A Low-cost Capacitive Sensor for Water Level Monitoring in Large-Scale Storage Tanks

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Abstract—Water-level sensors are indispensable for monitoring the level of water in storage tanks, which are used in drinking water distribution networks. In this paper, a long-range capacitive-type water-level sensor is presented. The proposed sensor is constructed using widely-available multilayer tubes, which are used for building drinking water systems. Thus, both the manufacturing cost of the sensor and the cost of the associated electronic circuits, which are used for interfacing the sensor to a digital data-acquisition unit, are low. The performance of the proposed sensor has been evaluated in a water storage tank of a city-scale water distribution network. The experimental results indicate that the accuracy of the proposed experimental prototype sensor is equivalent to that of a commercially available ultrasound water level sensor, while, additionally, its manufacturing cost is significantly lower.

Keywords— Sensor; Capacitive; Water level; Data-acquisition

I. INTRODUCTION

Sensors are used for monitoring the level of liquids in storage reservoirs, containers and tanks. Multiple alternative liquid level measurement techniques have been applied, such as magnetic, radar, ultrasonic etc., since varying the range, installation conditions and liquid type impose different specifications for the sensor [1]. The ultrasound and Time Domain Reflectometry (TDR) sensors are frequently employed for measuring the level of liquids in storage tanks. However, these sensors exhibit various disadvantages. The ultrasound sensor measurements are affected by the bubbles in liquid surface, which can result in the scattering of the sound waves in the surrounding air, causing errors in measurements. TDR sensors comprise a very accurate measurement solution; on the other hand, the cost of monitoring pulse-duration changes with high resolution increases significantly the cost of the overall data-acquisition system [2], [3]. In [4], a long-range sensor is presented, using an optical fibre Fabry-Perot interferometer. The results indicated an excellent resolution with small error in water measurements. However, specific instruments are required and a complicated installation process for applying this measuring technique, which may not be feasible in case of tanks installed in an urban environment.

Capacitive-type liquid-level sensors are also frequently employed for measuring the capacitance developed between the electrodes immersed in the desired liquid, which is then used for calculating the corresponding level of the liquid in the tank. Printed Circuit Board (PCB) electrodes were designed in [1] for developing a capacitive water-level sensor in a monitoring system that was designed to measure the rise of the water level for avoiding floods, without been affected by the chemical composition of the water. That sensor was tested in the range of 0-30 cm, exhibiting good linearity. In [5], the circuit design for floating and grounded capacitive sensors fabricated on a PCB, is presented. Operational amplifiers are used, which results in linear behavior and an acceptable accuracy. Cylindrical capacitive electrodes were developed in [6] for a liquid-level sensor. A linearization network for the capacitance measurement circuit was also used, providing results with good linearity in the scale of 0 - 25 cm. A capacitive-type liquid level sensor was presented in [7], consisting of two non-inductive, two-layer windings mounted on coaxial cylinders immersed in the liquid, which was contained in a metallic storage tank. Results are demonstrated for a maximum liquid level of 60 cm with excellent linearity. However these electrodes exhibit the disadvantage that it is difficult to be transported to remote locations due to their non-flexible structure. The design of long-range capacitive sensors has been studied in [8], but it has only been limited to computer simulations. The water level capacitive sensors reported in [9-13] have been designed to operate over a relatively small range (i.e. below 1 m). The capacitive-type sensor, which is presented in [14], can operate only in metal tanks, since in that case the tank shell acts as one of the capacitive-sensor electrodes. Although capacitive sensors exhibit good linearity, the use of an Artificial Neural Network is proposed in [15] in order to increase the linear range of capacitive sensors and provide self-calibration features to the measurement system.

As cities are expanding, together with the increase of water and energy prices, sustainability of water-supply systems is vital. Thus, an important application of level sensors is for measuring the level of water, which is temporarily stored in large-scale tanks contained within the water distribution networks of communities, cities etc. In these systems, the water level information acquired by a large number of water storage tanks is typically transmitted to a central monitoring

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station where appropriate water management processes are applied. Due to the large number of water storage tanks employed in such drinking water distribution networks, a large number of water level sensors must be installed. Also, the water tanks are frequently installed in remote locations, as imposed by the structure of the water distribution network, where there is lack of electricity for power-supplying the sensor and associated electronic circuits (e.g. amplifiers, wireless transmitters etc.). Thus, the use of low-power consumption water-level sensors is required in order to minimize the cost of the Renewable Energy Sources (e.g. photovoltaics) which are employed for covering the electric energy requirements of the data-acquisition equipment. Optimization methods for sensor placement in such distribution networks were proposed in [16], in order to improve operational parameters of water distribution networks.

In this paper, a capacitive sensor is presented, which is capable to cover the requirements of water level monitoring in city-scale water distribution networks. Compared to existing design approaches, the proposed water level sensor has been designed such that it exhibits low construction and lifetime maintenance costs. Additionally, due to its low power-consumption feature, it can be easily installed in remote locations where it can be power-supplied by Renewable Energy Sources of small scale and low cost. Experimental results are presented, which demonstrate the successful operation of the proposed level sensor in a water storage tank of a city-scale water distribution network.

II. THE PROPOSED CAPACITIVE SENSOR

Target of the design of the water-level sensing device was to derive a capacitive sensor of low cost and low power consumption, without, however, compromising the accuracy and long-term stability of the sensor. The adverse environmental conditions that prevail at the installation sites of the water level sensor under design (i.e. the water storage tanks), such as the high level of humidity, which accelerates the corrosion of metallic materials over time, were also considered during the sensor development process.

In order to fulfil these targets, the proposed sensor has been developed using widely-available polyethylene pipes, which are used for constructing water distribution networks in buildings, industries etc. These tubes are multilayer, comprising three different layers of materials. A cross-section of such tubes is illustrated in Fig. 1(a). They are composed of an inner and an outer layer of polyethylene, which are bonded to an intermediate layer of aluminum. The pipes of this type combine the advantages of metal pipes (small linear expansion and high mechanical strength) with the advantages of plastic pipes (flexibility, no formation of salts inside the pipe, resistance to electro-corrosion, fast and easy installation). Various configurations of setting the electrodes of the sensing capacitor, comprised of pipes of this type, were tested. It was experimentally detected that forming the sensor electrodes by installing two such pipes in parallel with the inner aluminum layers acting as the capacitor electrodes, has the disadvantage that the total capacitance developed between these electrodes is affected by the presence of nearby objects. The total capacitance of such a configuration was measured for multiple distances between the two tubes. It was observed that the linearity of the sensor was significantly affected by the accuracy of maintaining the two tubes in parallel. In the applications of drinking water distribution networks under consideration, the depth of the water storage tanks is expected to be in the range of 2-6 m. Since maintaining in parallel the tubes of such a length would require increased manufacturing efforts, thus increasing the construction cost of the sensor, the design of the sensor diverted to a concentric configuration of the tubes, as analyzed next.

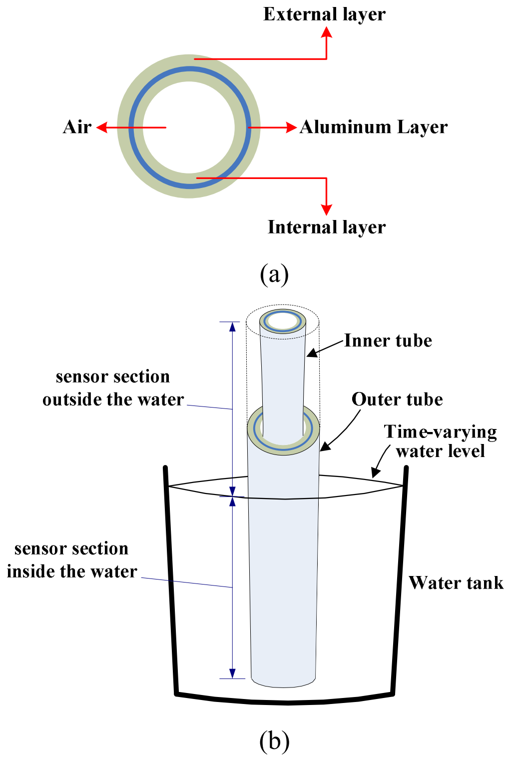

Fig. 1. (a) A cross-section of the multilayer tubes, (b) The structure of proposed water-level sensor.

A schematic diagram of the proposed water level sensor is shown in Fig. 1(b). A multilayer tube is fitted in the internal of a longer diameter multilayer tube of the same type and the entire structure is immersed into the water storage tank to be monitored. During operation, the water of the tank is in contact with the outer surface of the external tube and the internal surface of the inner tube. Installing proper mechanical materials at the bottom of the sensor prohibits water entrance between the two tubes. The aluminum layers of the two tubes comprise the electrodes of the proposed capacitive-type water-level sensor. Since the aluminum layer of both tubes does not have an electrical contact with the measured liquid, provides the vital advantage of avoiding metal corrosion, which increases the reliability and stability of the proposed capacitance sensor over time.

The electric behavior of water depends on the excitation frequency. As analyzed in [12], at operating frequencies up to hundreds of kilohertz the water is practically conductive, exhibiting an equivalent ohmic resistance, while its capacitive

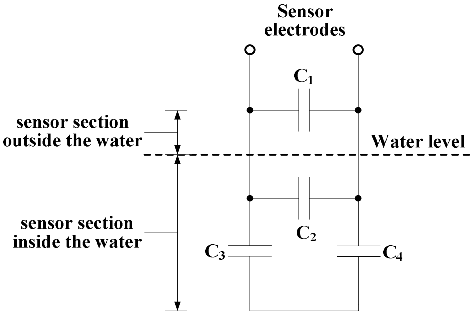

Fig. 2. The equivalent circuit of the proposed sensor for excitation frequencies in the range of tens to hundreds of kHz.

and inductive characteristics are negligible. Also, its electrical characteristics are affected by the existence of dissolved solutes [17]. These properties has been exploited during the design of the proposed water-level sensor by selecting the excitation frequency of the capacitive sensor, which has been developed, to be within the above range such that the water interacting with the sensor parts behaves as a conductor.

In the proposed sensor, a capacitor is formed by the two sections of the sensor, which are inside and outside the water level, respectively [Fig. 1(b)]. The length of these sections changes during the sensor operation according to the level of the water in the storage tank. In the section of the sensor that is above the water level, a capacitor is formed between the aluminum electrodes, with the two intermediate polyethylene layers acting as a dielectric (i.e. C_1 in Fig. 2). The section of the sensor which is below the water level behaves as follows: a capacitor is formed between the two electrodes of the tubes, where the two polyethylene layers comprise the capacitor dielectric (i.e. C_2 in Fig. 2), another capacitor is formed between the water entering the inner tube and the aluminum layer of that tube with the polyethylene layer of the tube acting as a dielectric and, finally, a third capacitor is formed between the aluminum layer of the outer tube and the water at its outside surface (i.e. C_3 and C_4 in Fig. 2). The water in the storage tank behaves as a conductor, connecting electrically the individual capacitors, according to the equivalent circuit diagram of the proposed sensor, which is depicted in Fig. 2. The water resistance has been assumed negligible. The total capacitors formed above and below the water level, respectively, are electrically connected in parallel. The values of all capacitors are modified as the water level in the storage tank changes. At low values of water level, the capacitance C_1 in Fig. 2 predominates the total sensor capacitance. As the water level rises, the values of C_2 - C_4 are increased accordingly, while C_1 is reduced. The values of the individual cylindrical capacitors formed in the proposed sensor configuration are calculated using the following equation [12]:

$$C_x = \frac{2\pi \cdot \varepsilon_0 \cdot \varepsilon_r}{\ln\left(\frac{d_2}{d_1}\right)} \cdot h \tag{1}$$

where ε_o is the electric permittivity of vacuum, ε_r is the relative dielectric constant of the insulator between the capacitor electrodes, d_1 and d_2 are the internal and external, respectively, diameters of the multi-layer tube and h is the length of the capacitor electrodes.

The aluminum layers of the tubes are not in direct contact with the water, which enhances the long-term durability of the sensor by avoiding the impact of metallic corrosion on the sensing capacitor electrodes.

A signal-conditioning circuit for the proposed sensor has also been designed, producing water-level measurements in digital format, which are then interfaced to a data-acquisition unit for further processing. Due to the specifications of the target application under study, the data-acquisition unit is based on the ALIX 3d2 system board, providing an I^2C port available for communication with the proposed measurement system. Techniques such as the wireless transmission or the employment of industrial connection interfaces (e.g. the 4-20mA protocol etc.) are frequently adopted for transmitting the sensor measurements to the data-acquisition unit. The main disadvantage of such industrial protocols is that they raise the cost of the overall data-acquisition system, while additionally impose specific restrictions to the design of the signal-conditioning circuit. For designing the signal-conditioning circuit, special consideration was given to the fact that in practical applications the water level sensor is installed inside a water tank, which is typically at a long distance away from the data-acquisition unit. Various time-varying conditions in the environment of the water storage tanks, which affect the performance of the sensor, have also been considered for designing the signal-conditioning circuit, such as the changes of ambient temperature and water conductance (e.g. due to salinity, temperature etc.). This is indispensable in order to be able to maximize the accuracy performance of the proposed water level sensor.

For measuring the capacitance of the water level sensor, a circuit with operational amplifiers was developed and prototyped. The signal-conditioning circuit sensitivity and measuring range can be easily set by adjusting the value of some passive components. A block diagram of the signal conditioning circuit is illustrated in Fig. 3. The capacitive sensor is connected to a charge amplifier, which is excited by a 32 kHz square wave. As analyzed above, using this frequency provides the advantage of the water performing as a resistor. Since the feedback components R_F and C_F in Fig. 3 are set by the circuit designer at constant values, the response of the charge amplifier depends on the water-level-determined capacitance of the sensor. Thus, the output of the charge amplifier is also a square wave, having amplitude proportional to the total capacitance of the water-level sensor. Then, a full-wave rectifier is used to rectify the generated square-wave, as well as a low-pass filter which produces a DC voltage which is proportional to the total capacitance of the sensor. The circuits of the charge-amplifier, full-wave rectifier and low-pass filter are implemented using the AD8515 operational amplifier. The output of the low-pass filter is interfaced to the AD7745 integrated circuit, which is capable to convert either capacitances or analog signals into a 24-bit digital format.

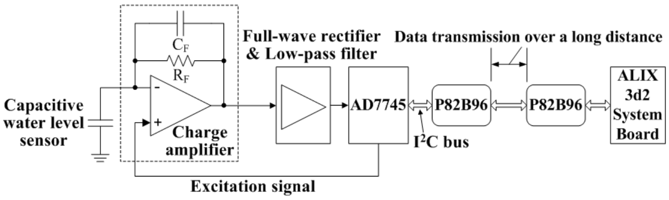

Fig. 3. A block diagram of the signal-conditioning circuit which was developed for interfacing the water-level measurements to an ALIX 3d2 system board.

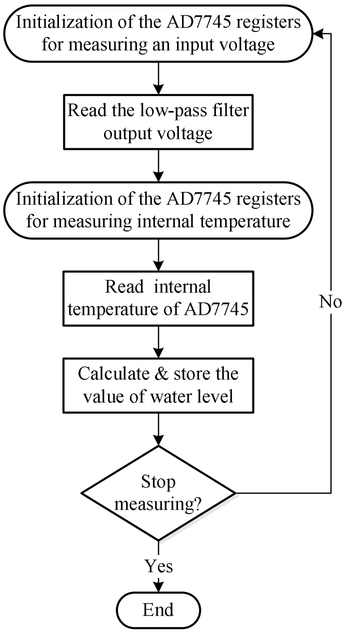

Fig. 4. A flowchart of the software program executed by the ALIX 3d2 system board for collecting the water level measurements.

This chip also generates the excitation signals required for the operation of the charge amplifier. The AD7745 contains an on-chip temperature sensor, which is used to estimate the ambient temperature of the water level sensor. This information is required for compensating the changes of the water level sensor with temperature, in order to improve the measurement accuracy of the proposed data-acquisition system, as analyzed in the following. The AD7745 provides an I^{2}C compatible serial output, using two wires for communicating with the host computer board. Frequently, the water storage tanks of drinking water distribution networks are divided in multiple separate departments and a water level sensor is installed for monitoring the water level in each department. The water level measurements from all departments are then collected to the same data-acquisition unit for further processing. Using the I^{2}C protocol for transferring the water level measurements to the host data-acquisition unit enables to easily extend the number of water level sensors connected to the host device through the same bus using a multiplexer, thus providing a scalability feature to the proposed measurement system.

The basic operation of the I^{2}C protocol supports a communication distance of up to 5 m, which is not always adequate for the water-level monitoring applications under study. In order to provide a long-distance transmission capability to the signal-conditioning system of the proposed sensor, the P82B96 I^{2}C bus extension chips are connected at the ends of the communication link connecting the signal-processing circuits of the proposed sensor with the ALIX 3d2 system board, in order to increase the transmission distance up to 30 m. The signal-conditioning circuits are power-supplied by the ALIX 3d2 system board, as well as an external power source through a standard UTP cable. Due to the low power consumption characteristics of the integrated circuits, which were employed, the total power consumption of the proposed water-level measuring system, including the sensor and signal-conditioning circuits, is 12 mW. A script executed by the ALIX 3d2 data-acquisition unit, was developed using the Python programming language for communicating with the AD7745 chip. A flowchart of this program is depicted in Fig. 4. Initially, the internal registers of the AD7745 chip are initialized for measuring the low-pass filter output voltage. The capacitance of the proposed sensor is affected by the changes of ambient air temperature. Thus, temperature compensation of the water-level measurements provided by the sensor is also performed in the software, using measurements of the AD7745 internal temperature sensor. The water level, L (m) is calculated using the measurements of the low-pass filter output voltage, V_f (V) and AD7745 internal temperature, T_a (^oC), according to the following equation:

$$L = \alpha_1 \cdot V_f + (T_a - T_{ref}) \cdot \alpha_2 + \alpha_3 \qquad (2)$$

where α_1, α_2 and α_3 are calibration constants and T_{ref} is the reference temperature. The values of α_1 - α_3 are obtained by setting the proposed sensor to operate concurrently with a reference water level sensor, in the same water storage tank. The water-level measurements acquired are stored in the flash card of the ALIX 3d2 system board. The software executed by the ALIX 3d2 system board was tested to run on two Linux releases: Debian and Voyage. The code uses the system addresses that the AD7745 chip devotes for connecting with other I^{2}C-compatible devices over the I^{2}C bus.

III. EXPERIMENTAL RESULTS

The experimental prototype of the proposed water-level sensor for measuring a 2 m water level is shown in Fig. 5. It consists of a multilayer tube with a 16 mm diameter, which has been fitted, concentrically at the inside of a multilayer tube of the same type having a 26 mm diameter, both of the same manufacturer (www.solin.gr). During the construction process, the length of the proposed sensor is set equal to the maximum depth of the water in the storage tank where it will be installed. Adapting the length of the electrode tubes accordingly, easily fulfills this requirement, while the remaining construction characteristics of the sensor remain unaltered. Thus, the complexity of constructing the proposed water-level sensor and the associated manufacturing cost, are relatively independent of the measuring range. Due to the flexibility of the multilayer tubes, the proposed sensor can be

Fig. 5. The experimental prototype of the proposed water-level sensor for measuring a maximum water level of 2 m.

easily folded, for transferring it to remote locations, where, frequently, the drinking water storage tanks of water distribution networks are placed. Additionally, this flexibility enables easy elimination of the tubes bending, during installation of the proposed sensor, thus improving the linearity of its response. The water-level sensor that was developed has been experimentally tested under various operating conditions. The first sets of experiments were conducted in the laboratory, by immersing the sensor inside a plastic container and using an LC-meter to measure the capacitance of the sensor. The experimentally measured total capacitance of the proposed sensor at various water levels is shown in Fig. 6. The non-linearity Root-Mean-Square (RMS) error is 0.63 % and the Mean Absolute Error (MAE) is 0.61%.

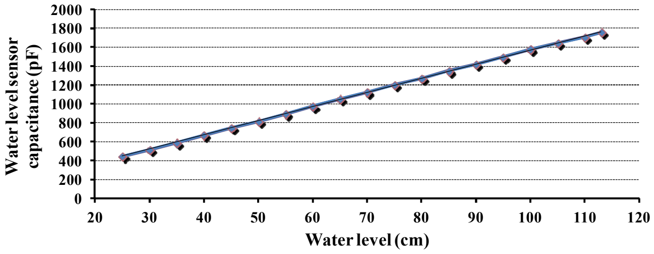

Fig. 6. The experimentally measured total capacitance of the proposed sensor at various water levels.

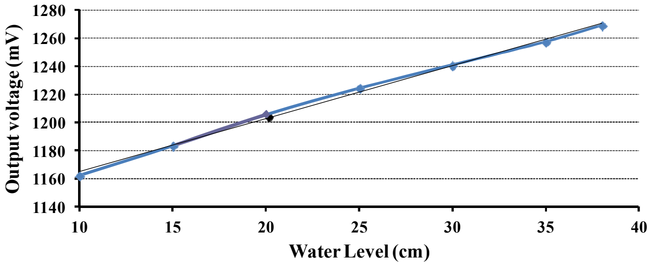

Fig. 7. The DC output voltage produced by the low-pass filter of the signal-conditioning circuit at various water levels.

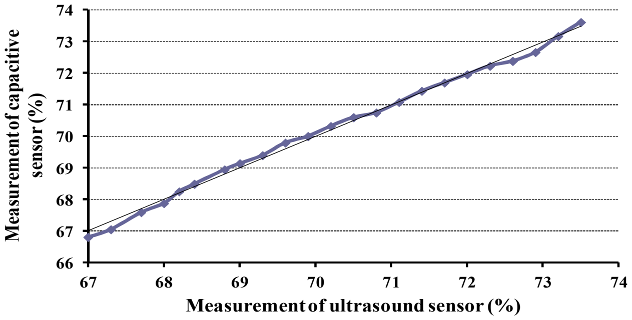

Fig. 8. The measurements acquired by the proposed capacitive-type water-level sensor versus the corresponding measurements of the ultrasound sensor, when both operating in a water storage tank of the Municipal Enterprise for Water and Sewage of Chania (Greece).

The variation of the DC output voltage produced by the low-pass filter of the signal-conditioning circuit, which is then converted to digital using the AD7745 chip, at various water levels, is presented in Fig. 7. In this case, the non-linearity RMS and MAE errors are 0.69 % and 0.64%, respectively. Also, the laboratory tests, which were conducted, indicated that the impact of water salinity on the performance of the proposed water-level measurement system was negligible. In order to evaluate its performance, the proposed sensor has also been tested in a drinking water storage tank (constructed of concrete) of the Municipal Enterprise for Water and Sewage of the city of Chania (Greece). An experimental prototype of the proposed sensor having 4 m length has been constructed for that purpose, in order to adapt the sensor to the depth of the corresponding water storage tank, which has been allocated for performing the experimentation process. An ultrasound water-level sensor was already installed in that tank by the Municipal Enterprise for Water and Sewage of Chania, for monitoring the water level of the tank, in order to apply the appropriate water management procedures. Prior its installation in this tank, the proposed capacitive water-level sensor had been calibrated, using the ultrasound water-level sensor as a reference. The two different types of sensors were then set to operate in parallel for a time period of 6 hours. A plot of the measurements acquired by the proposed capacitive sensor versus the corresponding measurements of the ultrasound sensor is presented in Fig. 8. The RMS and MAE of the deviation between the measurements obtained using the proposed water-level sensor from the corresponding measurements of the reference ultrasound sensor are 0.88 % and 0.81 %, respectively. This accuracy is acceptable for applying water management techniques in city-scale water distribution networks.

The total time required for the software executed by the ALIX 3d2 system board to produce a water-level measurement (including the communication with the signal-conditioning circuit) is approximately 1.02 sec.

The proposed water-level sensor and signal-conditioning circuits have been designed to operate using low cost materials and devices, thus reducing the total cost of the overall water-level measurement system. In order to calculate the total construction cost of the proposed water level sensor, the prices of the required materials when provided in small quantities in the local market, were considered. For a measuring range of 0-4 m, the total construction cost is approximately 22.95 € and increases by about 2.5 € per additional meter of sensor length. The total cost of the electronic devices required to implement the signal-conditioning circuits is approximately 13 €. These costs are expected to drop substantially when purchasing large quantities of the required materials and devices in case of an industrial implementation of the proposed design. Also, the total system cost is significantly lower than that of an industrial ultrasound water-level sensor (typical cost higher than 300 €), although their performance in terms of accuracy, in the application under consideration, does not differ significantly.

IV. CONCLUSIONS

Water-level sensors are indispensable for monitoring the level of water in storage tanks, which are used in drinking water distribution networks. In this paper, a capacitive-type water-level sensor has been presented. The proposed sensor has been designed to be immersed in the water tank under monitoring and its capacitance varies according to the water level of the storage tank. The proposed sensor is constructed using widely available and flexible multilayer tubes, which are used in drinking water systems. Thus, both the manufacturing cost of the sensor and the cost of the associated electronic circuits, which are used for interfacing the sensor to a digital data-acquisition unit, are low. The design of the proposed sensor enhances its long-term reliability by reducing the impact of metallic corrosion through direct contact of the capacitor electrodes with the water.

The performance of the proposed sensor has been experimentally evaluated in a 4 m water storage tank of a city-scale water distribution network. The experimental results indicate that the accuracy of the proposed experimental prototype sensor is similar to that of a commercially available ultrasound water-level sensor, while, additionally, its manufacturing cost is significantly lower.

Future work includes further testing of the proposed water level sensor in the water storage tanks of the water distribution network of the city of Chania, in order to evaluate its long-term performance.

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