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Water level sensing: State of the art review and performance evaluation of a low-cost measurement system

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ABSTRACT

Nowadays, the management of water is of paramount importance for modern societies due to the high water-availability requirements. The application of water management schemes requires the installation of water level data-acquisition systems in multiple, geographically isolated large-scale storage tanks of water distribution networks. Existing techniques for liquid level sensing have either been applied over a relatively small measurement range, or require special scientific equipment of high cost, or they are not convenient for transportation, installation and long-term maintenance in multiple large-scale water storage tanks of water distribution networks in cities, communities, etc. In this paper, a review of prior art on liquid level sensing is initially presented. Then, the operational characteristics and performance of a novel capacitive-type water level measurement system are investigated through simulations and experimental tests conducted in two water storage tanks of a city-scale water distribution network. It is demonstrated that the proposed capacitive water level measurement system achieves equivalent performance with that of a commercially-available ultrasound water-level sensing device and simultaneously exhibits a much lower manufacturing cost.

1. Introduction

Liquid storage tanks are an essential part of vital operations in various industrial applications. Sensors suitable for monitoring the level of many different kinds of liquids are currently available, such as short- or long-range sensors for hazardous or nonhazardous liquids, exhibiting a variety of resolution and accuracy performances [1]. An ideal liquid level sensing system should be able to feature stability, high resolution and be of low cost. Simultaneously, the management of water becomes vital in the rapidly developing modern societies, due to the increase of water availability requirements (e.g. for residential and/or agricultural use, etc.). In such applications, it is required to monitor the level of water contained in large-scale storage tanks of water distribution networks, which exhibit a significant depth (e.g. 2–6 m). Due to the typically large number of water storage tanks contained in water distribution networks (e.g. in communities, cities, etc.), a high number of water level data-acquisition systems must be installed within the water distribution system, in order to obtain accurate information of water availability. The collection of data from water level tanks is essential for applying appropriate water management schemes. Thus, long-range, easy to install and low-cost water level sensors are required to monitor this vast amount of water tanks.

In this paper, an extensive review of the existing state-of-the-art techniques for liquid level monitoring is initially performed, in order to explore the suitability of current technologies for possible incorporation in the water management applications under consideration. Prior work already presented by the authors in [2] is further extended by investigating the operational characteristics and performance of a novel capacitive-type water level measurement system. Simulation and experimental studies, performed in water storage tanks of a city-scale water distribution network, are presented, demonstrating its superiority for the target application under consideration, compared to existing industrial water level sensing systems.

This paper is organized as follows: a review of techniques applicable for monitoring water level is presented in Section 2; the proposed water level measurement system is described in Section 3, while comparative experimental results derived by installing the proposed measurement system in water storage tanks of a city-scale water distribution network, where a commercially-available ultrasound water-level sensing device of significantly higher cost was also under operation, are discussed in Section 4. Finally, conclusions are drawn in Section 5.

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2. Review of water level measurement techniques

An excellent solution for measurement systems in water level applications is the usage of capacitive sensors. This type of sensors has been proven to be stable, can provide high resolution and can be constructed using various materials, therefore being of low cost. Capacitive-type sensors can be of various shapes, in order to provide the ideal capacitor, which will be affected by the least undesirable parameters, such as the cable capacitance, variations due to temperature or parasitic capacitances created between the sensor and nearby objects. Cylindrical capacitive sensors provide an excellent solution for improving the stability of the sensor structure [2–7]. Designs using shielded cable [3], stainless steel [4], printed circuit board (PCB) [5], plastic, metallic rods [6,7], or even wire insulated with polytetrafluoroethylene (PTFE) [4], have been reported in the past. The operating principle of capacitive sensors is the same as that of a standard capacitor component. Thus, the materials from which the system is fabricated are essential for a stable result of the total capacitance and operation of the sensing system. The required measurements are obtained by measuring the capacitance between two metal plates that essentially create the sensing capacitor. The level of liquid contained between these metal plates alters the total capacitance of the sensor. Depending on its chemical composition and operating frequency, the liquid contained between the sensor electrodes can behave electrically as either a conductor, or an insulator. Thus, the operation of a capacitive-type liquid level sensor is determined by the nature of the measured liquid. During operation in a data-acquisition system, its capacitance varies with the level of the measured material [2–7]. Due to wide available range of materials in the industrial market, which are appropriate for their construction, capacitive-type liquid level sensors can be of low cost and certified for contact with drinking water.

The electrodes that compose a capacitive sensor are often stainless steel rods [4], certified for drinking water applications, such as the 316L and 304L types. Due to their lack of flexibility, the metallic rods that very often comprise at least one part of a capacitive liquid level sensor structure, limit the capability of this type of sensors to be easily transported and installed in remote locations. The sensor constructed with a bendable shielded cable that is proposed in [3], solves the problem of transportation. Additionally, this type of cable is widely available and the sensor can be used in both grounded metallic and plastic containers. Its construction materials are waterproof in order to keep the inner parts of the sensor protected. However, the cable is reported to be constructed by PVC (polyvinyl chloride), which can be found in several forms that may not be certified to be suitable for installation in drinking-water storage tanks. Regarding the signal-conditioning system, a capacitance-to-digital converter was employed in [3] for measuring the sensor capacitance variations, providing the resulting data to a microcontroller. The overall system was tested in liquid level ranges up to 200 cm, exhibiting a measurement error of less than 1%.

The main disadvantages of the capacitive-type sensing approach are that it can be affected by parasitic capacitances and that the long-term performance of the construction materials has to be tested. Furthermore, the cable material, which is used to construct the sensor, must be certified in terms of its hygienic suitability for contact with drinking water, in order to be appropriate for use in drinking water storage tanks.

Multiple different versions of capacitive-type liquid level sensors have been presented in the past, constructed with various materials and focusing to the low cost, easy of installation and high linearity characteristics [2–5]. Typically, these sensors have been tested in a laboratory using an LCR meter for measuring the sensor capacitance [3–6]. The most typical variations in capacitance measurements are caused by temperature shifting [3,6]. In order to be suitable for application in large-scale storage tanks, it is crucial for the liquid level sensor to enable easy installation and be fabricated in a way that it can resist when operating in rough environmental conditions. For example, during operation in a liquid storage tank, the temperature variations during the year, together with the presence of water, can create a high level of humidity that can corrode and destroy steel, if it is not of stainless steel type.

A capacitive-type water level sensor of low cost and high linearity, constructed using a Printed Circuit Board (PCB), was presented in [5]. This type of capacitive sensor is called inter-digital capacitive sensor and it is developed using two comb electrodes. It is based on the same operating principle as the standard capacitor formed by two parallel plates that comprise its electrodes. The water level measurements had been obtained using a simple measuring circuit based on a PIC16F887 microcontroller (Fig. 1). The experiments were limited to a 30 cm range within a laboratory environment, indicating a 0.2 cm resolution. However, this type of sensor requires a special PCB design and construction. Also, since the sensor electrodes are formed by a continuous PCB layer, its employment in long-range applications (e.g. water storage tanks of city-scale water distribution networks), where the sensor length should exceed 0.5 m, is difficult. The overall cost of the sensor and signal-conditioning system has been reported to be equal to approximately \$32/m of sensor length.

Capacitive sensors can also find application into in-pipe measurement systems, measuring the variations of liquid flow. The system proposed in [8] estimates the fractional area occupied by each fluid in a specific type of pipe, by measuring the various capacitors formed between its electrodes. Testing of this technique indicated that the two-phase liquid flow can be monitored accurately by using such capacitive-type sensors. It has also revealed that it is important to select an appropriate operating frequency for the sensor, in order to obtain the necessary sensitivity, since when the capacitive sensor is operated within the appropriate frequency range, parasitic phenomena can be neglected, as also analyzed in [4]. Capacitive-type sensing was also employed in other applications, such as monitoring stirred tanks [9]. In this case, the influence of the stirring system on the measured capacitance of the sensor was examined experimentally by simulating various circumstances within the stirred tank. The experiments were conducted by measuring the influence of plexiglass propellers. The results showed that variations of the sensor capacitance may occur due to air entrainment. Also, during solid–liquid mixing, the

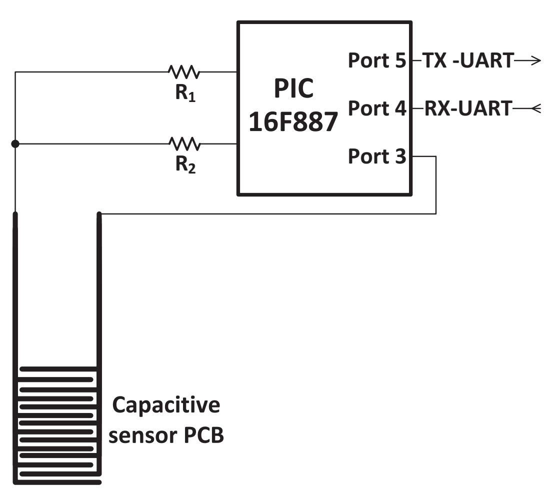


Fig. 1. The inter-digital capacitive-type water level sensor and signal-conditioning circuit proposed in [5].

sensing capacitance varies along with the increase of stirring speed because of the decrease of volume fraction of solid particles near the sensor.

Liquid monitoring applications can also be found in various industrial processes, such as pico-liter measurements of liquids in microfluidic channels. In [10], a capacitive sensor was installed into the wafer channel by using vertical silicon electrodes, in order to detect liquid level variations. To develop this sensor, a six-mask IC-compatible process was applied. This capacitive sensor exhibits a very high measurement resolution and extends the applications of capacitive-type sensing in demanding industrial fields.

Another type of sensors that are commonly used for liquid level measurement is that of optical sensors. Different types of optical sensing techniques have been implemented for obtaining liquid level measurements. With optical sensors, control of the liquid level sensing process can be implemented by using types of materials other than PVC or stainless steel, that are not altered by liquid contact, extending the application of level monitoring to dangerous chemical liquids. An optical level sensor with a fiber modal interferometer based on polarization has been presented in [11]. The experiments indicated a high sensitivity with temperature that affects the measurement results. Therefore, despite the excellent linearity results, the application of such optical sensors in liquid tanks of large dimensions will be ineffective. Moreover, the advantages of the non-invasive all-fiber structure are important for the measurement of chemical liquids in small quantities, which require a high resolution. Such a measurement system can be easily fabricated, however the sensor must be placed at the two ends of a container (Fig. 2), limiting the possible applications range.

Fiber Bragg gratings (FBGs) are often affected by several parameters, which are studied in [12]. In the first part of that study, the FBG effective refractive index and its experimental characteristics, such as the sensitivity and the time-evolution of the Bragg wavelength during etching, were investigated. An analytic expression was created, correlating the radius of etched FBG and the effective refractive index. The performance of etched FBGs as liquid level sensors for water and olive oil was evaluated experimentally by immersing the FBG sensor into the liquid. It was concluded that water results in a shift of the diffracted wavelength, while olive oil causes a reduction of the reflected power. The experiments were performed for low levels of the liquid (up to 5 mm). Therefore, this technique cannot be employed for measuring a wide range of liquid levels, which is required in large-scale water tanks.

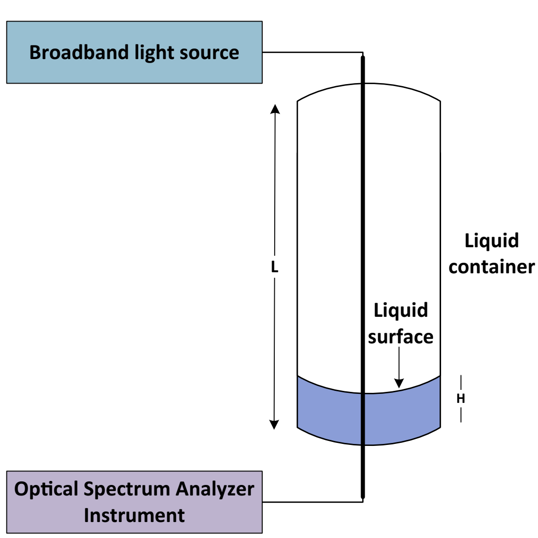


Fig. 2. A fiber modal interferometer used as an optical level sensor [11].

A fiber optic liquid level sensor based on the bending of FBG was also proposed in [13]. FBG is placed on a cantilever rod a such that the contractions of the Bragg grating, due to bending of the cantilever rod, provide data on the changes of liquid level (Fig. 3). The rise of water causes the cantilever rod edge to move upwards, causing a shift of the FBG Bragg wavelength. As the water rises, the wavelength increases, while when the water level drops the wavelength returns to its initial value. For measuring the shift of the Bragg wavelength, usage of an optical spectrum analyzer (OSA) is required. Also, the usage of the LABVIEW software platform was required during the experiments for data-acquisition and processing, together with signal monitoring and user-interfacing devices. Finally, to compensate the impact of the temperature variations of the developed sensor head, temperature measurements must also be performed. Experiments were conducted for measuring water level in the range of 0–36 cm in room temperature, demonstrating excellent linearity and stability during both the rise and fall of the liquid level. The experimental results indicated that this system can provide a satisfactory performance in terms of linearity, as well as a simple structure and reproducibility. However, due to the necessary external hardware and software, the overall measurement system cost is high.

Another optical sensor that has been reported for liquid level measurements uses a Fabry–Pérot interferometer [14]. This sensor system can be used for long-range measurements, providing an excellent resolution of 0.7 mm at a length of 5 m. The optical sensor of this type is based on a diaphragm-based extrinsic Fabry–Pérot interferometer (DEFPI). Temperature variations are reported to affect the measurements of EFPI [15], however the application of an appropriate fabrication technique may reduce the measurement error of liquid level [14]. In order to provide results, the sensor was connected to an Optical Sensing Interrogator instrument and the resulting data were processed with the LABVIEW software platform. Usage of external scientific equipment raises the cost of the overall system, limiting the range of possible applications for obtaining liquid level measurements. In addition, the sensor has to be installed in a specific position in the liquid tank, making its usage in large-scale tanks difficult. Nevertheless, this sensor can be used with several liquid types, features a long-range measurement capability and can be an alternative in industrial applications.

In order to measure the level of liquids either by using a pressure sensor with a FBG, or with a Fabry–Pérot pressure sensor, previous knowledge of the specific gravity of the liquid is required. In [16], these two types of sensors are immersed at different depths in the liquid in order to derive simultaneously the values of both specific gravity of the liquid and its level (Fig. 4).

The fiber-loop ring-down technique has been presented in [17] for low liquid levels, where a short section of etched fiber is used. The experimental setup, shown in Fig. 5, consists of several instruments and the tests of this method took place only within a laboratory environment. Nevertheless, this method produced excellent

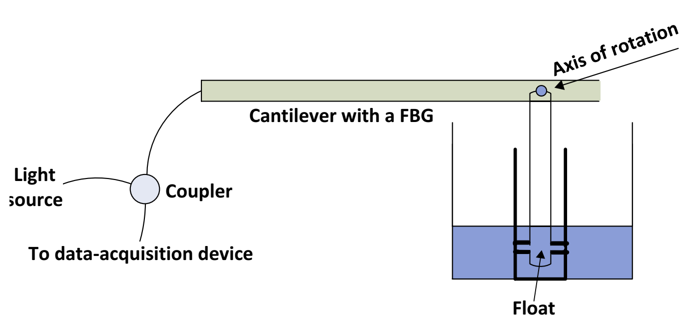


Fig. 3. Cantilever rod used for liquid level measurements in [13].

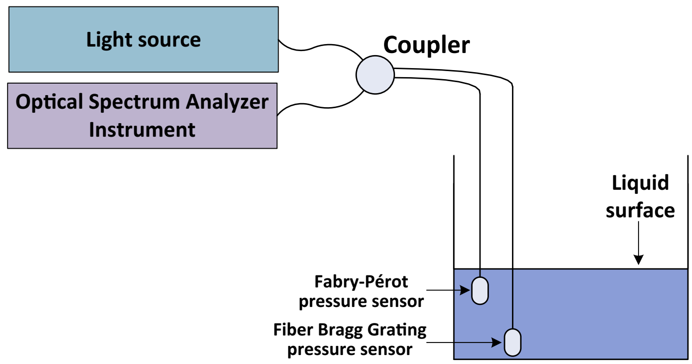


Fig. 4. The experimental setup applied in [16] for measuring the specific gravity and level of the liquid.

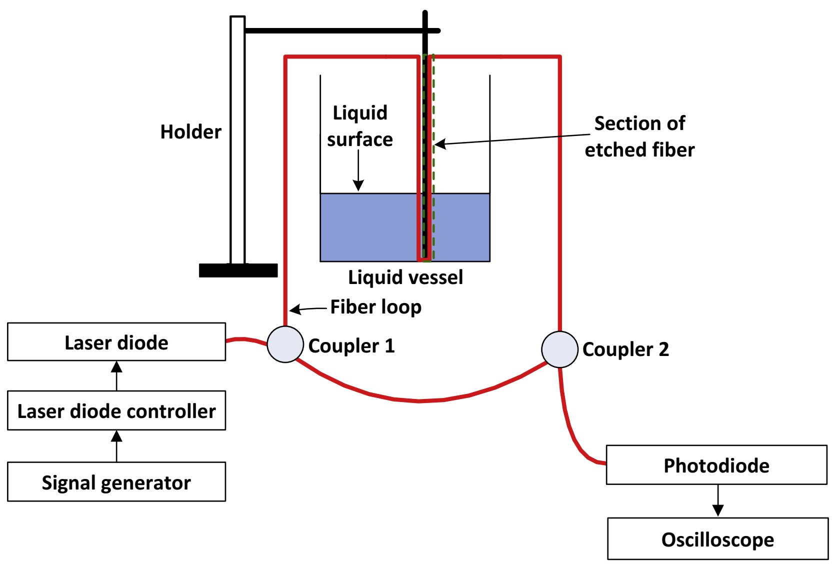


Fig. 5. The experimental setup of the measurement system presented in [17].

results with very precise liquid level measurements. This type of measurement system has potential application for monitoring low levels of liquids in cases where the presence of chemical substances may deteriorate the performance of other invasive-type sensors (e.g. for use in applications containing carbon disulfide, gasoline, etc.). On the other hand, this type of measurement system is relatively complicated and very expensive for acquiring wide-range liquid level measurements in applications such as the monitoring of city-scale water storage tanks.

An optical fiber with engraved grooves immersed in the liquid is employed in [1] for measuring the liquid level. As the number of grooves covered by the liquid is increased during rising of the liquid level, the leakage of transmitted optical power is reduced accordingly. The resolution of measurements depends on the distance of grooves on the optical fiber surface. This measurement technique is mostly suitable for industrial applications involving flammable liquids, but it is not suitable for use in low cost liquid level measurement systems due to the special construction of the optical fiber and the relatively complex signal-processing electronic circuits required.

For low liquid level applications, the use of tilted fiber gratings (TFGs) has been proposed in [18]. In that case, a TM-polarization technique was applied in order to develop a sensor system that monitors water level with a relatively linear response. Application of this method may reduce the measurement system cost, compared to other optical-based sensing structures, since a polarization controller is not required, but it is still a very expensive alternative for the monitoring requirements of a water distribution network. A sensor combining temperature and liquid level sensing capabilities was also developed by using a fiber laser sensor in [19]. The measurement system is based on two taper structures formed in a single-mode fiber, comprising an interferometer, which is combined with a FBG. As demonstrated experimentally, this sensor exhibits a high resolution and sensitivity in liquid level measurements. However, due to the operating principle of this sensing technique, it is suitable only for low liquid level applications.

The application of the Raman optical fiber scattering method is proposed in [20] for measuring liquid level in oil wells. However, the implementation cost of this technique is relatively high due to the requirement of employing an optical demodulator instrument and a signal processor. A digital camera is employed in [21] for detecting the displacements of a float during variations of the liquid surface. The drawback of this approach is that the electronic equipment required for capturing and analyzing the images of the liquid surface and float is of relatively high cost.

Extensive work has also been performed in the area of wireless monitoring systems, since they are ideal for the collection of measurements by multiple sensors through the formation of Wireless Sensor Networks (WSNs). Such a measuring system for resistive and capacitive sensors has been presented in [22]. Environmental monitoring is essential and several wireless sensors may provide data that are required for proper protection of several locations. In [22], the data-collection system collects data from capacitive and resistive sensors. The capacitive sensor integrates a capacitance-to-frequency conversion stage and the use of a phase-locked loop at the receiver for converting the detected frequency to voltage (Fig. 6). A capacitive pressure sensor was used to measure the pressure into a tube of water and was connected to a wireless communication module. A resistive-type temperature sensor was also used for transmitting the temperature from inside the tube. The Microchip PIC18F452 microcontroller was used in the sensor circuit for data collection, as well as in the base station.

Water level sensing has been reported in agriculture applications in [23]. A WSN was created for monitoring data from a tea plantation facility, where water level and temperature measurements are essential for the plants to grow efficiently. However, monitoring water with a high resolution is not critical in this application, thus the level sensor was used in that case only for the detection if the level reached a pre-defined level. Data imported from the sensors were processed with the LABVIEW software platform.

Another type of sensor that is used for monitoring water level in marine and non-marine environments is a microwave radar sensor. It has been used in applications such as wave height measurement systems [24] due to its high measurement accuracy and low sensitivity in humidity and temperature. The performance of a commercially available microwave radar sensor was evaluated experimentally in [24]. Although the initial cost of such a measurement system is considered to be high for application in water distribution networks, the corresponding maintenance costs are relatively low due to absence of sensor contact with the water.

Liquid level measurements are also required in dynamic environments, where the conditions alternate fast. In [25], an ultrasound sensor and a signal processing technique using a Support Vector Machine (SVM) were used to develop a measurement system for a vehicle fuel tank. This hybrid system reduces the measurement error of single ultrasound sensors. Various SVM models were developed and tested in order to obtain maximum accuracy. System cost may be high with this approach, but accuracy in various applications, such as in fuel tanks of race cars, is essential and this system can provide a more reliable solution.

Time-domain reflectometry (TDR) is another technique that it widely used for liquid monitoring [26–29]. TDR-based sensors are suitable for monitoring water-level tanks, because they can be constructed by stainless steel rods proper for drinking water usage. Flexible or compact rods are used as TDR electrodes in [26,28,29]. The electrodes are immersed into the liquid and the variations of liquid level are measured with the use of external scientific equipment. Applications of TDR are also extended in non-invasive measurements in [27], with the use of electrodes that can be installed outside a chemical infusion bottle. The use of flexible two-wire probes has been reported in [28,29] for monitoring liquids such as vegetable oil and water, in metallic and non-metallic containers. This type of sensors is also suitable for detecting physical properties of the liquid such as its conductivity and permittivity [30–32]. Overall, TDR-based sensors are an excellent solution for liquid level measurement. However, the use of external scientific equipment for performing the required measurements raises the total data-acquisition system cost. Also, this external equipment makes installation of the system in remote locations, such as those encountered in city-scale water management systems, difficult.

Pressure sensors are another alternative for performing water level measurements. These pressure sensors can also be constructed using low temperature co-fired ceramics (LTCC) [33,34]. Evaluation of their performance in [33], under cyclic pressure loading conditions, indicated that the presence of water does not significantly affect critical performance characteristics. Pressure-type sensors are capable of operating reliably under rough environmental conditions. However, to provide a better accuracy, calibration must be performed frequently. Also, the use of a protective coating is preferable for improving their performance [33]. Pressure-type sensors have been reported to monitor water flow in a water distribution network [35]. They were selected because they are easy to install inside water pipes and exhibit a relatively low cost. A leak detection methodology was developed based on the use of pressure sensor measurements and proper calibration of the sensors was reported to be of importance for improving the accuracy of the results produced by the algorithm. The leak detection methodology considers sub-networks called district metered areas (DMAs), where pressure sensors are placed and provide real-time data to a pre-installed SCADA system. Application results have shown that the data from the pressure sensors can indicate the leakage area location after appropriate processing. The performance of pressure sensors is deteriorated by the changes of the liquid density and pipeline vibrations, which increase the noise amplitude in the liquid level measurements acquired. A technique based on Wavelet transform is presented in [36] for removing such a noise from the measurements of a differential pressure sensor.

A low-cost wireless sensor network for water quality monitoring is described in [37]. Sensors are installed into pipes to monitor water for bacteria and heavy metal presence. It is vital for such a system to be of low cost and feature easy implementation and installation capabilities. It is also essential that the sensors are reliable for long time operation. The sensors transfer their data to a microcontroller, which can communicate with a central data-collection node via a ZigBee-based communication link. In addition to monitoring, detection algorithms of contamination events have also been developed, to trigger event alarms.

All liquid level sensing techniques described above have some serious drawback: they have been applied for measuring liquid level over a relatively low range of values, special scientific

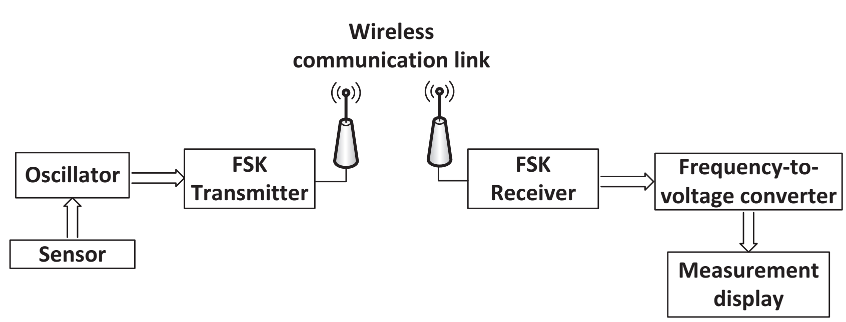


Fig. 6. Block diagram of the wireless monitoring system proposed in [22].

equipment of high cost is required for conditioning and processing the electric signal produced by the liquid level sensor, or they are not convenient for transportation, installation and long-term maintenance in multiple large-scale water storage tanks of water distribution networks in cities or communities. Applications such as the monitoring of water-distribution networks of cities require to concurrently monitor a very large number of storage tanks, in order to centrally manage the water of the network. This is performed by installing water level measurement sensors in each tank under monitoring. Due to the high cost of the water level measurement sensors and the large number of such sensors that must be installed, the total cost of the monitoring system is also very high. Thus, the development of a low-cost and low-power water level measurement system suitable for such applications is desirable.

3. The proposed water level measurement system

In order to achieve the targets of low cost and low power consumption, which enable the installation of multiple water level sensors in large water storage tanks of city-scale water distribution networks, the operation and performance of the capacitive water level sensing structure depicted in Fig. 7, which was initially proposed in [2], is further studied in this work.

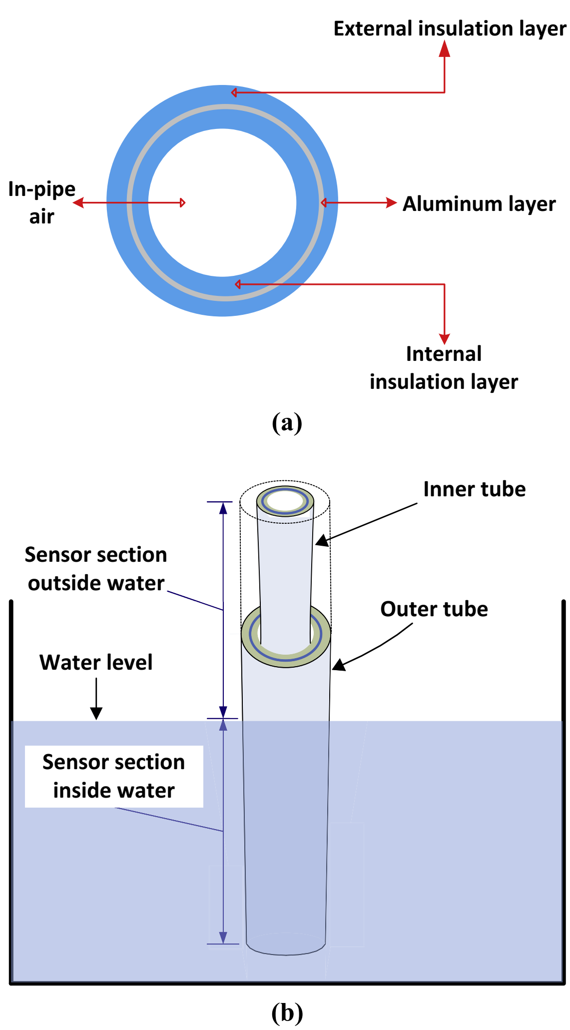


Fig. 7. The structure of the water-level sensor under study: (a) the multilayer pipe and (b) the sensor inside a water tank.

The proposed sensor is constructed using multilayer polyethylene tubes, employed for constructing distribution networks of hot and cold water (e.g. in buildings). They consist of two layers of electrically insulating material containing a metal layer between them. The sensor is constructed by placing concentrically two of these multilayer tubes with different cross-sectional diameters, such that the tube of smaller diameter is placed at the internal of the tube with the larger cross-sectional diameter. This set-up of the two tubes is placed vertically into the water of the tank whose level is measured. The cylindrical and concentric configuration of the proposed probe offers the required stability and protects the water level sensor from parasitic capacitance noise (e.g. in contrast to placing the two sensor probes in parallel) [2,4,6].

During sensor operation, both the internal and the external parts of the tube come in direct contact with the water filling the tank. At the end of each multilayer tube, which is placed into the water of the tank, a brass compression fitting is adapted, such that the plastic ring that it contains prohibits contact of the internal metal layer of each multilayer tube with the water of the tank. Thus, their electrochemical corrosion is avoided. The components and technique used for sealing the sensor tubes are also employed in conventional plumping applications, ensuring the long-term mechanical and chemical stability of the proposed sensor. The metal layers contained in the two multilayer tubes comprise the two electrodes of the sensor. The total length of the sensor is chosen so that it is at least equal to the maximum depth of the water which is desirable to be measured. Since the multilayer tubes are produced in any desirable length, the proposed sensor can be regarded as widely scalable. As analyzed in [4], by setting the excitation frequency of the capacitive-sensor equal to tens of kHz, water behaves as a conductor. In such a case, the proposed water level sensor behaves electrically as a capacitor, with a total capacitance equal to the sum of the individual capacitances formed by the parts of the sensor located inside and outside the water surface, respectively. Thus, the total capacitance of the proposed sensor varies with the level of water in the tank.

The multilayer tubes and the insulating materials, which are required for constructing the proposed sensor, are widely available commercially and have a low cost and also the construction of the sensor is simple. Thus, the water level sensor described above exhibits a much lower construction cost compared to the existing level measurement sensors.

In order to measure the capacitance of the sensor with high accuracy, an active signal-conditioning circuit based on operational amplifiers (op-amps) was designed. A block diagram of this circuit is shown in Fig. 8. The capacitive sensor is connected to a charge-amplifier, which is excited by a 32 kHz square-wave generator signal, such that the water of the tank behaves electrically as a conductor, as noted above. For that purpose, one of the water level sensor electrodes is connected to the signal-ground (corresponding to 0 V) of the signal-conditioning circuit. A square-wave is produced by the charge amplifier with amplitude proportional to the capacitance of the sensor, which, in turn, varies with the level of water in the tank. This high-frequency square-wave is then converted to a DC signal, through a full-wave rectifier and a low-pass filter. The circuits of the charge amplifier, full-wave rectifier and low-pass filter have been built using the AD8515 low-noise and low power op-amps. The low-pass filter output signal is finally transferred to an AD7745 capacitance-to-digital converter and uses its input voltage pin to measure the DC input signal with a 24-bit resolution. The AD7745 converter provides a digital output compatible with the I^2C protocol, which enables the serial transmission of the acquired measurements to a remote data-acquisition device (e.g. microprocessor board). In contrast to other solutions for obtaining capacitance measurements, such as the frequency-shifting technique

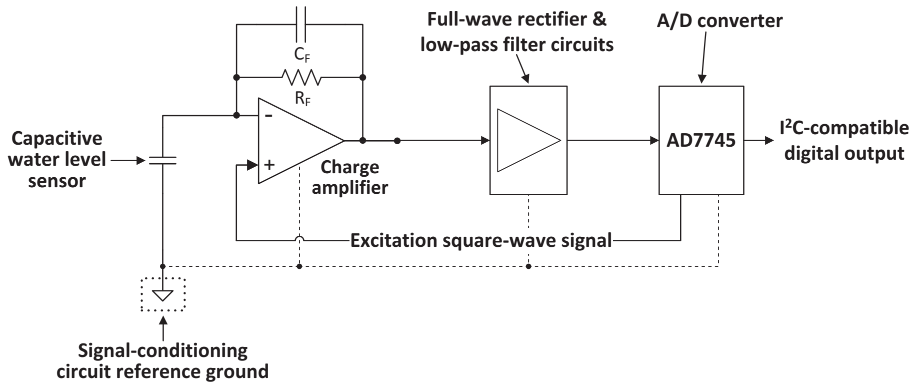


Fig. 8. A block diagram of the signal-conditioning circuit of the proposed water level measurement system.

based on oscillator circuits, this signal-conditioning configuration provides the most accurate measurements for the overall system.

The charge amplifier operation was tested with the proposed model of the capacitance sensor through simulations performed with the National Instruments MultiSim software program. The waveforms of the excitation signal and the charge-amplifier output voltage for various values of the water level sensor capacitance, C_s, are illustrated in Fig. 9. The capacitance values considered in these simulation results have been extrapolated by an experimental prototype water level sensor with a length of 6 m, which has been built according to the technique described above. It is observed that, although the amplitude of the excitation signal is kept constant, increasing the capacitance of the water level sensor (i.e. increasing the level of water in the storage tank) results in an increase of the charge-amplifier output voltage amplitude.

The variation of the amplitude of the charge amplifier output voltage with the water level sensor capacitance, C_s, is illustrated in Fig. 10. The amplitude of the charge amplifier output voltage varies linearly with C_s, exhibiting non-linearity Root-Mean-Square (RMS) error and Mean Absolute Error (MAE) of 0.13% and 0.11%, respectively. Thus, by measuring the rectified output voltage of the charge-amplifier, as analyzed above, it is possible to accurately calculate the corresponding level of water in the storage tank.

4. Experimental results

Experimental prototypes of the proposed sensor were constructed in order to evaluate its performance in water storage tanks of a city-scale water distribution network. Commercially available multilayer tubes were used for that purpose (www.solin.gr). Two experimental prototype sensors were built by placing such a multilayer tube with a 16 mm diameter at the internal of a multilayer tube of the same type but with a 26 mm diameter. The lengths of these water level sensors were set at 4 m and 6 m, respectively, such that they correspond to the depth of the target water storage tanks where they would be installed. Both of these prototype sensors were installed in two tanks of the water distribution network of the Municipal Enterprise for Water and Sewage of the city of Chania (Greece). The prototypes of the proposed water level sensor installed in these water tanks are illustrated in Fig. 11. In order to operate in these water tanks, the prototypes of the proposed sensor have been attached on plastic bases mounted on the wall of the corresponding tank. As shown in Fig. 12, due to the flexibility of the multilayer tubes employed for its construction, the proposed water level sensor is foldable. This enables its easy transportation to remote locations, where the water storage tanks of city-scale water distribution networks

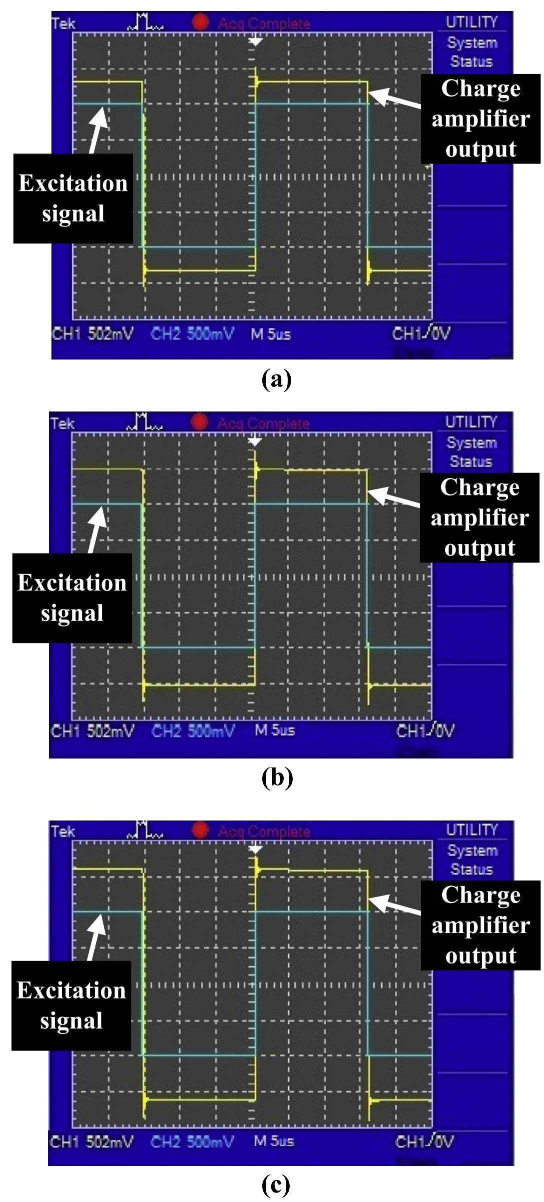


Fig. 9. The waveforms of the excitation signal and the charge-amplifier output voltage for various values of the water level sensor capacitance: (a) C_s = 1200 pF, (b) C_s = 1900 pF, and (c) C_s = 2100 pF.

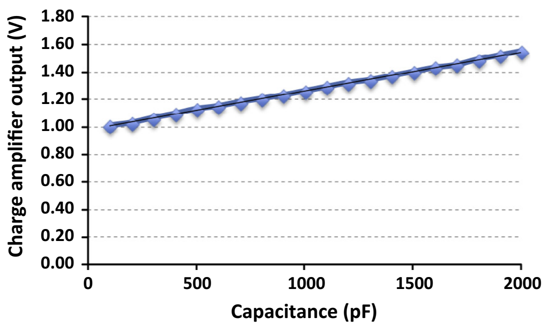
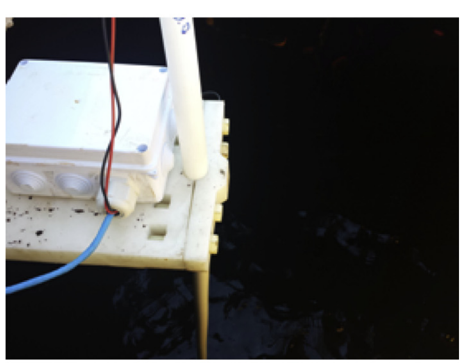


Fig. 10. The variation of the amplitude of the charge amplifier output voltage with the water level sensor capacitance, C_S.

(a)



(b)

Fig. 11. The experimental prototypes of the proposed sensor installed in: (a) water tank #1 and (b) water tank # 2 of the water distribution network of the Municipal Enterprise for Water and Sewage of the city of Chania (Greece).

are typically located. However, although the multilayer tubes used to construct the proposed sensor are flexible enough to be foldable prior installation in a water tank, also their stiffness is adequate to

Fig. 12. The proposed water level sensor in foldable form for easy transfer to remote installation sites.

ensure that during operation in a water tank, sensor wobbling, due to movement of water entering or exiting the tank, is avoided.

A photo of the signal-conditioning circuit PCB of the proposed water level measurement system, which was constructed as described in Section 3, is shown in Fig. 13. When installed in the water storage tanks, this PCB was placed inside an IP65 protective case to ensure that it is not affected by the adverse environmental conditions which prevail inside the water tanks (e.g. high humidity, water drops, corrosion of metals, etc.). The power consumption of the signal-conditioning system has been measured to be equal to 12 mW. Such a low power consumption favors the incorporation of the proposed system for water-level monitoring in geographically remote water storage tanks, such as those comprised in city-scale water distribution networks, where, due to the lack of electricity, small-scale Renewable Energy Sources (e.g. Photovoltaic modules) are frequently employed for producing the electric energy required for sensor operation.

During the experimental process, the water level measurements were collected by an ALIX 3d2 system board. The communication between the AD7745 capacitance-to-digital converter of the sensor signal-conditioning circuit and the ALIX 3d2 system board was implemented using the I^2C protocol, via a UTP cable. The data transmission distance was extended by using a pair of P82B96 I^2C bus extension integrated circuits, which support a low-cost and easily implementable bidirectional data transfer over an I^2C bus with various operating voltage levels between 5 and 12 V.

In order to verify that the proposed water level measurement system (i.e. capacitive sensor and signal-conditioning circuit) achieves equivalent performance with existing industrial water level measurement systems, its operation was evaluated against the measurements provided by a commercially-available ultrasound water-level sensing device that was also installed in the same tanks for managing the operation of the water distribution

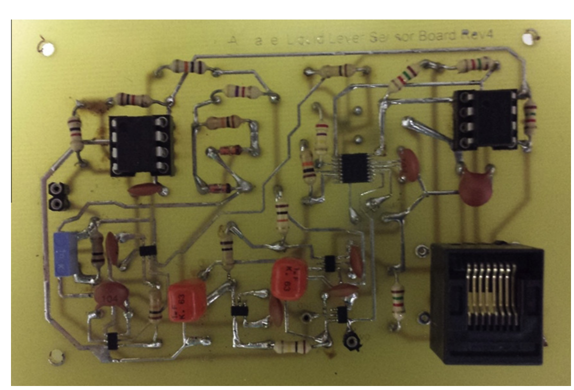


Fig. 13. The signal-conditioning circuit PCB of the proposed water level measurement system.

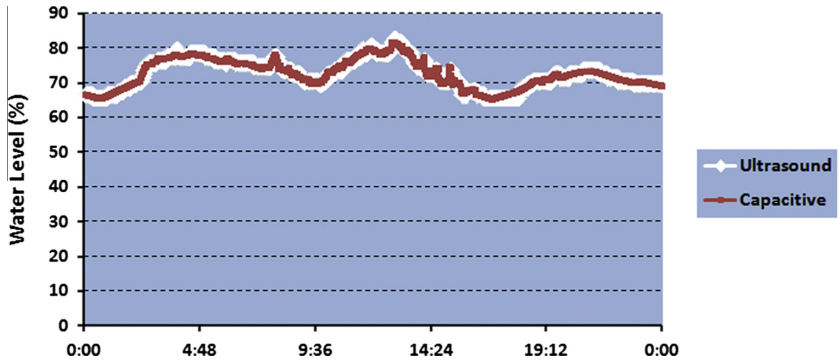


Fig. 14. Experimental measurements of the proposed and ultrasound water level measurement systems at water storage tank #1 (4 m depth) during 4/3/2015: the RMS error is 0.49% and the MAE is 0.38%.

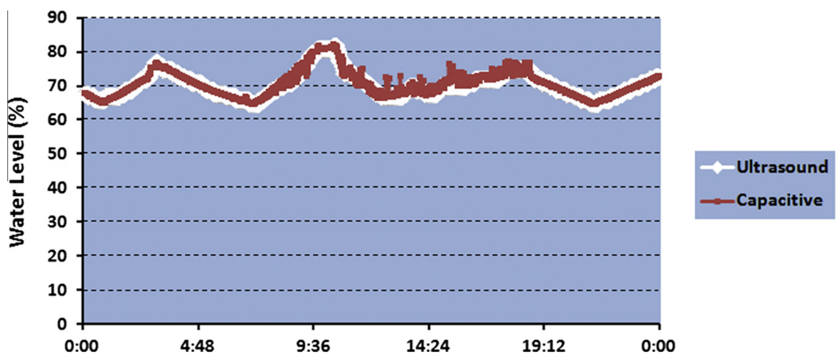


Fig. 15. Experimental measurements of the proposed and ultrasound water level measurement systems at water storage tank #1 (4 m depth) during 16/3/2015: the RMS error is 0.79% and the MAE is 0.52%.

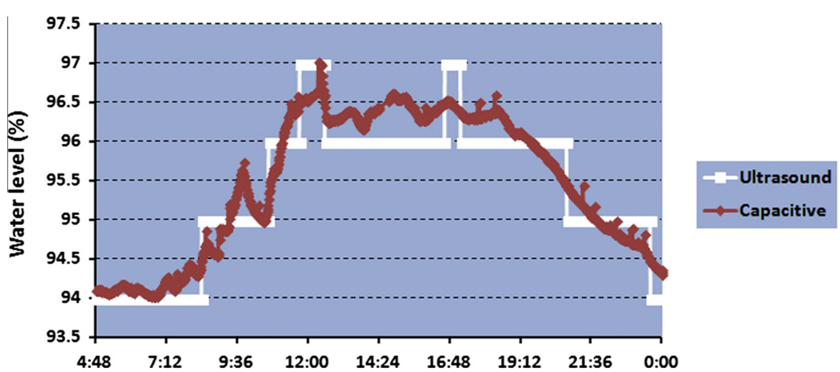


Fig. 16. Experimental measurements of the proposed and ultrasound water level measurement systems at water storage tank #2 (6 m depth) during 19/6/2015: the RMS error is 0.32% and the MAE is 0.28%.

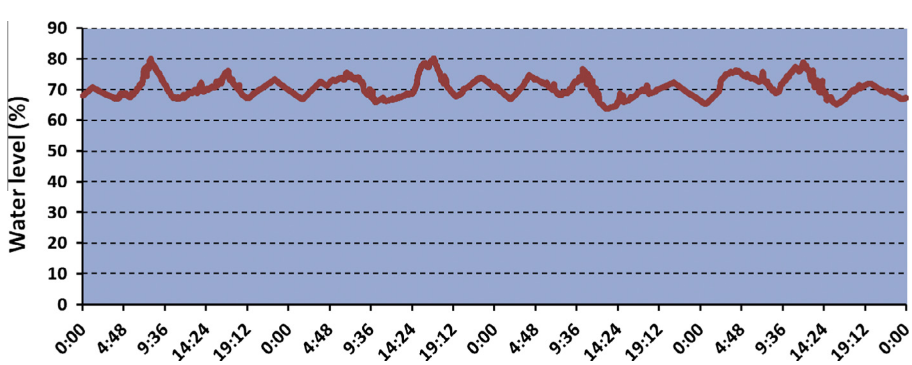


Fig. 17. Experimental measurements of the proposed water level measurement system at water storage tank #1 during 7–10/3/2015.

network. The time-series of the experimental measurements provided by the proposed and ultrasound water level measurement systems at water storage tank #1 (featuring a 4 m depth), as a percentage of the maximum level of the water tank, during two different time periods, are plotted in Figs. 14 and 15, respectively. The corresponding experimental results obtained at water storage tank #2, which features a 6 m depth, are presented in Fig. 16. Due to its pre-configured settings for incorporation in a SCADA system, the data provided by the ultrasound water-level measurement system have a sampling rate of 1 sample per 2 min and also no decimal point resolution is provided. However, the measurements provided by the ultrasound water-level sensing device are adequate to be used as a reference for evaluating the performance of the proposed measurement system, which has the flexibility to provide a much higher resolution (24-bits due to the AD7745 capacitance-to-digital converter) and also provides a higher sampling rate. In order to increase the measurements accuracy, the experimental prototypes of the proposed water level measurement system were calibrated using the measurements provided by the on-board display of the ultrasound sensing devices, featuring a resolution of 1 decimal point. It is observed that in all cases investigated, the measurements acquired by the proposed water level measurement system deviate by less than 0.8% from the corresponding measurements of the industrial ultrasound water-level sensing device. This percentage includes the deviations due to the intrinsic non-linearity of the capacitive sensor (e.g. due to slight bending of the sensor tubes), as well as the non-idealities of the signal-conditioning electronic circuit (e.g. input offset voltages of the op-amps) and the overall measurement system parasitics (e.g. sensor cable capacitance). Also, these experimental results reveal that although the ambient conditions (i.e. temperature and humidity) change during the test periods, the performance of the proposed measurement system is not deteriorated. Thus, the performance of the proposed water level sensor is acceptable for the city-scale water management application under consideration.

The experimental measurements acquired by the proposed water level measurement system at water storage tank #1 during 4 consecutive days, are illustrated in Fig. 17. It is observed that the level of water in the storage tank exhibit hourly and daily variations, due to the continuous mismatch between the water supply into the tank and the time-varying consumption of water by the users of the water distribution network.

Using construction materials from the local market, the total manufacturing cost of the two experimental prototype capacitive water level sensors, which have been developed, is 15.36€ and 20.36€, respectively, while the cost of the corresponding signal-conditioning circuit is 13€. Both of these costs have the potential to drop substantially in case that a large quantity of the required materials and devices are purchased within the framework of an industrial implementation. Therefore, the total cost of the proposed water level measurement system (i.e. sensor and signal-conditioning circuit) is much lower than that of commercially-available ultrasound water-level sensing devices (typically higher than 300€). Simultaneously, as demonstrated by the experimental results, the proposed measurement system achieves an equivalent performance with the industrial ultrasound sensing device, in terms of accuracy, for the water monitoring application under consideration.

5. Conclusions

Due to the high water-availability requirements of modern societies, the management of water is of paramount importance nowadays. In such applications, it is required to monitor the level of water contained in multiple, geographically isolated large-scale storage tanks of water distribution networks in order to apply the appropriate water management schemes.

In this paper, a review of the past-proposed techniques for liquid level sensing has been performed, revealing that either they have been applied for liquid level sensing over a relatively low range, or special scientific equipment of high cost is required for conditioning and processing the electric signal produced by the liquid level sensor, or they are not convenient for transportation, installation and long-term maintenance in multiple large-scale water storage tanks of water distribution networks in cities, communities, etc. Then, the operational characteristics and performance of a novel capacitive-type water level measurement system have been investigated through simulations and experimental tests conducted in two water storage tanks of a city-scale water distribution network. It has been demonstrated that the proposed capacitive water level measurement system achieves equivalent performance with that of a commercially-available ultrasound sensing device and simultaneously exhibits a much lower manufacturing cost. Thus, compared to the existing industrial water-level monitoring systems, it comprises a competitive alternative for incorporation in water management systems, where the massive deployment of water level sensors in a large number of water storage tanks is typically required.

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