A Low-cost Sensor Based on Time-Domain Reflectometry for Water Level Monitoring in Environmental Applications

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***Abstract*—The implementation of water management techniques in various environmental applications requires the measurement of the level of water stored in artificial storage tanks (e.g. in cities, communities etc.) or natural reservoirs. In this paper, the design of a water-level sensor is presented, which is based on the Time-Domain Reflectometry (TDR) technique. The proposed TDR sensor comprises a sensing probe constructed using low-cost and widely-available multilayer and stainless steel tubes. A simple signal-conditioning circuit has been designed for interfacing the acquired measurements to a digital data-acquisition device through an I^2C communication bus. Thus, the manufacturing cost and power consumption of the proposed sensor are relatively low, enabling its incorporation in Wireless Sensor Networks which are power-supplied by Renewable Energy Sources. The operation of the proposed sensor has been tested in a city-scale storage tank of drinking water. The experimental results verify that the proposed sensor achieves equivalent accuracy performance with a commercially available ultrasound water-level sensor, which, however, is of higher cost.**

Keywords*—Sensor; Time-Domain Reflectometry; Water level; Data-acquisition

I. INTRODUCTION

Nowadays, water and energy availability are major parameters under consideration for achieving a sustainable growth of modern societies, both having a direct impact on the environment. Wireless Sensor Networks (WSNs) enable to measure the water stored in multiple artificial storage tanks or natural reservoirs, which are distributed across wide geographical areas in cities, communities etc. in order to apply appropriate water management techniques [1]. Since in such environmental applications wireless data-acquisition networks are typically installed in remote sites, where access to electricity is not available, Renewable Energy Sources (RES) are employed for providing electric power to the data-acquisition equipment. Thus, water-level sensors of low cost and low power consumption are indispensable, which are capable to operate autonomously without requiring the use of specialized laboratory instruments, in order to minimize the cost of the overall data-acquisition system.

Measuring the level of liquids is important in many environmental and industrial applications, so numerous methods have been developed in the past for acquiring precise liquid-level measurements [2]. However, as new applications continuously appear, which impose new operational requirements, the need for even more improved techniques escalates accordingly. Currently, ultrasound sensors are most commonly used in large-scale liquid storage tanks, because they are non-invasive, can be easily installed and their operation does not depend on the liquid type. Nevertheless, these sensors exhibit the major disadvantage that the sound waves emitted on the liquid surface may be scattered due to e.g. liquid motion, existence of bubbles etc. In such a case, the sound waves received by the data-acquisition unit after having been reflected on the liquid surface, are degraded, which results in a deterioration of the overall accuracy of the sensor. Other widely used sensing elements are the capacitive sensors, which have also been proved to be an excellent alternative for measuring the level of many liquid types [3, 4]. Their operation is based on the formation of an equivalent capacitor between the liquid under monitoring and the sensor probe. The resulting capacitance depends on the level of the liquid where the capacitive sensor has been immersed in. This measuring technique can provide an excellent resolution; on the other hand, the operation of capacitive sensors can be affected by several parameters that can alter the overall capacitance of the sensor, such as the ambient temperature, air humidity etc. Also, a special construction of the capacitive sensor probe is required, such that the construction material of the tank, where the liquid under monitoring is stored, does not affect the liquid level measurements through the formation of parasitic capacitances with the sensor probe, which could create an undesirable interference to the measuring system. Capacitive sensors often require calibration to different ambient temperature levels, in order to improve their accuracy.

Liquid level monitoring also involves numerous additional techniques, which have been employed in various applications. In [5], a water-level sensor is presented, which is based on the use of an optical fibre Fabry-Perot interferometer. The results indicated a small measurement error in water-level measurements, with good resolution and the capability to apply this method in long-range measurement systems. The instruments that should be used to provide the measurement results, as well as the special installation process, which is required for applying this operating principle, constitute this

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approach a complex solution for urban usage. An alternative approach for measuring large-scale water levels up to 10 m using a low-cost optical sensor, which is based on the fiber bending effect, was presented in [6]. The performance of this sensor was evaluated through field tests. The results indicated a very promising sensing alternative for obtaining water-level measurements. However, an Optical Time Domain Reflectometry (OTDR) instrument is required for extracting the distance-related information from the sensing elements, which operates by injecting optical pulses into a fiber under test and measuring the light which is backscattered due to the Rayleigh effect. Thus, the water-level measurement system is not autonomous, since the use of an external electronic instrument is required, which also increases the overall cost.

The Time Domain Reflectometry (TDR) method is based on the propagation of an electrical signal along a transmission line and the measurement of the time-delay that occurs until a part of the initially transmitted signal is reflected back to the source, due to the specific arrangement of the transmission line, or impedance mismatching between the transmission line and an electric load [2, 7, 8]. Generally, TDR systems are of high accuracy and they are able to perform a wide range of measurements. A TDR-based data-acquisition system is comprised of sensing electrodes, which constitute the sensor probe, as well as electronic circuits for measuring and analyzing the reflected wave in order to derive the required information. Depending on the application, the TDR sensors probes can be configured in 2- or 3-rod structures, or even comprise circular rods [2, 7-11]. The TDR principle has been applied in the past in environmental monitoring applications, as well as for detecting cable faults, evaluating soil water content, electric-circuit testing, liquid-level detection etc. [8, 10]. Several different forms of sensing probes have been developed, which have been suited to the specifications of the target application. In liquid-level monitoring applications, the TDR probe is immersed into the liquid of interest. Due to its high resolution capability, the TDR technique is mostly employed in large-scale applications, where minor deviations in the level of the liquid correspond to a high volume of stored liquid. However, measuring specific characteristics of the electric signal which propagates along the transmission line of the TDR sensor-probe (e.g. reflection time etc.) can be proven very complicated to implement, thus raising the overall cost of the measuring system. A water level sensor using a closed-loop probe, consisting of a standard RG58 coaxial cable, was tested for long and short measuring ranges in [7]. The probe was connected to the 1502B Tektronix TDR instrument. That measurement system was tested in the field, where it was observed that its performance was degraded at low-temperature operating conditions, due to the reduction of the value of the water dielectric constant. Multi-length TDR probes were used in [10] for measuring soil moisture, which affects the growth rate of plants. A coaxial configuration of TDR sensor stainless-steel probe for liquid-level monitoring was presented in [11], which was used in combination with the Campbell-Scientific TDR-100 Time-Domain Reflectometer. The corresponding configuration is depicted in Fig. 1. Several liquid types were tested, obtaining a measurement uncertainty of less than 2%. The advantage of the coaxial configuration of the sensor probes, which has been implemented in that study, is that it provides rigid probes that can be easily adjusted for constructing sensors with different ranges. Also, they can be easily replicated, without exhibiting deviation in their operational characteristics. In [9], a flexible two-wire TDR probe for liquid-level measurement is presented. In this configuration, non-invasive monitoring of the tank is performed, since the TDR sensor can be placed on the outside surface of the tank. However, this technique can only be applied in non-metallic containers. The use of a plastic container with oil was demonstrated in [11], to support this non-invasive method. Also, simulations were performed for testing the performance of the sensor with respect to various design parameters, such as the container wall thickness and its relative dielectric permittivity. In [12, 13], a TDR sensor with a two-strip probe connected to a Hyperlabs HL1500 TDR unit, was attached on the infusion bottle of a medical device for monitoring the level of the liquid (i.e. physiological solution of NaCl) that it contained. In order to reduce the cost of the external instrument, which is required for performing the TDR measurements, a lower cost Time-Domain Transmission sensor (TDT), that measures the transmission time of a signal, was employed for soil water-content measurements in [14].

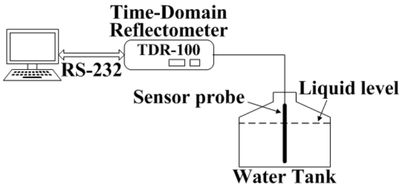


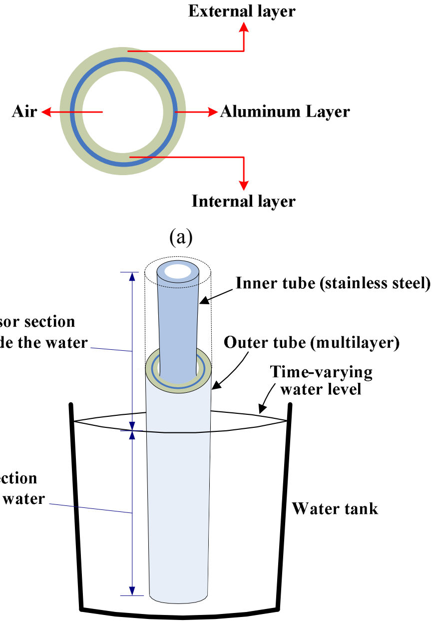
Fig. 1. The configuration of the TDR-based system presented in [11].

Although most of the past-proposed TDR systems have employed several sensor probe structures with excellent performances, the corresponding measurements were obtained with the use of external commercially-available instruments, where the sensor probes were connected to. Thus, the same equipment that is typically used in applications such as the measurement of cable length, the detection of cable faults etc., has also been used to deliver data for the liquid-level monitoring systems. However, as analyzed above, this approach is not sufficient for implementation in environmental applications where WSN-based water-level monitoring must be performed across geographically distributed areas with low cost and low power consumption, in order to facilitate the employment of low-cost RES-based power-supply units. In this paper, the design of a sensor based on the TDR technique is presented, which is suitable for measuring the level of drinking water in large-scale storage tanks or natural reservoirs. The proposed TDR sensor comprises a sensing probe constructed using low-cost materials, which are widely available in the market, accompanied by a relatively simple electronic circuit. Thus, the manufacturing cost and power consumption of the proposed sensor are low, favoring its incorporation in geographically isolated, water-level monitoring WSN nodes, which are power-supplied by RES. The operation of the proposed sensor has been tested in a city-scale drinking-water storage tank and the corresponding experimental results are presented.

II. THE PROPOSED TIME-DOMAIN REFLECTOMETRY SENSOR

During the development of the proposed water level sensor it was taken into account that it should be suitable for use in drinking-water storage tanks, under a high level of air humidity, which affects the long-term integrity of metallic materials. Also, in order to ensure a reliable operation, the materials used for the construction of the sensor must be also appropriate for long-term use in water, with the lowest possible corrosion risk. In addition, for enabling its incorporation in geographically isolated WSN nodes, power-supplied by RES, the data-acquisition system of the proposed sensor must be capable to operate with autonomous electronic circuits, which monitor the changes of the pulses injected along a transmission line and provide the water-level data. For designing the signal-conditioning circuit of the proposed water-level sensor, special consideration was also given to the fact that, in practical environmental applications, the water-level sensor is installed inside a water tank or natural reservoir, which typically resides at a long distance away (usually 5-30 m) from the data-acquisition and wireless transmission units of the WSN node.

In order to develop a water-level monitoring system that fulfills the above specifications, the proposed sensor is constructed using widely available multilayer polyethylene tubes. Such tubes are used in water distribution and heating/cooling applications. A cross-section of a multilayer tube is illustrated in Fig. 2(a). It consists of an aluminum layer, which is placed between an inner and an outer layer of polyethylene. As shown in Fig. 2(b), the proposed TDR water level sensor consists of a stainless steel tube, which is installed coaxially inside a multilayer tube, thus forming a transmission line immersed into the water of the storage tank. The stainless-steel tube is of 304L type, which follows the standards of American Iron and Steel Institute (AISI) [15]. The stainless steel tube and the aluminum layer of the multilayer tube form the electrodes of the proposed TDR sensor. Appropriate mechanical fittings are installed at the ends of the stainless steel and multilayer tubes, which are placed in the water, in order to avoid water entrance between these two tubes, as well as to protect them from corrosion. The water of the storage tank is in contact with the outer surface of the multilayer tube and the internal surface of the stainless steel tube. The length of the sensor is selected according to the maximum depth of the storage tank or natural reservoir under monitoring. Thus, modifying the length of the multilayer and stainless steel tubes, which comprise the probes of the proposed TDR sensor, enables to easily adapt to the water-level range specifications which are imposed by the target application. According to [4], water is practically conductive at excitation frequencies up to hundreds of kilohertz and in this case, its capacitive and inductive characteristics are negligible. Thus, in the proposed water-level sensor, the frequency of the sensor-probe excitation signal, which is produced by the signal-conditioning circuit as described in the following, has been selected to be within this range such that the water of the storage tank behaves as a conductor when interacting with the different parts of the proposed sensor probe.



(a)

(b)

Fig. 2. (a) A cross-section of a multilayer tube and (b) The structure of proposed TDR water-level sensor.

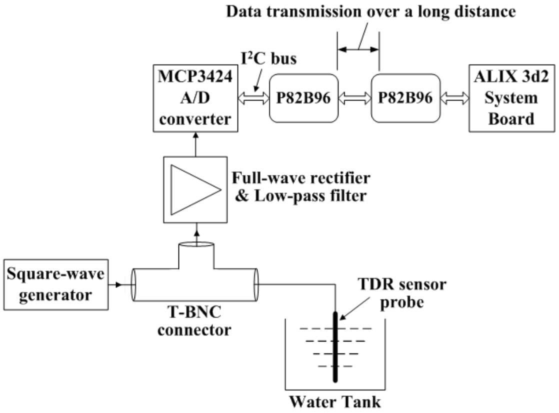


Fig. 3. A block diagram of the signal-conditioning circuit, which was developed for operating the proposed water-level sensor according to the TDR principle and interfacing the water-level measurements to an ALIX 3d2 system board.

In order to operate the proposed sensor according to the Time Domain Reflectometry principle, an appropriate signal-conditioning circuit has been designed. A block diagram of this circuit is illustrated in Fig. 3. The sensor probe, which has been described above, is connected to one port of a T-BNC connector. A square-wave generator and a circuit for measuring the reflected wave are connected to the other two ports of the T-BNC connector. For the generation of the square-wave, an ICM7555 timer was used. The timer was set to produce a 250 kHz square wave with a 50% duty cycle. In order to drive the sensor probe with a low rise-time, the output of the timer is connected to six 74HC04 inverters, which are connected in parallel. The output voltage of the inverters drives the sensor probe through a 50 Ω coaxial cable, which is connected to one of the T-BNC connector ports. The transmission line formed by the probe of the proposed sensor [Fig. 2(b)], behaves as a distributed circuit at the high

(a) (b)

Fig. 4. Experimental waveforms of the signal received by the signal-conditioning unit in case that the probe length of the proposed sensor is equal to 1.8 m and the water level is: (a) 0 cm and (b) 35 cm.

frequencies, which are contained in the wide-bandwidth square-wave signal that it is driven by. Thus, according to the TDR principle, during the propagation of the square-wave signal along the probe of the proposed sensor, a part of it is reflected, resulting in a distortion of the signal received at the measuring port of the T-BNC connector. The strength of the distortion depends on the level of water in the storage tank where the proposed sensor has been immersed in. As an example, the modification of the shape of the signal received at the measuring port of the T-BNC connector (i.e. at the input in the signal-conditioning circuit) due to the variation of the water level is shown in Fig. 4. In order to measure the strength of the variation of the reflected waveform with the level of water contained in the storage tank, a full-wave rectifier is employed for rectifying the bipolar square-wave received at the corresponding port of the T-BNC connector. Then, a low-pass filter is used for producing a DC output voltage, which is proportional to the water level. The MCP3424 Analog-to-Digital Converter (ADC) is used for converting to digital the DC voltage produced by the low-pass filter. The full-wave rectifier and low-pass filter have been implemented using the AD8515 operational amplifier ICs. The MCP3424 ADC provides an 18-bit digital output, which is compatible with the I^{2}C serial communication protocol. Its sampling resolution is programmable from a software script executed by a master communication device. In the proposed system, this software script is executed by the ALIX 3d2 system board, which acts as the data-acquisition device, being responsible for collecting the water-level measurements. The I^{2}C protocol has been used for implementing safe data transactions since the late 80's (e.g. for sensor monitoring, acquisition of medical images etc.) and it is an excellent alternative to other communication protocols that are used in industrial applications [16, 17]. Techniques such as the wireless transmission or the employment of industrial communication interfaces, such as the 4-20mA protocol, are also frequently adopted for transmitting sensor measurements to a central data-acquisition unit. However, the main disadvantage of such industrial protocols is that due to the hardware required for their implementation (e.g. wireless transceivers, antennas, current-to-voltage converters etc.), the cost and design complexity of the overall data-acquisition system are increased. The ALIX 3d2 system board, which is used as a data-acquisition unit in the target application under study, comprises an I^{2}C port, which is available for data transmission/reception purposes.

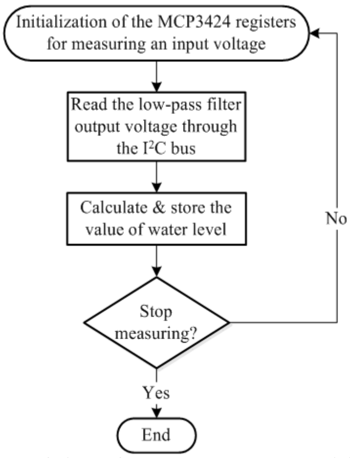


Fig. 5. A flowchart of the software program executed by the ALIX 3d2 system board for collecting the water level measurements.

The ALIX 3d2 system board executes a software script in order to communicate with the MCP3424 ADC for acquiring the water level measurements and providing them to other software applications of the WSN node for further processing. A flowchart of this script, which was developed using the Python programming language, is presented in Fig. 5. Initially, the internal registers of the MCP3424 ADC chip are initialized for measuring the output voltage of the low-pass filter. The water level, L (m), is calculated using the measurements of the low-pass filter output voltage, V_f (V) according to the following equation:

$$L = c_1 \cdot V_f + c_2 \qquad (1)$$

where c_1 and c_2 are calibration constants. The values of c_1 and c_2 are derived by comparing the response of the proposed sensor at various water levels with the corresponding measurements obtained by an industrial water-level sensor (e.g. an ultrasound water level meter), which is used as a reference during the calibration process. The water level data acquired by the ALIX 3d2 system board are stored in an on-board flash card. The software script executed by the ALIX 3d2 system board for the water level monitoring process can be executed in any Linux release. For the tests conducted within the framework of this study, the Voyage and Debian versions were used. The script software code uses the system addresses that the MCP3424 chip devotes for connecting with other I^{2}C-compatible devices over the I^{2}C bus. An additional benefit of using MCP3424 ADC is that it includes dedicated address pins on its package, for providing different I^{2}C addresses. Thus, if required by the target application (e.g. in case that the water storage tank under monitoring comprises multiple, isolated water-storage segments), then more than one water-level sensors can be connected with the same terminal data-acquisition unit through the same I^{2}C bus. The signal-conditioning circuits are power-supplied by the ALIX 3d2 system board, as well as from an external power source. For establishing a safe communication between the two ends of the communication link, a standard UTP cable is used. In order to extend the communication distance supported by the I^{2}C protocol beyond the 5 m limit, the P82B96 I^{2}C bus

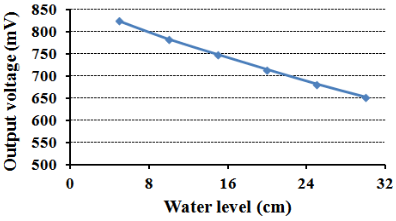


Fig. 6. The experimentally measured output voltage of the low-pass filter of the proposed sensor signal-conditioning circuit at various water levels.

extension chips are connected at the two ends of the communication link, which is formed between the MCP3424 ADC and the ALIX 3d2 system board. Thus, the data transmission distance can be increased by up to 30 m, which enables to easily adapt to the typical installation requirements of environmental water-level monitoring applications.

The proposed TDR sensor has been designed to operate autonomously, without requiring the use of external laboratory instruments for acquiring and analyzing the TDR waveform, and provides water-level data to an external digital system board for acquisition and further processing. Thus, the sensor probe and signal-conditioning circuit described above comprise a complete data-acquisition system, which can be employed in autonomous WSN systems for environmental applications.

III. EXPERIMENTAL RESULTS

An experimental prototype of the proposed TDR sensor with a length of 1.8 m was initially constructed as analyzed above and tested in the laboratory. It comprised a TP304/304L stainless steel pipe with a diameter of 16 mm, which has been fitted coaxially at the inside of a commercially-available multilayer tube with a 26 mm diameter (www.solin.gr). The first sets of experiments were conducted by immersing the proposed TDR sensor into a plastic container. The experimentally measured voltage, which is produced by the low-pass filter of the signal-conditioning circuit of the proposed sensor at various levels of water, is plotted in Fig. 6. The non-linearity Root-Mean-Square (RMS) error is 0.65 % and the Mean Absolute Error (MAE) is 0.62 %. Then, the performance of the proposed water level sensor was also tested experimentally in a drinking-water storage tank, constructed of concrete, which was allocated by the Municipal Enterprise for Water and Sewage of the city of Chania (Greece) for that purpose. In order to adapt to the depth of the target storage tank, a prototype of the proposed sensor with a 4 m length was constructed, which is depicted in Fig. 7. In the same water storage tank, a commercially- available ultrasound water level sensor had also been installed by the Municipal Enterprise for Water and Sewage of Chania for controlling the operation of the water distribution network. The ultrasound sensor was used as a reference for calibrating the proposed TDR sensor under various operating conditions in the tank and also for evaluating its performance. These two different types of sensors were set to operate concurrently in the same storage tank for a time period of 6 hours. It was observed that the proposed sensor produced stable results during both the rise and the fall of the water level in the tank. A plot of the experimental measurements acquired by the proposed TDR sensor versus the corresponding output of the ultrasound sensor, under various water-level conditions, is illustrated in Fig. 8. The RMS and MAE values of the deviation between the corresponding measurements of the two types of sensors are 0.23 % and 0.19 %, respectively. Thus, the proposed TDR sensor fulfils the accuracy requirements of water-management schemes, which control the operation of city-scale water distribution networks.

Fig. 7. An experimental prototype of the proposed sensor for a measuring range of 4 m.

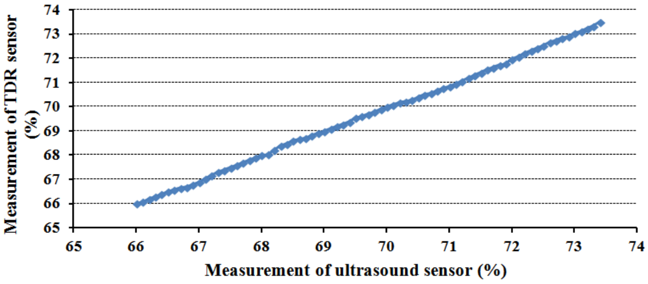


Fig. 8. The measurements acquired by the proposed water-level sensor versus the corresponding measurements of the ultrasound sensor, when both operating in a water storage tank of the Municipal Enterprise for Water and Sewage of Chania (Greece).

The total power consumption of the signal-conditioning circuits of the proposed TDR sensor is equal to 5.67 mW. Such a low power consumption is advantageous in WSN applications of the proposed water level sensor, where the wireless sensing nodes are power-supplied by photovoltaic or wind-generator renewable energy sources, since it enables to minimize the overall cost of the energy production and storage (i.e. battery bank) units. The total time required by the software, which is executed in the ALIX system board to accomplish the acquisition of each water-level measurement, is approximately 0.43 sec. This time interval includes the time required for communicating with the signal-conditioning circuits through the I^2C bus, as well as the data-processing time according to the flowchart depicted in Fig. 5.

The proposed TDR sensor and signal-conditioning circuits have been constructed using materials and electronic components of low cost and wide availability in the market. The manufacturing cost of the probe tubes of the proposed sensor is proportional to the water-level measuring range, but the cost of the signal-conditioning unit remains constant. Purchasing materials and electronic components in small quantities, resulted in a total construction cost of the proposed TDR sensor probe for a 4 m measuring range, which is equal to 48.55 €, while the total cost of the signal-conditioning circuit is 11.43 €. Both of these costs will fall substantially in an industrial manufacturing process, where the required materials and electronic components are purchased in massive quantities. As discussed above, the proposed sensor exhibits equivalent performance with a commercially-available ultrasound water-level sensor in terms of accuracy in water-level monitoring applications in city-scale water distribution networks. However, the total cost of the proposed water-level measurement system is lower than that of commercially-available ultrasound water-level sensors (typically higher than 300 €).

IV. CONCLUSIONS

The application of water management techniques for addressing the water availability problems of modern societies in an environmentally-friendly manner, requires the measurement of the level of water stored in multiple artificial storage tanks or natural reservoirs, which are distributed across wide geographical areas in cities, communities etc.

In this paper, the design of a sensor based on the Time Domain Reflectometry (TDR) technique has been presented, which is suitable for measuring the level of drinking water in large-scale storage tanks. The proposed TDR sensor comprises a sensing probe, which is constructed using low-cost and widely-available multilayer and stainless-steel tubes. A low-cost and low power consumption signal-conditioning circuit has been designed in order to properly operate the probe of the proposed sensor according to the Time Domain Reflectometry technique and interface the acquired measurements to a digital data-acquisition device through an I^2C communication bus. These features favor the incorporation of the proposed sensor in RES-power-supplied WSNs, which are employed in various environmental applications. The performance of the proposed sensor has been experimentally evaluated in a 4 m depth water storage tank of a city-scale water distribution network. The experimental results verify that the proposed sensor achieves equivalent accuracy performance with a commercially available ultrasound water-level sensor, which, however, is of higher cost. Future work includes further testing of the proposed TDR water level sensor in a city-scale water-storage tank, in order to evaluate its performance in the long term.

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