototype costs.

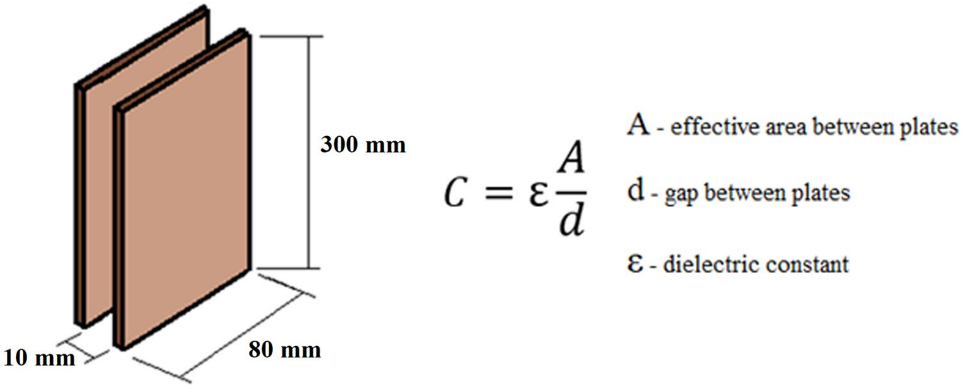
2.2 Signal conditioning of R–C circuit

The capacitance variation due to changes in liquid level in the tank has been converted into voltage variation with the application of a parallel R–C circuit, as shown in Fig. 4. A DC source with a fixed operating voltage of 9 V was used to power the circuit. The IC/NE 555 oscillator integrated circuit was used to output uninterrupted frequencies during system operation. Such frequencies varied according to the signal emitted by the sensor connected in parallel to that frequency signal. Voltage divider was used to facilitate the integration of a liquid crystal display (LCD) for better visualization of the obtained result. The oscillator output signal was treated by a rectifier diode and by the circuit R–C.

For a simple R–C equivalent circuit, the current decay, evoked by a potential step, is:

$$i(t) = \frac{u}{R_E} \exp\left[\frac{-t}{R_E C_{Total}}\right] \tag{3}$$

Fig. 3 Dimensioning and design of the plates used as electrodes in the capacitive sensor



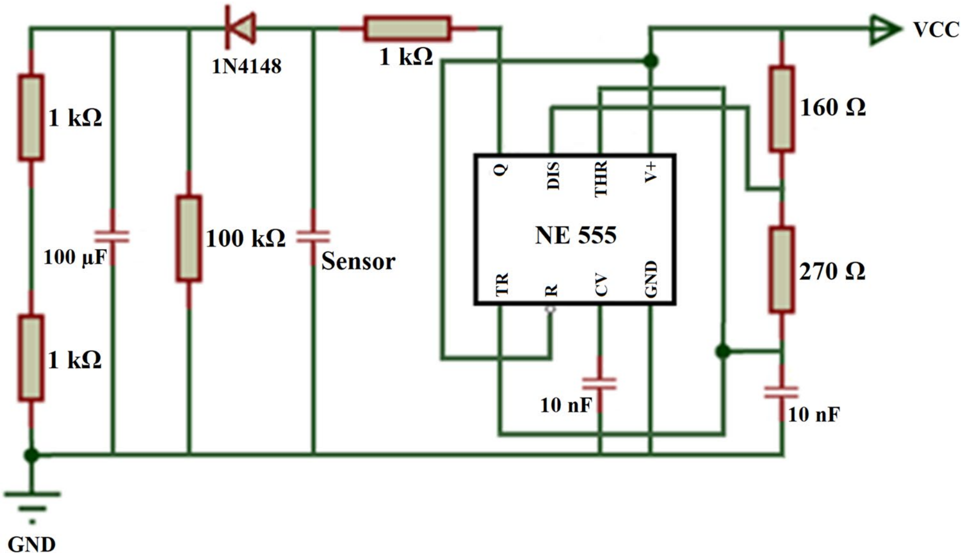


Fig. 4 Electric diagram of the capacitive sensor circuit. The proposed model consists of the sensor electrodes, a parallel R–C filter, and for the IC/NE 555 oscillator integrated circuit

where *i*(*t*) is the current in the circuit as a function of time, u is the applied pulse potential, R_E is the electrical resistance of elements serially connected to the layer, t is the time elapsed after the potential step was applied, and C_{Total} is the total capacitance measured at the working electrode/solution interface.

In this configuration, the IC/NE 555 oscillator was connected to 160 Ω and 270 Ω resistors, and to two capacitors of 10 nF, in order to provide the system with an output frequency of 130 kHz. Already in the sensor mesh network, the 1N4148 diode was used to rectify the output signal and to protect the circuit against possible overvoltage. R–C circuit was employed to attenuate the output voltage, being composed of a 100 kΩ resistor and a 100 µF capacitor. The sensor electrodes were constructed from two copper phenolite plates—more indicated because of their resistance to chemical corrosion by prolonged use in water. One of the boards was coated with contact-type plastic film for insulation, since in electrically conductive liquids an insulating layer must be molded around a rod, which serves as an electrode. The other electrode of the capacitor may be the shell itself or a new rod, as used in this work. The plates were arranged parallel to 10 mm, to form the sensor capacitive effect, and fixed in a plastic base. Plates act like the walls of a capacitor: one connected to the positive pole of the circuit and the other to the negative pole, parallel to the output signal of the oscillator. The PIC18F4520 microcontroller has been selected to perform level control of the sensor, powered with a voltage of 5 V and with its negative pole connected to the ground of the circuit. The microcontroller was used to calculate the capacitance between the electrodes, relating the electric discharge time to the water level. This method is a practical technique of measuring the water level, where the electrodes are used as level and reference sensors. This technique can be applied directly to water under different conditions and without recalibration.

2.3 Experimental simulation and theory of the sensor operation

The principle of sensor operation is based on the overall block diagram of the real-time capacitive sensor system shown in Fig. 5. During the measurement, when the sensor electrodes are immersed in the liquid, the liquid level is linearly converted to the corresponding capacitance signal at the same time. Then, the capacitance measurement is sent to IC/NE 555 oscillator, and treated by a R–C filter sequentially, obtaining a DC voltage signal. This output voltage signal is supplied to the PIC18F4520 microcontroller, which control the LCD to display the liquid level and communicate with other devices by a transmitting frequency signal that contains the liquid level information.

Simulations were initially performed to verify the capacitive sensor behavior and its linearity during the readings. The level measurements simulation was performed in a

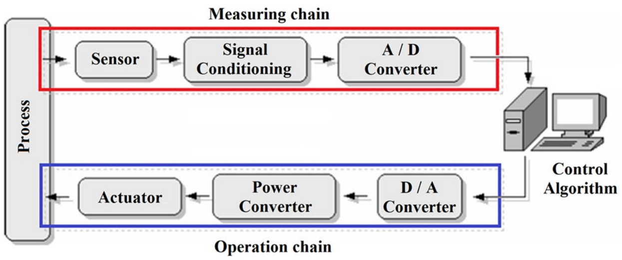


Fig. 5 Block diagram shows the real-time capacitive sensor system

tank with a volumetric capacity of 2.0 L, filled with water without any additives, and with adequate dimensions so that the sensor could enter without obstructions, according to Fig. 6. The water had the function of acting as the dielectric present between the capacitor plates, being responsible for the capacitance values obtained during measurements. The dielectric constant between the plates is proportional to the water level. Tests were carried out to calibrate the system in order to define the operating principle and to elaborate the measurement, storage and data transfer procedures.

3 Results and discussion

3.1 Experimental setup

Figure 7 shows the experimental setup used to demonstrate the proposed real-time capacitive sensor system. The sensor electrodes were immersed into the PVC cylindrical tank. The 9 V power source provided basic electrical power to the proposed sensor system through the power cables. The sensor capacity changes were tested during immersion the sensor in water to a depth ranging from 0 to 180 mm. The sensor was able to measure absolute water levels with a resolution of 2 mm. The output voltage measurements were carried out using a digital voltmeter during the simulations.

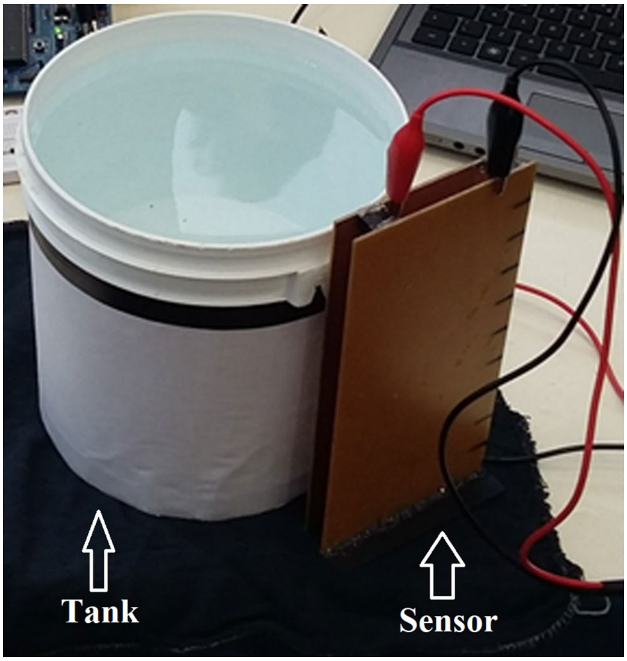


Fig. 7 Prototype of the developed capacitive sensor model, and experimental setup

3.2 Real-time liquid level measurements

The voltmeter indicated an output voltage value of 1.58 V with the empty tank. It was observed the output voltage variation from the sensor submersion in the tank loaded with water. The output voltage value was 0.95 V with the fully filled tank. There was voltage values variation obtained at the output of the circuit from the water level height variation present in the tank. Table 1 shows the measurements realized directly on the tank (mm) and the respective voltage values (V) obtained by the capacitive level sensor. The observed behavior occurred due to the progressive increase of the capacitance value between the phenolite plates, as the air dielectric is subjected by the water dielectric. The sensor mean sensitivity was determined to 3.5×10^{-3} V mm^{-1}.

The capacitive sensor calibration was realized from the voltage values obtained at different liquid levels, thus identifying the curve that best corresponds to the behavior of the results, and their respective behavioral equation (Eq. 4), where *x* represents the height of the liquid level on real-time, and *V* is the output voltage. The coefficient of

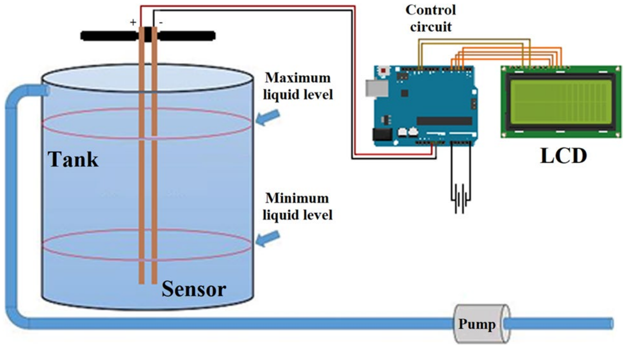


Fig. 6 The real-time capacitive sensor mounted on tank side, and its operation principle of proposed model with dielectric liquids

Table 1 Performance of the proposed real-time liquid level capacitive sensor

Height of water level (mm)	Output voltage (V)
Zero	1.58
20	1.27
40	1.18
60	1.15
80	1.09
100	1.04
120	1.01
140	0.99
160	0.97
180	0.95

determination (R^2) was equal to 0.9985, which shows the excellent correlation between the capacitive sensor and the standard scale used.

$$V = (2 \times 10^{-5})x^2 - (7 \times 10^{-3})x + 1.5 \tag{4}$$

Figure 8 shows the relationship between the water level in the tank and the output voltage values. Comparing the experimental and estimated data by the adjusted equation, it can be noted that the behavior observed between the values is proportional, with a semi-linear characteristic. The results suggest a change in sensor behavior under larger depths: its response time became slower when the sensor submerged deep into the water (Fig. 8b). Several experimental simulations were carried out to observe the effects of water contamination on the capacitive sensor behavior. Figure 9 exhibits the results for pure water as a reference, and different salt concentrations. All contaminations were mixed to 2.0 L of deionized water. The behavior experiments were tested with a water level of 40 mm—around to the limit of the sensor linear behavior. The results indicated an insignificant variation during water level measurements. Such behavior suggests that, since the common use water filtered, its chemical composition did not interfere on the sensor operation.

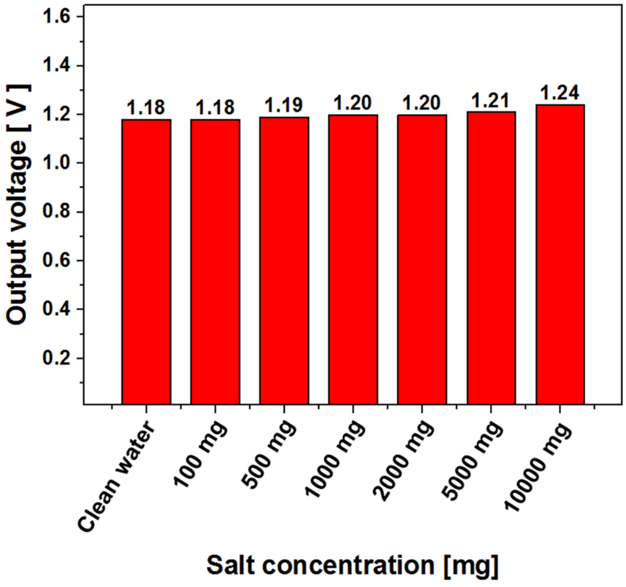


Fig. 9 Sensor output voltage behavior versus several salt concentrations in the water

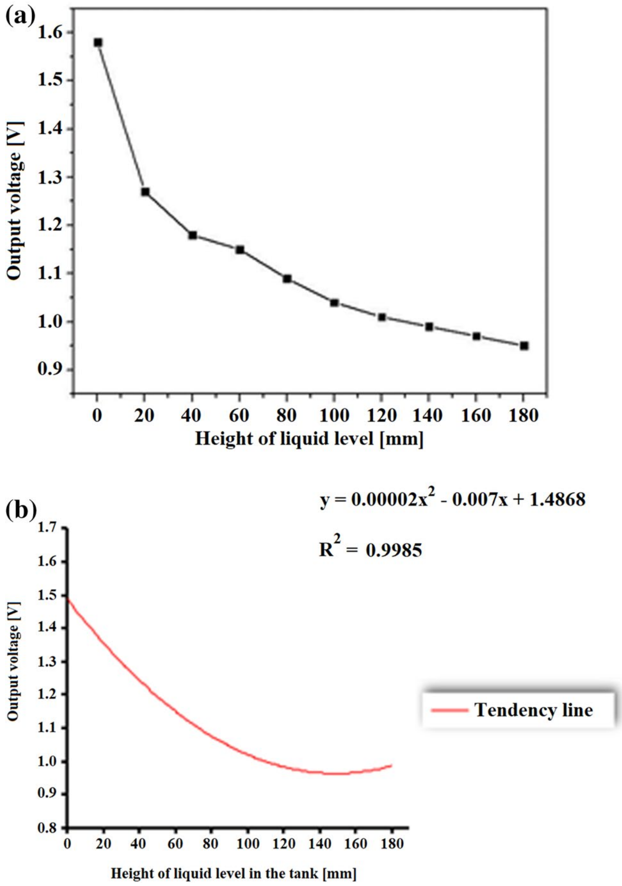


Fig. 8 **a** Experimental data of characteristic behavior of the capacitive sensor; **b** fitted results of the voltage variation with liquid level

Equation 4 was used for sensor calibration, and as a factor for the converter calculation applied in the program created in C language used in the microcontroller—responsible for converting the analog voltage values into digital values, and decoding these values into a dimensional quantity directly proportional to the height of the water level, exhibiting it on the LCD. In this way, according to the height of the water level present between the capacitive sensor plates, the capacitance of the circuit changed promoting the output voltage variation of the circuit. This voltage was converted by the program carried out by the microcontroller and presented on the LCD screen, with values proportional to the height of the water level in the tank, as shown in Figs. 9 and 10.

The sensors developed by Paczesny et al. [17], Qurthobi et al. [19], and Nascimento et al. [20] presented a similar trend to that reached by the present study, being that the variations found, characteristic curve and reading accuracy, were due to the cylindrical shape used in the procedure. The probability curves measured were extremely similar to those acquired during our experiment. In resume, the results obtained with the development of the system and in the application of the capacitive sensor prototype proved to be satisfactory. A reliable and easy installation methodology was used to validate the values reached by the suggested model. According to the data referring to the measurements taken in the study and simulation stage of the sensor (Fig. 8), the tank level readings curve presents a normal probability distribution, both

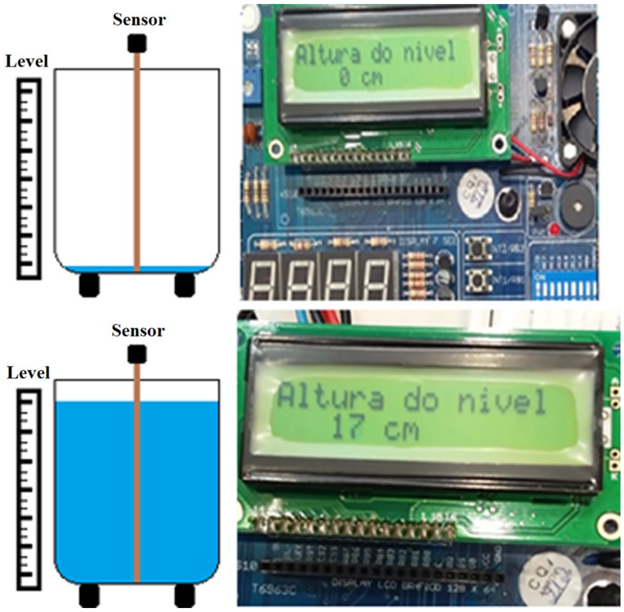


Fig. 10 Summary result of experimental simulations of real-time capacitive sensor operation with tank water level variation

for small and large levels of measurements under natural conditions, with good repeatability. The real-time capacitive sensor exhibits an attractive cost value—due to the components used in its construction—easy installation, simple maintenance and good measurement accuracy, when compared to gradients commonly used for this purpose, which guarantees its promising employment in an innovative and dynamic way in several areas of application, such as control equipment for irrigation, biomedical area—in the interaction between antibody–antigen or protein-DNA, aerospace and pharmaceutical industry, gas sensors, and automation solutions.

4 Conclusions

A real-time capacitive sensor for automatically measuring liquid level in the tank has been successfully designed and developed. In the present configuration, the capacitance variation was converted into output voltage variation by a parallel R–C circuit instead of conventional bridge circuit for simplicity. The proposed model not only displays the output voltage, but also displays the liquid level in real-time. Experimental simulations using the capacitive sensor indicated that this model has good linearity, high operating autonomy, and repeatability in the measured range. The low cost of the electronic components used and easy installation of the system allow the use of the capacitive level sensor in several applications, with high efficiency and extensive measuring range. The developed model could be applied to lingraphs, rain gauges and other equipment to measure hydrological variables—since the level sensors available on the market are expensive and do not apply to small reservoirs—as well as to track, for example, the rising tide of water level instantly. The communication between the analog circuit and the microcontroller made the sensing process more dynamic, which facilitated the liquid level measurement. Both hardware and software are educational and simple to build, confirming its promising and attractive application in measurement with high confidence. The behavior experiments under different salt concentrations showed that the water chemical composition does not interfere on the sensor operation. Future improvement may include experiments using liquids of composition and different properties, in order to avail the behavior of the sensor in different conditions. Further the software development to facilitate data analysis, such as calculation of the mean and standard deviation of replicate analysis, as well as adjustment of the system for portable field analysis would also be useful.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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