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Low cost sensors for water level monitoring in large scale storage tanks

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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 thesis, the design of two low cost water level sensors is presented, which are based on the capacitive and Time Domain Reflectometry (TDR) principles, respectively. The proposed sensors are comprised of sensing probes constructed using low cost and widely available multilayer and stainless steel tubes. Signal-conditioning electronic circuits have also been designed for both of these sensors, in order to interface the acquired water-level measurements to a digital data-acquisition device through an I^2C communication bus. The manufacturing cost and power consumption of the proposed sensors are relatively low, enabling their incorporation in Wireless Sensor Networks, which are power supplied by Renewable Energy Sources. The performance of the proposed sensors has been evaluated experimentally in a city-scale network of drinking-water storage tanks. The experimental results verify that the proposed sensors achieve equivalent accuracy with a commercially-available ultrasound water-level sensor, which, however, is of significantly higher cost.

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Publications

The work of this thesis was presented in the following papers:

1. Loizou, K., Koutroulis, E., Zalikas, D., Liontas, G. ”A low-cost capacitive sensor for water level monitoring in large-scale storage tanks”, *2015 IEEE International Conference on Industrial Technology*, Seville, Spain, 17-19 March 2015,

2. Loizou, K., Koutroulis, E., Zalikas, D., Liontas, G. ”A low-cost sensor based on time-domain reflectometry for water level monitoring in environmental applications”, *2015 15th International Conference on Environment and Electrical Engineering*, Rome, Italy, 10 -13 June 2015.

Patent

Also the capacitive sensor design has been patented with a Greek national patent with the following international identification number (INT. CL^8): G01F 23/26. and title *Capacitance sensor for measuring water level in tanks.*

Contents

Chapter 1

Introduction

Water-level sensors are indispensable for monitoring the level of water in storage tanks, which are used in drinking water distribution networks. Water is present everywhere around us, covering more than 70 % of the Earth surface. Nevertheless, since most of that water is not drinkable, more than 12 % of the world population does not have access to fresh water [1]. Commercial water export to the countries that suffer from water shortage would only preserve the water supply problem that has caused the "global water crisis". The only answer is to respond to population'As growing demands for water by increasing supply. Additionally, this demand has led to the draining of lakes, the exhaustion of water supply and destruction of aquatic ecosystems around the world.

Therefore, the optimal usage of the available water resources is essential for every modern city. In order to be able to act in the best possible way and be able to continuously monitor the water quality in the distribution networks, automated sensor systems must be installed in all tanks that operate within the network. Consequently, these sensors must be of low price and high accuracy in order to reduce the cost of the overall water monitoring/ management system.

1.1 Thesis Contribution

The contribution of this thesis is the development of low cost water level sensors that addresses the problem of installing multiple sensors in a wide-scale network, for monitoring water tanks over large areas. The extensive background of liquid level sensors was initially studied and alternative liquid level monitoring techniques were evaluated, based on the length of the required sensors and their cost. Then, two different type water level sensors were developed; a long-range capacitive water-level sensor and a time domain reflectometry (TDR) based water level sensor. The proposed sensors are constructed using widely-available material such as multilayer tubes, which are mostly used for building drinking water systems. The electronic signal-conditioning circuits for both sensors were designed from scratch in order to operate in stand-alone applications, without the need for external hardware. The developed sensors, after extended experimental testing were proven to perform equally good as the pre-installed industrial ultrasound sensors. However, the developed sensors have a significantly lower cost of construction, making them affordable for installation into multiple water level tanks. By monitoring the water level in various tanks across a city-scale network, water management algorithms can be applied with substantial accuracy, thus achieving to save water resources. The benefits of installing various sensors are numerous, since the administrator of the water distribution network knows the condition of the water tank in real time, having the monitored parameters under control. Therefore, administrator's actions can be proven vital for the saving of large water quantities.

1.2 Thesis Outline

Chapter 2 describes the past-proposed work on liquid level sensors and especially sensors that could be candidates for drinking water monitoring. In Chapter 3, the capacitive and TDR-based water level sensors that were designed within the framework of this thesis are presented. Also, the development of the corresponding signal-conditioning circuits is described, along with the connection of the sensor circuits with the Alix 3d2 system board, the circuit design and the necessary drivers used for the communication of the water-level measurement system components. Chapter 4 describes the prototyping procedure of the proposed measurement systems. Both circuit and sensor probes are presented with the additions required for proper installation in the water tanks. The prototyping process is also described with the alternative circuits and programming languages that were used during the development process. In Chapter 5, the experimental evaluation process of the proposed measurement systems is presented, with data of water level for various tanks in the Chania water distribution network. In Chapter 6, the developed water level measurement systems are evaluated. Finally, suggestions for further improvement of the proposed measurement systems are proposed.

Figure 1.1: Ag. Ioannis water tank in Chania.

Chapter 2

State of the art review

The United Nations Secretary Ban Ki-moon has stated that water is the most important aspect that connects people around the world [1].

> ”Saving our planet, lifting people out of poverty, advancing economic growth... these are one and the same fight. We must connect the dots between climate change, water scarcity, energy shortages, global health, food security and women's empowerment. Solutions to one problem must be solutions for all.”

Water level sensors [2] have vital applications in modern cities and industries worldwide. It is widely acceptable that 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 sensors in multiple, geographically isolated large-scale storage tanks of water distribution networks. Existing techniques for water level sensing have either been applied over a relatively low measurement range, or require special scientific equipment of high cost. Furthermore, most of the available sensors are not convenient for transportation, installation and long-term maintenance in multiple large-scale water storage tanks of water distribution networks in cities or smaller communities. Communication between these tanks is often based on high-cost transmitters and therefore several tanks are left completely unconnected and unmonitored. Wireless Sensor Networks (WSNs) enable measurement of the water stored in multiple artificial storage tanks or natural reservoirs, which are distributed across wide geographical areas in order to apply appropriate water management techniques [3]. The implementation of smart and reliable wireless networks can help to develop advanced solutions for water management. As a result, the measurement systems must consume low power, in order to be powered from Renewable Energy Sources (RES) without increasing the cost of the WSN [4].

In this chapter, an extensive review of the state of the art on liquid level sensors is presented. The different types of sensors are also evaluated for their targeted applications, since liquid level sensing is applied in numerous different situations. The studied sensors vary in targeted depth, price, accuracy etc.

2.1 Liquid Level Measurement Techniques

2.1.1 Capacitance Sensors

Measuring the level of liquids is important in a wide range of environmental and industrial applications, so numerous methods have been developed in the past for acquiring precise liquid level measurements [5]. However, as new applications which impose new operational requirements, continuously appear, 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 [6, 7]. 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 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. Additionally, in harsh environments their pulse generator screen is affected by vapours from the monitored liquid evaporation. These conditions can create completely wrong liquid level measurements.

To address these problems, a widely used solution, especially for small-range level measurement systems in water level applications, is the usage of capacitive sensors. This type of sensors is proven to be stable, while providing high resolution with the superiority that they can be constructed using various materials, therefore being of lower cost. The implementation of capacitive sensors is based on the structure of the sensor probes and the resulting capacitance depends on the material used for the sensor construction. The dielectric of capacitive sensors is based on the material of the probes. The capacitance that the probes create, alternates its values based on the water level shifting. Therefore, capacitive-type sensors can be of various shapes, in order to create the ideal capacitor, which will be affected by the least undesirable parameters. Limitations such as the cable capacitance, variations due to temperature, or parasitic capacitances created between the sensor and nearby objects can add a significant measurement error. Water level tanks are usually complex environments because of the continuous high humidity and low light situations. Cylindrical capacitive sensors provide an excellent solution improving the stability of the sensor structure [2, 8, 9, 10, 11]. These sensors are typically constructed using various materials, such as stainless steel [9], plastic, insulated solid metallic rods [10, 11], shielded cable [8], Printed Circuit Board (PCB) rods [7], or even insulated electrodes with polytetrafluoroethylene (PTFE) [9]. Capacitive sensors have an overall simple operating principle. The electric capacitor is a passive two-terminal electrical component which is used to store energy temporarily. The forms of practical capacitors vary widely, but all contain at least two electrical conductors separated by a dielectric (i.e. an insulator that can store energy by becoming polarized). In the form of water level sensor, the capacitor durability is always based on the materials from which the system is fabricated. They are essential for a stable result of the total capacitance and the overall operation of the sensing system. The level of liquid contained between these metal plates alters the resultant capacitance of the sensor system. Operating frequency and liquid chemical composition define how the liquid contained between the sensor electrodes would behave electrically as either a conductor, or an insulator. The electric behaviour of water depends on the excitation frequency. As analysed in [9], at operating frequencies up to hundreds of kilohertz the water is practically conductive, exhibiting an equivalent ohmic resistance, while its capacitive and inductive characteristics are negligible. This makes the created capacitive sensor easier to use. The water electrical characteristics can be affected by the existence of dissolved solutes [12] These properties have been exploited during the design of the proposed capacitive water-level sensor by selecting the excitation frequency, to be within the above range such that the water interacting with the sensor parts behaves as a conductor.

Capacitive sensors can be constructed from a wide range of materials which are easily available in industrial market and can be at low cost or even certified for contact with drinking water. In [9], two stainless steel rods combined with PTFE insulation are used for creating a capacitive water level sensor. The electrodes that compose the water sensor can be from 316 L or 304 L stainless steel type. This type of stainless steel is certified by American Iron and Steel Institute (AISI) for usage inside drinkable water. The 304 L has lower price and lower life span than 316 L, however, both stainless steel types are certified for safe water usage. Due to their lack of flexibility, these steel metallic rods, that often comprise at least one part of a capacitive liquid level sensor structure, limit the capability of capacitive type sensors for easy transportation and installation in distant locations. This issue is addressed by using bendable shielded cable, such as the one proposed in [8]. The type of cable used is widely available in the market and the sensor can be used in both grounded metallic and plastic containers. Its construction materials are also waterproof in order to keep the inner parts of the sensor protected. The main disadvantage of this construction method is that the cable is reported to be constructed by Poly Vinyl Chloride (PVC), which can be found in several forms that may not be certified to be suitable for installation in drinking-water storage tanks. The sensor system has its own signal conditioning circuit, a capacitance-to-digital converter that was developed for measuring the sensor capacitance variations, transferring 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 %. Multiple different versions of capacitive-type liquid level sensors have been constructed using various materials and focusing on low-cost fabrication, easy of installation and high linearity characteristics [7, 8, 9]. Experimentally, these sensors were tested in a laboratory using a LCR meter for measuring the sensor capacitance. To be suitable for water level sensing in large-scale storage tanks, it is crucial for the level sensor to be easily installed and designed to resist in rough environmental conditions. During operation in a liquid storage tank, the temperature variations within a year, together with the presence of water, can create a high level of humidity that can corrode and destroy metallic parts of the sensor structure.

A capacitive-type water level sensor of low-cost and high linearity, which was constructed using a Printed Circuit Board (PCB), was presented in [7]. This type of capacitive sensor is called inter-digital capacitive sensor and it is developed using multiple levels of comb electrodes. It is based on the same operating principle as the standard capacitor formed by two parallel plates comprising its electrodes. The water level measurements have been obtained using a simple measuring circuit based on a PIC16F887 microcontroller (Figure 2.1). The experiments were limited to the small range of 30 cm 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 reach over 4 m, is difficult. The overall cost of the sensor and signal-conditioning system has been reported to be equal to 30 $/meter of sensor length.

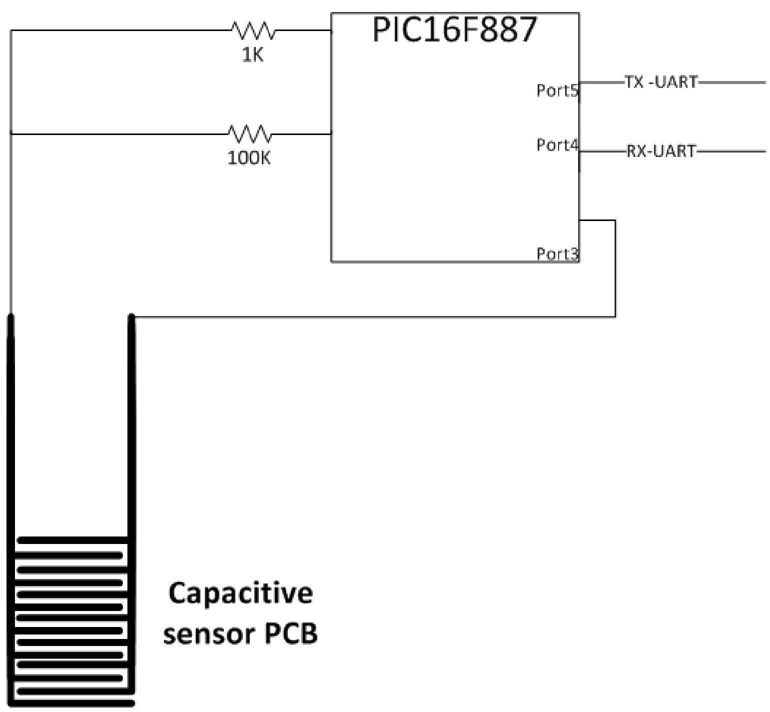


Figure 2.1: The inter-digital capacitive-type water level sensor and signal-conditioning circuit proposed in [7].

Capacitive sensors can also find different applications such as measuring the variations of liquid flow, for in-pipe measurement systems. The system proposed in [13] estimates the space occupied by each fluid in a specific type of pipe, by measuring the various capacitors created between its electrodes. The experimental results of this technique have revealed that the two- phase liquid flow can be estimated with accuracy using capacitive-type sensors. Capacitive-type sensing was also employed in other applications, such as monitoring the movement of propellers inside stirred tanks. Experiments in [13] simulate environmental variations within the stirred tank. Various factors such as temperature and humidity were observed as the most influential among the ones investigated. The results have shown that in the investigated two phase stirring systems, the most important variations occur with deionized water air entrainment, mostly when the propellers stirring speed reaches its highest value. On the other hand, in order to get results with deionized water and glass beads, solid particles must be mixed uniformly to observe them at rest. Capacitance variations occur along with the progression of stirring speed due to the decrease of volume fraction of solid particles inside the tank. The experimental process in stirred tanks showed that the suspension can create a difficult hydrodynamic situation which can also alternate stirring parameters, such as diameter of the solid particles and essentially create unnecessary capacitances. Therefore, capacitance-sensing technology provided important data in a situation that was difficult to use any other type of sensor. Finally, in [14] a liquid capacitive sensor is presented that can measure pico-liter liquids in the microfluidic channels of a PCB wafer. Using a developed sensor from vertical silicon electrodes, this capacitive sensor exhibits a very high measurement resolution. Therefore, capacitive sensors can find several applications for measuring liquid level, in different ranges, resolution values and cost.

2.1.2 TDR Sensors

The Time-Domain Reflectometry (TDR) principle can be applied in several environmental monitoring applications, as well as for detecting cable faults, evaluating soil water content, electric circuit testing and liquid level. The TDR principle was introduced in 1977 [15] and it is a pulse sampling technique that characterizes the distributed electrical properties of transmission lines [16]. TDR circuits are composed from instruments that launch low amplitude, high frequency pulses onto a transmission line, cable, wave guide under test or probe and then sequentially sample the reflected signal amplitudes and properties. The reflected pulse amplitudes are displayed on a calibrated time scale and can reveal information about the tested probe length, cable faults or liquid level. In this way, cable impedance changes, and discontinuities can be spatially located [17, 18, 19]. Transmission cables are used to drive and propagate time-modulated electromagnetic energy, thus they act as distributed circuits, instead of single, lumped elements. For measurement and simplicity purposes, transmission lines can be represented as a series of discrete circuit elements. As stated in [20], the basic point of TDR success is its ability to accurately measure the permittivity of a material and especially to indicate the relationship between the permittivity of a material and its water content. An additional advantage is the ability to estimate water content and measure bulk soil EC (Electrical Conductivity) simultaneously, based on the phase difference of the transmitted and received pulses. To create and develop a complete TDR-based system, the designer has to address issues such as the effective frequency of the TDR measurement and waveform analysis in dispersive dielectrics of the materials. The growing importance of both waveform simulation and inverse analysis of waveforms is important for the development of proper TDR probes. Also, TDR methods hold great potential for obtaining far more information from TDR waveform analysis. Due to its high accuracy TDR is another technique that it is widely used in liquid monitoring [5, 21, 22, 23, 24, 25, 26]. 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 [5, 21, 23]. The electrodes are immersed into the liquid and the variations of its level are measured with the use of an external scientific equipment such as the the Campbell Scientific TDR-100 Time Domain Reflectometer [5, 21, 23]. In [21, 24, 25], a TDR-based sensing 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. Several other sensing probes have been developed, which are suited to the specifications of the liquid measurement. 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), can be proven very complicated to implement, thus the overall cost for using a TDR-based sensor is significant. 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 [24]. In order to acquire the measurements, a 1502B Tektronix TDR instrument was used. Applications of TDR are also extended in non-invasive measurements in [22], with the use of electrodes that can be installed outside a chemical infusion bottle. This application is vital for medical equipment, since the infusion bottle requires a very low cost sensor, due to its usage as a disposable medical aid. Any other type of sensor cannot be placed inside the liquid (i.e. physiological solution of NaCl) because there is always the risk of infection. The TDR-based sensor probes can be comprised of 2 or 3 strips, depending on the application. Long-range electrodes have been reported for monitoring liquids such as oil and water. The flexible two-wire probes have two configurations, suited for metallic and non-metallic, respectively, containers [23]. This type of sensors is also suitable for obtaining data from mixed liquid materials. Every liquid has its own characteristics and provides enough data to distinguish the liquid type. For example with this method oil reflective wavelength is measured different than water's. The TDR method can also be used to measure vibrations in a complex fiber topology using phase-sensitive optical time-domain reflectometry. In that case, through the use of multiple reflective wavelengths, received from liquid materials, more complex structure properties can be measured [27]. Overall, TDR-based sensors are an excellent solution for liquid level measurement. However, the use of external scientific equipment for performing the required measurements rises the total data-acquisition system cost. Also, the external equipment makes installation for the TDR system in remote locations, such as those encountered in city-scale water management systems, unbeneficial and complex.

2.1.3 Other Liquid Level Sensors

Water level sensing is a high demand application and there are several other proposed solutions in the market and in research. In the following section, other types of water level sensors are presented. For every sensor, the advantages and disadvantages are explored, together with the reasons why these sensors were not appropriate for usage in long-range water-level monitoring applications.

Optical sensors are commonly used for liquid level measurement, since they can provide high-resolution measurements in a wide variety of applications. Different types of optical sensing techniques have been implemented for obtaining liquid level measurements. With optical sensors, monitoring the liquid level can be implemented by using different types of materials (other than PVC or stainless steel), extending the application of level monitoring to dangerous chemical liquids. An optical level sensor with a fiber model interferomenter, which is based on constant light polarization has been presented in [28]. The main disadvantage of this type of sensor is that the experiments indicate a high sensitivity with temperature that affects the measurement results. Therefore, despite the excellent linearity results in laboratory conditions, the application of optical sensors in liquid tanks of large dimensions will be ineffective. Moreover, the advantages of the non-invasive all-fiber structure, in addition to the stability offered by this water level sensing method, are important for the measurement of chemical liquids in small quantities, which require a higher resolution. For the implementation of the sensor, a Broad Band Super (BBS) light source is required together with an Optical Spectrum Analyzer (OSA). Such a measurement system can be fabricated. However, the sensor must be placed at the two ends of the container (Figure 2.2), limiting the possible applications and making it impossible to use in a long-range water level tank.

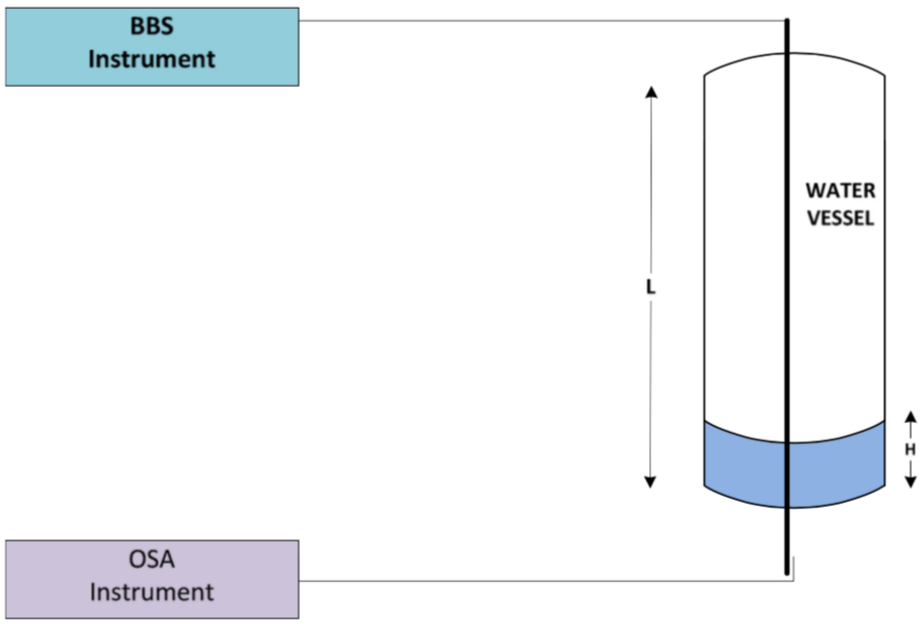


Figure 2.2: The inter-digital capacitive-type water level sensor and signal-conditioning proposed in [28].

Fiber Bragg Gratings (FBGs) are often affected by several parameters, which are studied in [29]. In the first part of this study, the effective refractive index of the thickness of Fiber Bragg and its experimental characteristics, such as sensitivity or time-evolution of its Bragg wavelength, were tested. An analytic expression was elaborated to connect the radius of etched FBG with the effective refractive index. The actual experimental tests were conducted after studying and adjusting the results to the thickness parameter and the output from the developed simulation models. Based on these experiments, etched FBGs performance was evaluated when used as liquid level sensors for water and oil. Water clearly has a shifted diffracted wavelength and the oil causes a reduction of its reflected power. This FBG sensor was dipped into the selected liquid to provide results with experimental testing on water and olive oil. The experiment was performed with a low level of the liquid (up to 5 mm). Therefore, this technique cannot be employed for measuring a wide range of liquid level, which is required in large-scale tanks. A fiber optic liquid level sensor based on the bending of FBG was also proposed in [30]. In this application, the FBG is placed on a cantilever rod in order to interact with the contractions of the Bragg grating with elongation, to provide data on the changes of liquid level. Experiments on level variations demonstrated excellent linearity and stability on the rise and fall of the liquid level. These measurements were performed in the range of 0-36 cm in a controlled room temperature. This sensor system can be installed in a tank with the use of a guardrail (Figure 2.3). The rise of water causes the cantilever rod to move upwards, creating a shift to the Braggs wavelength. As the water rises, the wavelength becomes higher and when the water level drops, the wavelength returns to its initial value. To record the measurement of the Bragg wavelength, usage of external equipment, such as an optical spectrum analyzer, is required. Also, the LABVIEW software platform was used during the experiments for data-acquisition and processing. Finally, to compensate the variation caused by the temperature shifting of the developed sensor head, temperature measurements must also be performed. The experimental results indicated that this system can provide a satisfactory performance in terms of linearity, a simple structure and reproducibility. However, due to the necessary external hardware and software, the overall measurement system cost is high and the range of measurements is relatively low.

The Fabry-Perot Interferometer (FPI) is studied for level monitoring in [31]. This optical

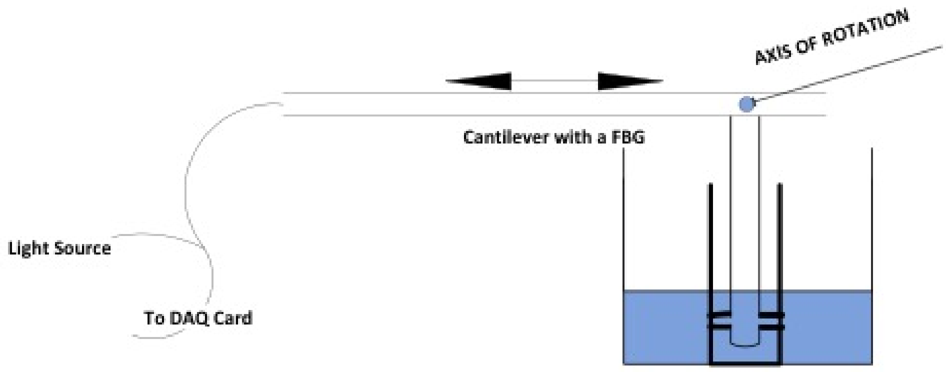


Figure 2.3: Fiber bragg placed on a cantilever rod [30].

sensor system can especially be used for long-range measurements, providing an excellent resolution of 0.7 mm at a depth of 5 m. However, the disadvantage of temperature variations has been reported to affect the measurements of FPI [32] and the placement of the diaphragm significantly reduces the measurement error of liquid level. For signal processing, the sensor is connected to a SM125 Optical Sensing Interrogator and data is processed with the use of the LABVIEW software platform. The use 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 low level in the liquid tank, making its usage in large-scale tanks almost impossible. Nevertheless, this sensor can be used with several liquid types and due to its long-range measurement capability it can be an alternative for application in e.g. oil reservoirs. The fiber-loop ring-down technique, which is demonstrated in [33], uses a short section of etched fiber for low level liquid level measurements. The experimental set up shown in Figure 2.4, consists of several instruments and the experimental tests of this method took place only within a laboratory environment. This method produced excellent results with very precise liquid level measurements. This measurement system has potential application for monitoring low-level liquids, where due to the presence of chemical substances other invasive-type sensors (e.g. for use in applications containing carbon disulfide and gasoline) cannot not be applied.

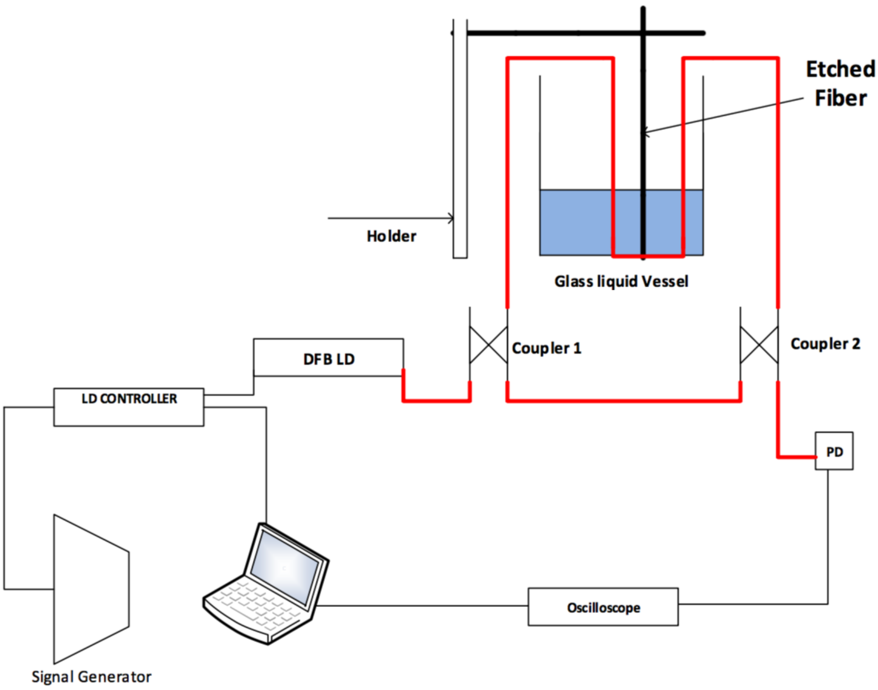


Figure 2.4: The fiber-loop ring-down technique which is demonstrated in [33].

For low-level liquid applications, the use of a Tilted Fiber Grating (TFG) with a Refractive Index (RI) hybrid system has also been proposed [34]. TM-polarization techniques are applied in order to develop a sensor system that monitors both temperature and liquid level. Application of this method has lower cost compared with the usage of an optical spectrum analyzer, but it is still a very expensive alternative for long-range applications, compared to capacitive or TDR sensors. A sensor combining temperature and liquid level sensing capabilities was also developed using a fiber laser sensor in [35]. The sensor is based on two taper structures operating with a FBG (Figure 2.5). As demonstrated experimentally, this sensor also exhibits a high resolution and sensitivity in both temperature and level measurements. The laser outputs

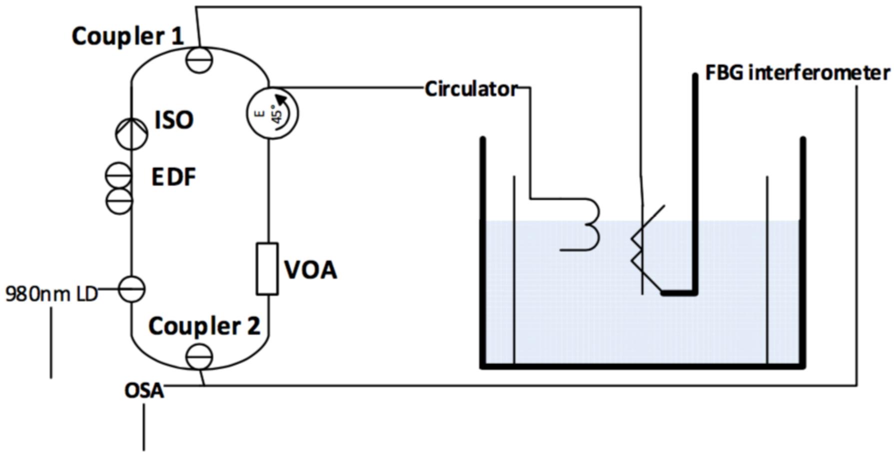


Figure 2.5: Fiber laser sensor used in [35] combining temperature and liquid level sensing in low level.

have fixed dual wavelengths, which produce different data between liquid level and temperature. However, due to the operating principle of this technique, its applications are limited in low-level liquids. It is proven that optical measurement systems are relatively complicated and very expensive for liquid monitoring and long-range measurements, in applications such as city-scale water storage tanks.

Pressure sensors are also used for water level measurements [36, 37, 38]. These water-level sensors are typically constructed using Low Temperature Co-fired Ceramics (LTCC), which exhibit a long operating lifetime, without any alteration of their characteristics. Evaluation on their performance [38], indicated that although water features parameters that are constantly changing (i.e. its temperature and salinity), the elastic properties, thickness of the protective layer and the overall cyclic loading does not affect critical performance characteristics. Extensive research has been performed to several types of pressure sensors [37], to determine if they can be applied in different atmospheric conditions. In order to provide a better accuracy, the sensors must re-calibrated over a short time period. To increase the sensor life span and improve its performance, the use of a protective coating is suggested [38]. Pressure-type sensors have been reported to control water flow in a distribution network [36]. They were selected because they are easy to install in the pipes and exhibit relatively low cost. A leak detection program was developed based on the sensors measurements. The program creates sub-networks called District Metered Areas (DMAs), where pressure sensors must be placed to provide real time data to a Supervisory Control And Data Acquisition (SCADA) system. Simulations have shown that the data from the sensors can indicate the leakage location. Pressure sensors can be an alternative solution for long-range monitoring of water tanks, since they are easily to install and can be of low cost. However, the frequent calibration required, makes their use difficult, especially in water tanks that are located in distant areas within a city network.

2.1.4 Wireless Sensor Systems

Extensive work has also been recorded in the area of wireless monitoring systems, since they are ideal for the collection of measurements by multiple sensors installed across multiple points. Such a measuring system for resistive and capacitive sensors is presented in [39]. Environmental monitoring is essential and several sensors provide data that are required for proper protection of several locations. In [39], the data-collection system collects data from capacitive and resistive sensors. The capacitive sensor integrates a capacitance-to-voltage conversion stage with the use of a phase-locked loop (Figure 2.6). A capacitive pressure sensor was employed for providing measurements in the range of 0-17 kPa. The capacitive pressure sensor was used to measure the pressure into a tube of water and was connected to a wireless communication module. A resistor-type temperature sensor was also used for transmitting the temperature from inside the tube. The Microchip PIC18Fx2 processor was used in the sensor circuit for data collection, together with the PIC18LF452, which was selected as a base station. Both sensors were properly calibrated to give the optimal results. Water level sensing has been reported in agriculture applications in [40]. A WSN was created for monitoring data from a tea plant facility. Water level and temperature measurements are essential for the tea plant to grow efficiently. In these applications, the water level is measured in the vessels that store the water supplied to the tea plants. 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. The data produced by the sensors were processed with the LABVIEW software platform.

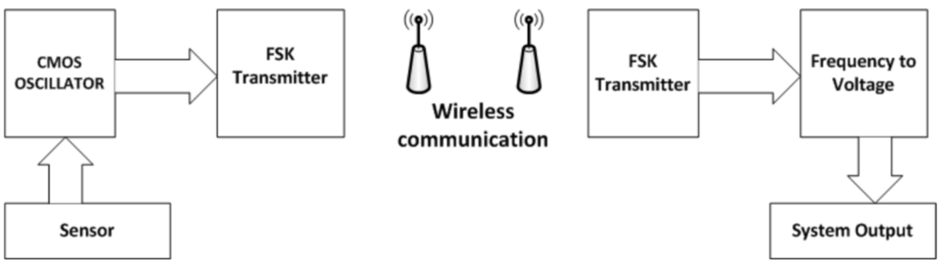


Figure 2.6: Capacitance-to-voltage conversion with the use of a phase-locked loop [39].

The water level measurement system has been designed to be part of a WSN and the nodes of this network are installed in geographically remote areas that are not necessarily supported with a stable power supply. Thus, their energy supply using renewable energy sources and a smart DC-DC power converter is essential for interfacing the generated energy to a battery bank and the electric load of the wireless transceiver of each node [41]. These specifications create the need to employ low-power electronic circuits. The developed sensors must be easy to build, easy to transfer and based on durable materials. Also, the electronic components must be able to operate with low power resources. Based on the aforementioned state of the art analysis, it is concluded that such a water level measurement system was not available in the market or proposed by previous research. During the development process, several materials were tested for constructing the sensor probes, in order to achieve the ideal combination of stability, cost, as well as easy-to-transfer and easy-to-produce capabilities.

Chapter 3

Sensor Design

In this chapter, the operating principles of the two types of water-level sensors that were developed within the framework of this thesis are presented. The software for acquiring the sensor measurements is also described, together with the circuit design of the sensor boards. Additionally, the connection of the sensor boards with the data-acquisition board is analyzed. Finally, an auto-calibration method for the developed water-level sensors, is presented.

3.1 The Proposed Capacitive Water Level Sensor

Based on the available state of the art information, the development of capacitive sensor probes was initially performed. 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 of the capacitive water-level sensing structure which was initially proposed in [2], is presented in this thesis. To achieve the goal of developing a sensor with low cost materials, several experimental set ups were tested. In the initial experiment, the use of parallel multilayer probes was tested (Figure 3.1).

These multilayer tubes provide the advantage that the inner aluminium layer does not come in contact with the drinking water of the storage tanks. Furthermore, the outer layer of the tubes is certified for installation into drinking water. The parallel probes form several individual capacitors because the water flows between the probes and acts as conductive liquid, between cylindrical capacitors. The capacitance of these capacitors is given by the following equation:

$$C_x = \frac{2\pi * \epsilon_0 * \epsilon_r}{ln\frac{d_2}{d_1}} * h \tag{3.1}$$

The experimental setups were tested for different distances between the probes. For water level measurements with a maximum level of 20 cm and the sensor probes having a distance of 5 cm between them, the Root Mean Square (RMS) error was 3.45 % and the Mean Average Error (MAE) = 3.24 %. The measurements resulting for distances of 2 cm and 0 cm, respectively, had even higher errors, i.e. RMS error = 4.25 % , MAE = 4.1 % and RMS error = 4.54 % , MAE = 4.27 %, respectively.

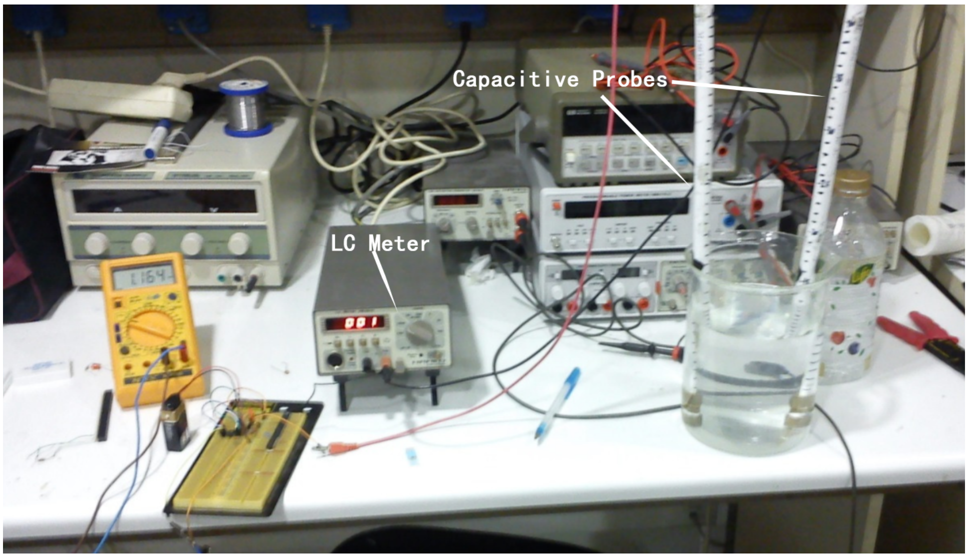


Figure 3.1: The initial experimental set up with two parallel probes.

This solution provided fairly good results especially for small-range water level measurements. The drawback of this configuration was the noise coupling at the sensor probes, due to the formation of parasitic capacitances with nearby objects. Also, with two parallel probes, the installation of the sensors in the water tanks would have been even more complicated. This approach was abandoned since the use of coaxial configuration of the sensor has lower noise interference due to parasitic capacitance between the sensor probes and nearby objects. 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 metallic layer between them (Figure 3.2).

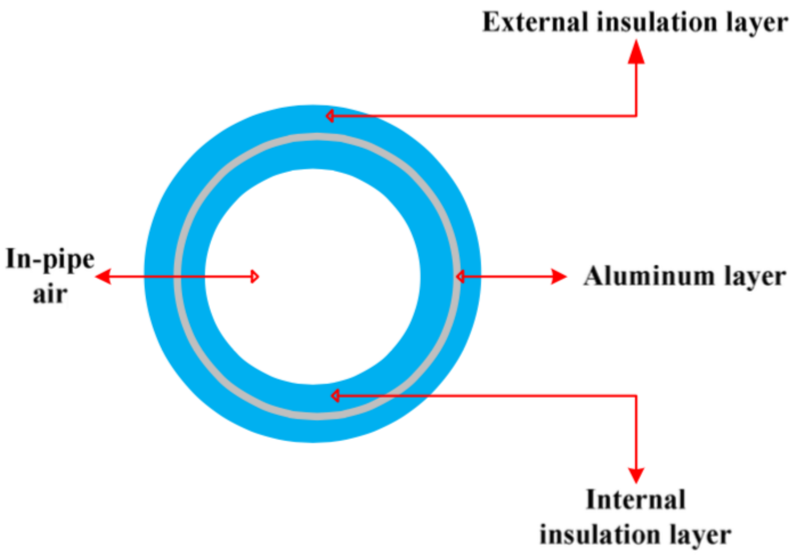


Figure 3.2: A cross-section of the multilayer tubes employed for constructing the probes of the proposed capacitive water-level sensor.

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 (Figure 3.3). The metal layers contained in the two multilayer tubes comprise the two electrodes of the sensor. This set up of the two tubes is placed vertically into the water of the tank whose level is measured. The cylindrical configuration of the proposed probe offers the required stability and protects the sensors from the coupling of parasitic capacitance noise [2, 9, 10]. The total length of the sensor is selected so that it is equal to the maximum depth of the water which is desirable to be measured. Since the multilayer tubes are light and bendable, they are easy to transfer and easy to install inside the tank. Especially in long range sensors the problem of transferring and installing the equipment in very important and difficult to deal with. As an example, the water storage tanks in Chania municipality reach a depth of seven meters and the sensor must be of that height to monitor water level changes. Since the multilayer tubes are produced in any desirable length, the proposed sensor can be regarded as widely scalable.

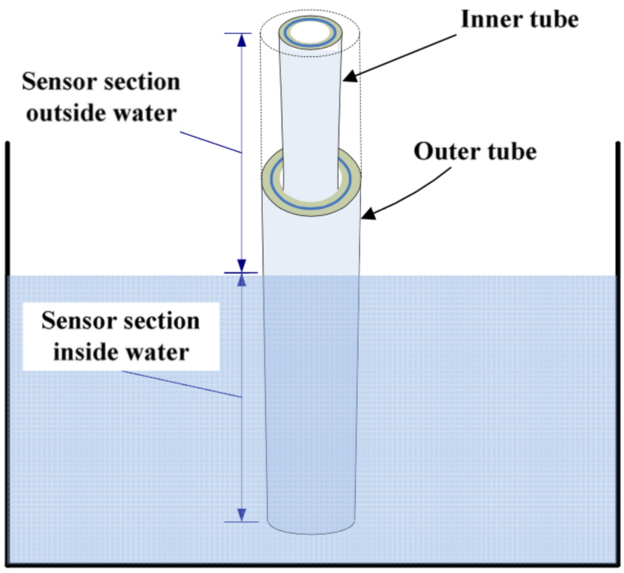


Figure 3.3: The structure of the proposed sensor probes.

The proposed capacitive sensor is composed of several parts of different capacitors formed. The first part comprises underwater capacitors and the second part is the tube above the level of water. The dielectric of these parts varies, since in above water operation the ambient air acts as a dielectric. On the other hand, in underwater operation, water connects the tube layers creating the capacitor. During the 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 sealing component and/or insulating material for sealing is attached, such that the metal layer of each multilayer tube does not come in contact with the water of the tank in order to avoid their electrochemical corrosion.

As analysed in [9], 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 measurement 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, additionally with a simple construction process for the proposed sensor. As a result, the water level measurement sensor described above exhibits a much lower construction cost compared to the existing water level measurement sensors.

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 Figure 3.4. 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 Figure 3.4 predominates the total sensor capacitance. As the water level rises, the values of C_2 , C_3, C_4 are increased accordingly, while

C_1 is reduced. The total capacitance of the proposed sensor is given by:

$$C = C_1 + C_2 + \frac{C_3 * C_4}{C_3 + C_4} \tag{3.2}$$

The lengths of these sections change 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 aluminium electrodes with the two intermediate polyethylene layers acting as a dielectric (i.e. C_1 in Figure 3.4). 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 Figure 3.4), another capacitor is formed between the water entering the inner tube and the aluminium layer of that tube with the polyethylene layer of the tube acting as a dielectric and, finally, a third capacitor is formed between the aluminium layer of the outer tube and the water at its outside surface (i.e. C_3 and C_4 in Figure 3.4).

3.1.1 Signal-conditioning Circuit Design for the Capacitive Sensor

Capacitance measurement is considered as a very challenging task because the result must have minimum errors, thus achieving a high accuracy. This occurs since capacitance from the sensor probes can be affected with various factors causing measurement errors, such as parasitic capacitances or cable losses. This is the reason that the circuits must be placed either in the closest possible distance, or either with the use of coaxial cable for protection [9]. The overall system that was developed for the proposed sensor converts that measurement data to a data type that transfers them safely. The I^2C protocol that was used in the proposed implementation guaranties a stable operation. The I^2C chips have significantly lower cost and lower power consumption than other widely used communication protocols (e.g. 4-20 mA).

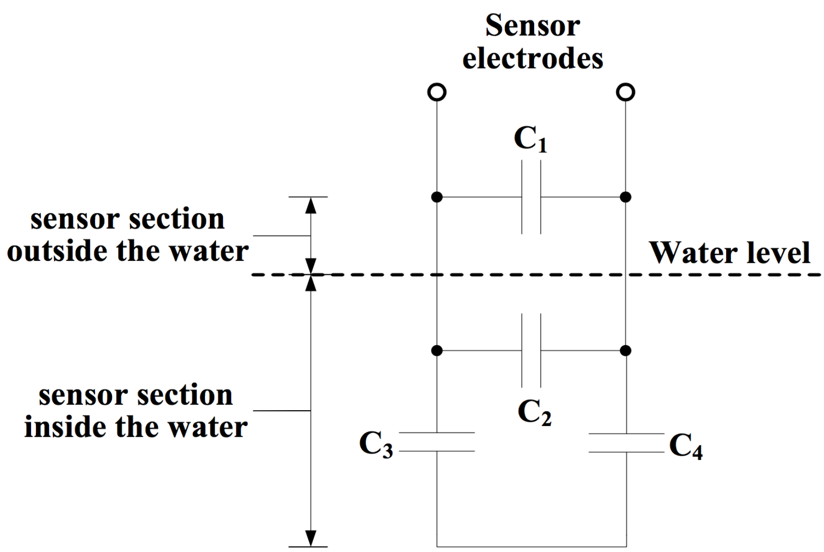


Figure 3.4: The equivalent circuit of the proposed sensor for excitation frequencies in the range of tens of kHz.

The I^2C protocol has been used for implementing safe data transfers since the late 80'As (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 [42]. The I^2C protocol uses only two bidirectional open-drain lines, Serial Data Line (SDA) and Serial Clock Line (SCL), pulled up with resistors, external or embedded in the chip. Typical voltages used for operation are +5 V or +3.3 V although operation with other voltage range is permitted. It was first designed by Philips Semiconductor, known today as NXP Semiconductors at 1982. The implementation of communication between the system and sensor board makes the system easier to monitor and easier to repair. If the capacitance measurements were transferred in the form of a voltage or capacitance signal, measurement variations could occur that would be unable to detect them. These variations create high measurement errors [9]. When a problem occurs, the data signals of the I^2C protocol sent an immediate signal to the monitoring (i.e.

data-acquisition) system. This information can be immediately obtained by the operator of the system, who can act to address these problems.

3.1.2 Implementation of Capacitive Measurement Circuit

In order to measure the capacitance of the sensor with high accuracy, a signal-conditioning circuit comprised of operational amplifiers was designed. A block diagram of this circuit is shown in (Figure 3.5). 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 analyzed in [9]. Figure 3.6(a) shows an equivalent circuit of a capacitive water-level sensor [9].

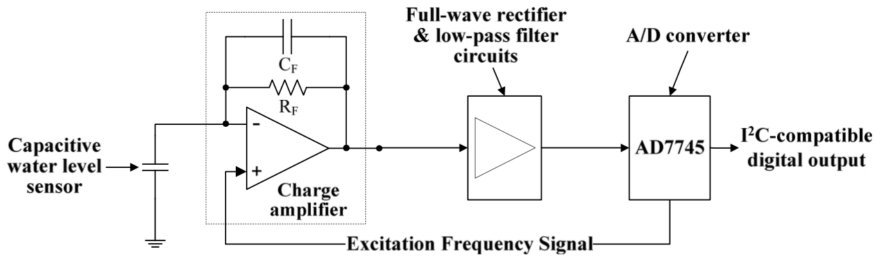


Figure 3.5: Block diagram of the capacitive sensor signal-conditioning circuit.

The capacitive C_x sensor is ideal when its design can be affected by the least possible parameters. R_w and R_w are the resistance and capacitance of the liquid , respectively, and L_s is the inductance of the current loop along the sensor. As it is reported in [43], when the frequency of the excitation signal of the sensor is higher than 20 kHz, the effects of the polarization impedance for liquids can be neglected. When the liquid is conductive and the frequency of the excitation signal is not higher than hundreds of kHz, the effects of R_w predominate over those of C_w , and the effects of L_s can be neglected. This simplifies the circuit model to that shown in Figure 3.6(b), where operation is closer to the ideal performance since it is only affected from the effects of R_w . For this reason, the proposed sensor excitation circuit will operate at this particular frequency. On the other hand, at high frequencies (i.e. above 120 kHz), the effects of C_w predominate over those of R_w (Figure 3.6(c)).

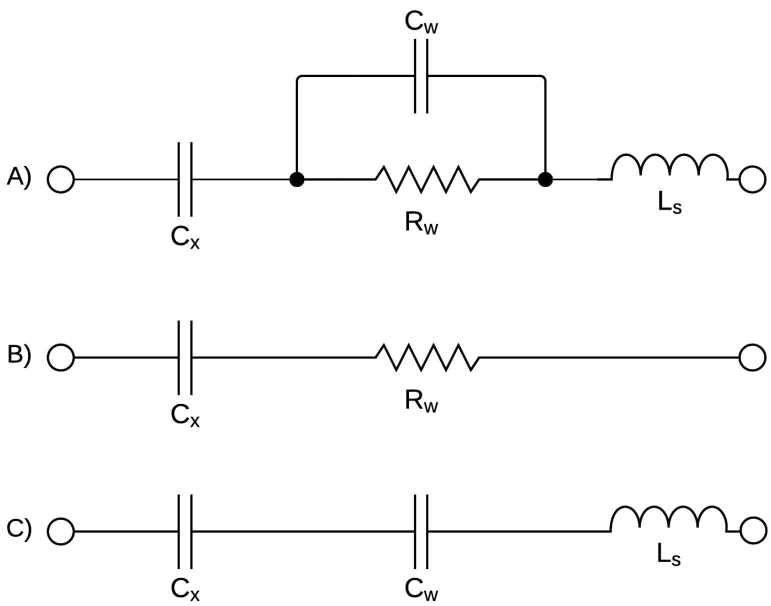


Figure 3.6: (a) Equivalent circuit of a capacitive liquid-level sensor. (b) Simplified low-frequency circuit. (c) Simplified high-frequency circuit.

In the designed circuit for the capacitive sensor, a square-wave is produced by the charge-amplifier (Figure 3.7) with an 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 (Figure 3.8) and a low-pass filter (Figure 3.9). The DC level is extracted unfiltered from the full-wave rectifier and contains the carrier-frequency-ripple. As a result a low-pass filter can remove the ripple. This results in a DC voltage that is a function of the charge-amplifier, closed-loop gain and not affected by external parameters.

A block diagram of the overall signal-conditioning circuit is demonstrated in Figure 3.10.

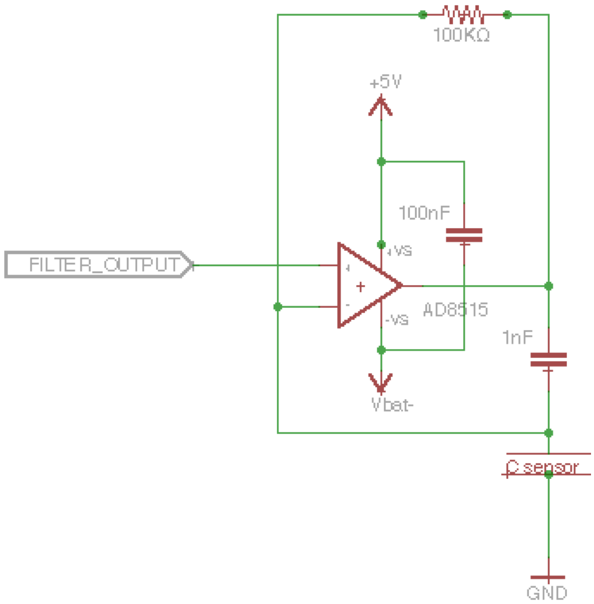


Figure 3.7: Charge amplifier circuit.

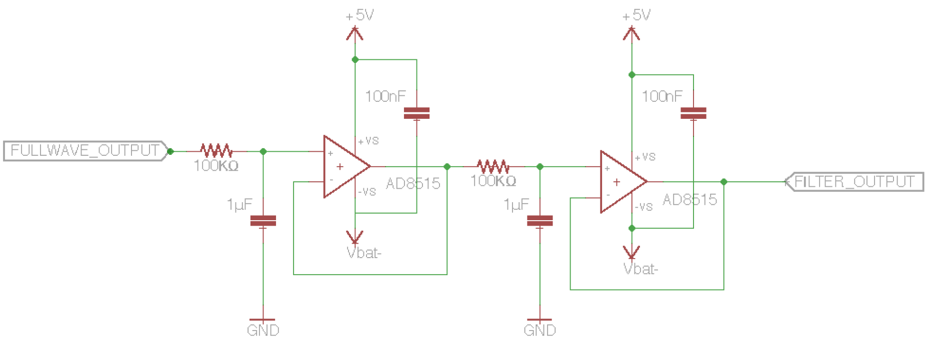


Figure 3.8: Full-wave rectifier circuit.

With this structure the capacitance of the probes is converted with excellent accuracy to a data signal. The components work together to create a linear measurement system that is not affected from environmental conditions. All of these circuits are active, constructed using operational amplifiers (op-amps), such that the linearity of the measurements is not degraded. They are designed 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

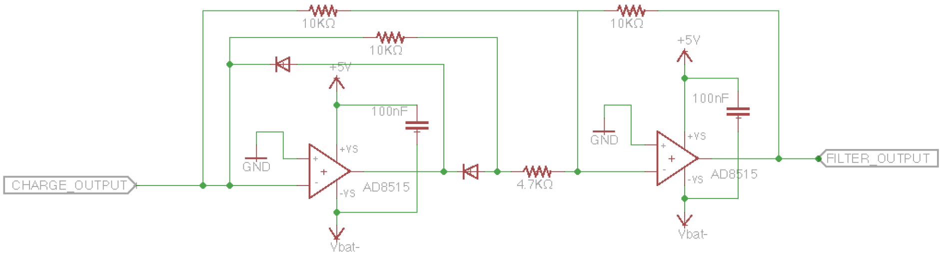


Figure 3.9: Low pass filter circuit.

and uses its voltage input 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). A flowchart of the software program executed by the data-acquisition device (i.e. the Alix 3d2 system board in this study) is shown in Figure 3.11. In contrast to other solutions for obtaining capacitance measurements, such as the frequency-shifting technique based on oscillator circuits, this signal-conditioning configuration provides the most accurate measurements for the overall system. The charge amplifier operation was tested within the laboratory for the affection of salinity. From these experiments, it was proven that the results of the capacitance measurements are not affected from the additional salinity in the water sample.

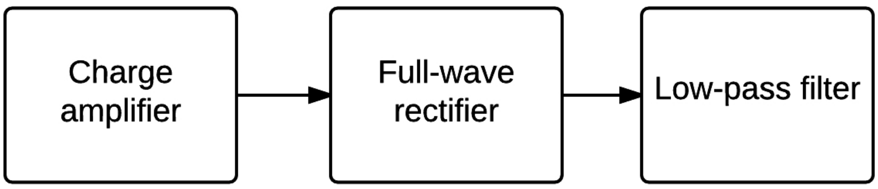


Figure 3.10: Flowchart of capacitance to voltage circuit.

Simulations were also performed with the National Instruments MultiSim software program. The waveforms of the excitation signal and the charge-amplifier output voltage for

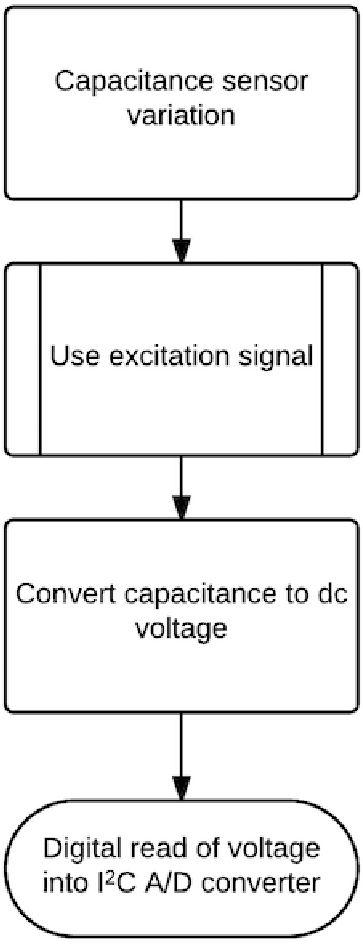
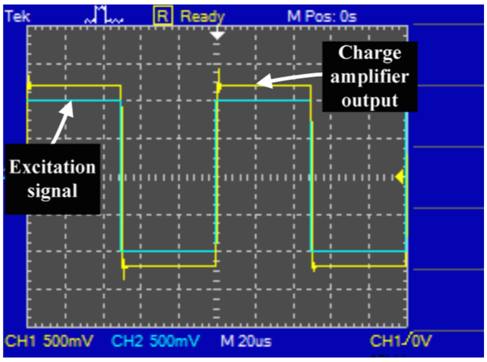
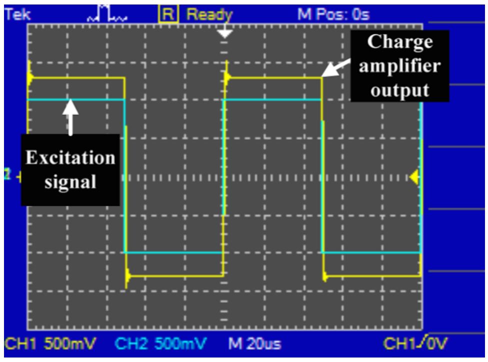


Figure 3.11: Flowchart of the overall signal conversion.

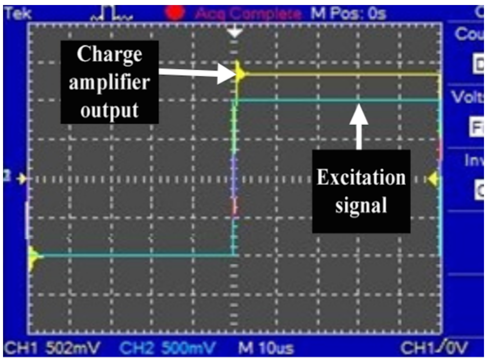
various values of the water level sensor capacitance, C_s, are illustrated in Figure 3.12. The capacitance values considered in these simulation results have been extrapolated by an experimental prototype water level sensor with a length of 6 m, which has been built according to the technique described above. As it is observed, since the amplitude of the excitation signal is kept constant and increasing the capacitance of the water level sensor results in an increase of the charge-amplifier output voltage amplitude and the circuit output also exhibits a linear increase. The implementation with the charge-amplifier provides another very important aspect to the sensor measurement system.



(a)



(b)

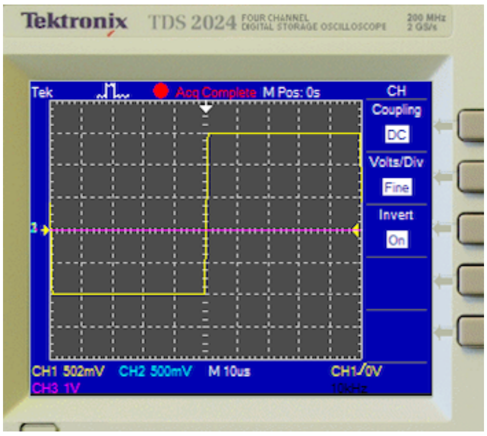


(c)

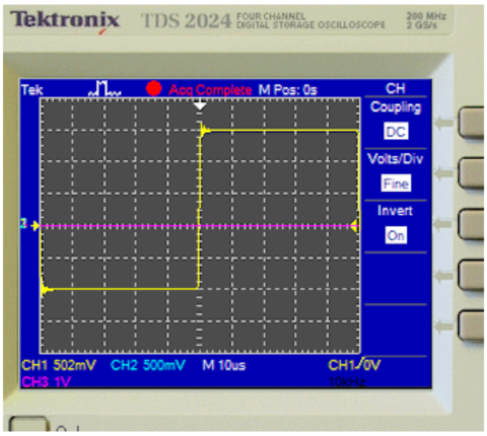
Figure 3.12: The waveforms of the excitation signal and the charge-amplifier output voltage for various values of the water level sensor capacitance: (a) C_s =1200pF, (b) C_s =1900pF and (c)C_s=2100pF .

The pulse amplitude is not affected by the changes of the water resistance. Thus, the pulse amplitude changes are only due to capacitance variation (Figure 3.13). Also, according to the data presented in [7, 44], the drinking water resistance is not higher than the values considered in the aforementioned simulations. Thus, it is safe to suggest that there were no significant deviations observed due to variation of water quality (i.e. resistivity) and the proposed sensor is appropriate for various water qualities.

The water level for the sensor L(m), is calculated using the measurements of the low-pass



(a)



(b)

Figure 3.13: The waveforms of the excitation signal and the charge-amplifier output voltage for various values of the water level sensor capacitance with 100 Ohm resistance and on right image with no resistance.

filter output voltage, V_f (V) and AD7745 internal temperature, T_a (^oC), according to the following equation:

$$L = a_1 * V_f + (T_a - T_{ref}) * a_2 + a_3 \tag{3.3}$$

where a_1 , a_2 and a_3 are calibration constants and T_{ref} is the reference temperature. The values of a_1 , a_2 and a_3 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^2C-compatible devices over the I^2C bus.

The board was designed and developed in the laboratory using Eagle CADsoft (Figure 3.14). The routing of the circuits was design to be implemented in a two layer design.

The proposed water-level sensor and signal-conditioning circuits have been designed to

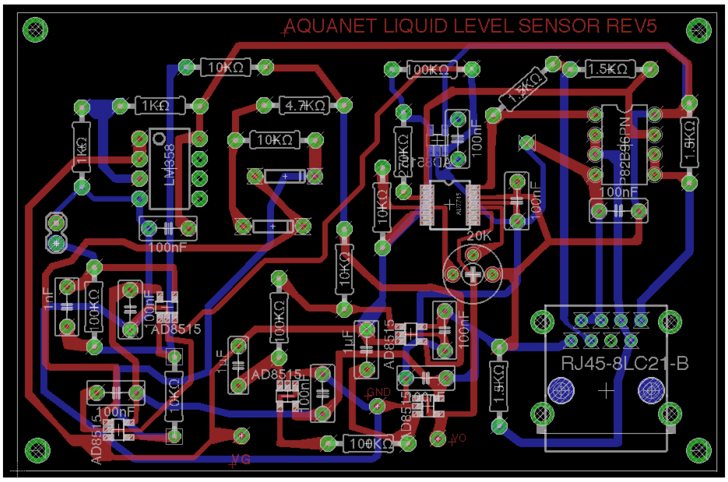


Figure 3.14: The board design of capacitance circuit with the use of Eagle CADsoft

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 were obtained from the local market. Therefore, when ordered in large quantities the prices can be significantly lower. For a measuring range of 0-4 m, the total construction cost is approximately 15.36 € and increases by about 2.5 € per additional meter of sensor length. The total cost of the electronic devices re-quired 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 does not differ significantly.

3.2 Proposed TDR-based Water Level Sensor

Time domain reflectometry is an excellent alternative for accurate water level measurements [21]. To implement a stable system, the combination of proper materials and unerring elec-tronics is crucial. As stated above, for 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, a harsh environment under a high level of air humidity, which affects the long-term integrity of metallic materials. In order to ensure a reliable operation, the materials used for the construc-tion of the sensor must be also appropriate for long-term use in water, with the lowest possible corrosion risk. In addition to that, 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. Therefore, the electronic circuit must be of low power consumption. 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 for 5-30 m) from the data acquisition and wireless transmission units of the WSN node. The materials that were used in the prototype of the TDR-based sensor probes, were the multilayer tubes and 304L stainless steel rods. The stainless steel is used as the inner layer of the sensor and the multilayer tube is the outer layer of the sensor. The multilayer tube (Figure 3.15) with the aluminium layer and the outer layer of polyethylene never come in contact with water.

To implement a stable system the combination of proper materials and unerring electronics is crucial. As stated above for 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, a harsh environment 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 to that, 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. Therefore the electronic circuit must be of low power consumption. 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 for 5-30 m) from the data acquisition and wireless transmission units of the WSN node. The materials that were used in the prototype of the TDR-based sensor probes, were the multilayer tubes and 304L stainless steel rods.The stainless steel is used as the inner layer of the sensor and the multilayer tube is the outer layer of the sensor. The multilayer tube (Figure 3.15) with the aluminium layer and the outer layer of polyethylene never came in contact with water.

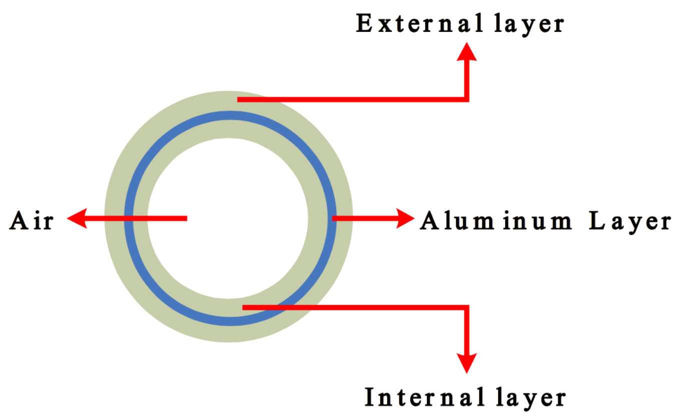


Figure 3.15: A cross section of a multilayer tube used for implementing the TDR-based sensor probes.

In order to create the TDR-based water level sensor the stainless steel tube is installed coaxially inside the multilayer tube, thus forming a transmission line immersed into the water of the storage tank. The stainless steel tube is of 304 L type, which follows the standards of American Iron and Steel Institute (AISI) and it is certified for drinking water use [45]. The stainless steel tube and the aluminium layer of the multilayer tube form the electrodes of the proposed TDR sensor (Figure 3.16).

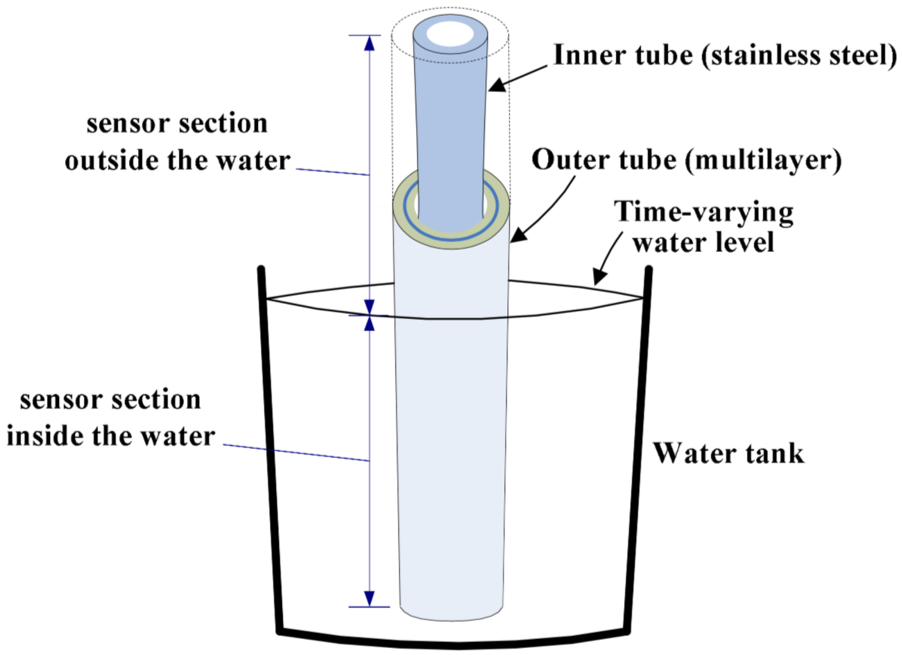


Figure 3.16: The structure of the proposed TDR-based water level sensor.

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 possible corrosion. The water around the sensor probes comes 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 [9], 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 TDR-based 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.

3.2.1 Signal-conditioning Circuit Design for the TDR-based Water Level Sensor

In order to operate the proposed sensor according to the Time Domain Reflectometry principle, an appropriate signal conditioning circuit has been designed. In the designed signal-conditioning circuit for the TDR-based sensor, a square-wave is produced by a timer circuit with a programmable amplitude, which is connected with the TDR probes and is reflected at the end of the TDR probe. The received high-frequency square-wave is then converted to a DC signal, through a full-wave rectifier and a low-pass filter (Figure 3.17).

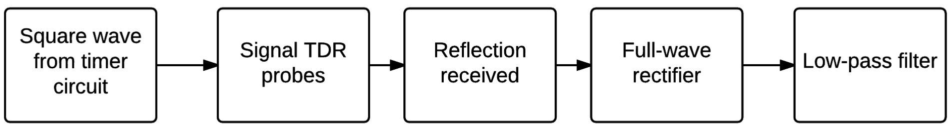


Figure 3.17: A flowchart of the signal conditioning process, which was applied for operating the proposed water level sensor according to the TDR principle and interfacing the water level measurements to an Alix 3d2 board.

A more detailed block diagram of this circuit is illustrated in Figure 3.18. The TDR-based sensor probe, is connected to one port of a T-BNC connector. Then, the circuits that were designed 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. With this advanced 555 timer chip, the generated pulse is stable and can be of various frequencies depending on the desired application. Additionally, the timer is far more linear and with lower power consumption than the original NE555 timer. Its output signal is set to the correct amplitude with the use of an LM358 dual operation amplifier (Figure 3.19).

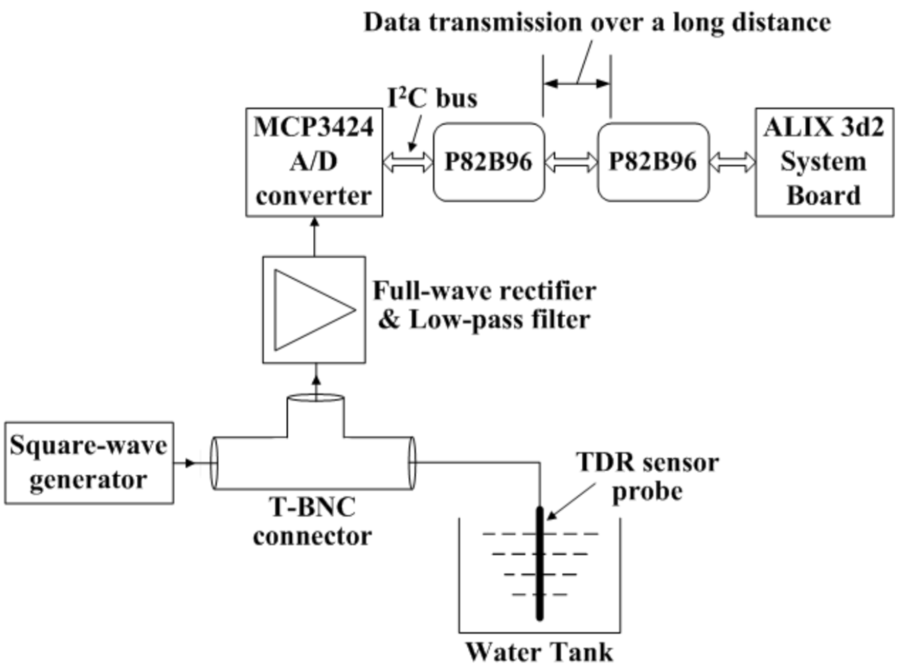


Figure 3.18: A block diagram of the TDR-based sensor signal-conditioning circuit.

3.2.2 Implementation of TDR-based Measurement Circuit

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 parallel inverters (Figure 3.20). The circuits for this timer are of low cost and low power

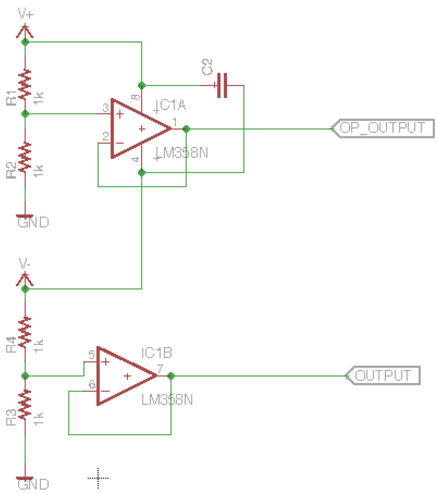


Figure 3.19: Pulse set circuit.

consumption and provide an excellent alternative to the usage of an external signal generator. 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.

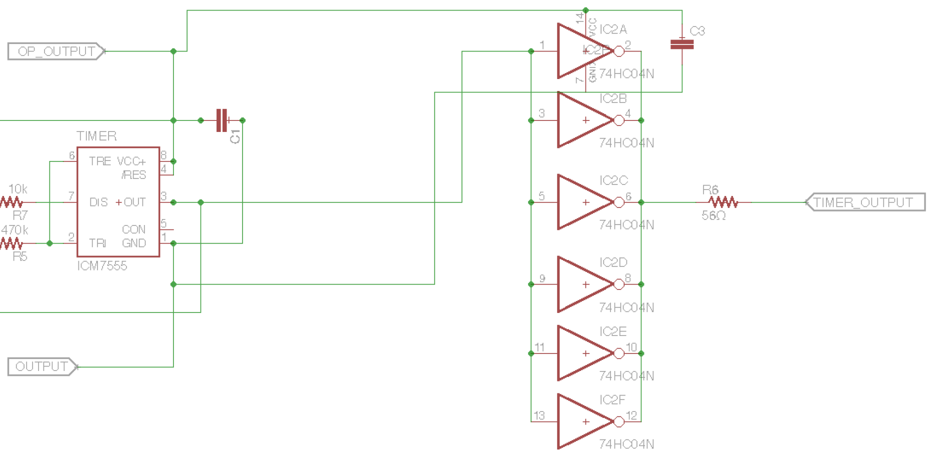
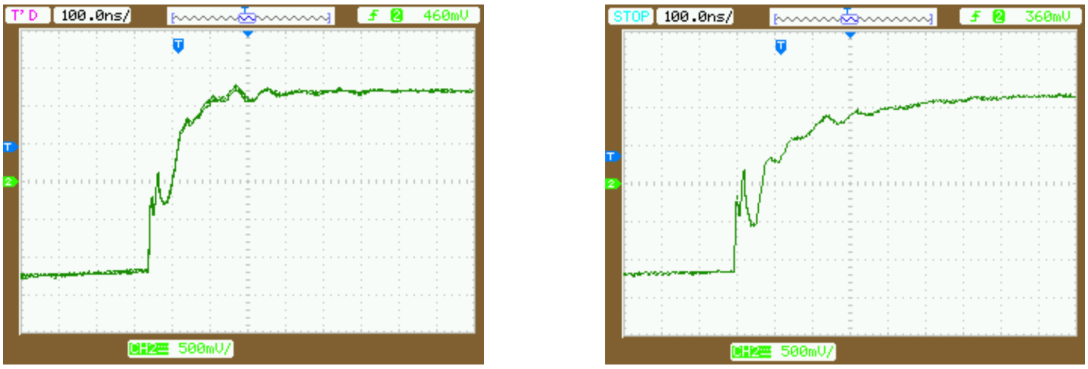


Figure 3.20: Timer circuit.

The transmission line formed by the probe of the proposed sensor, behaves as a distributed circuit at the high 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 with the probe of the proposed sensor, a part of this pulse is reflected, resulting in a distortion of the signal received at the measuring port of the T-BNC connector. The degree 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 Figure 3.21.



(a) (b)

Figure 3.21: 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.

The TDR-based measurement system performance was tested over a frequency range of 20 kHz to 1 MHz. Measurements distributed in low frequency range (20 kHz - 140 kHz) provided a very low voltage output on water level sensing (for example the overall voltage drops by only 5 mV for an 1 meter level variation under a frequency of 40 kHz). For frequencies over 700 kHz the pulse is transferred through the sensor probes faster than the system can detect its reflection. Therefore, the TDR-based system must be operated between 200 kHz - 400 kHz to provide ideal results. A TDR-based system measures reflections along an electrical transmission line. In order to measure those reflections, the TDR unit will transmit an incident signal onto the tested conductor and receive the reflection of the system. If the conductor has uniform impedance and it properly operates, then there will be no reflections and the incident signal will be absorbed at the far-end by the termination load. However, if there are impedance variations, some of the incident signal will be reflected back to the source. Therefore, a TDR sensor operates similar to the radar principle.

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 was designed to rectify the bipolar square-wave received from the corresponding port of the T-BNC connector. Then, a low pass filter is used for filtering the DC output voltage, which is proportional to the water level. The MCP3424 (Figure 3.22) Analogue 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 are implemented using the low noise, low power and high precision AD8515 operational amplifier ICs.

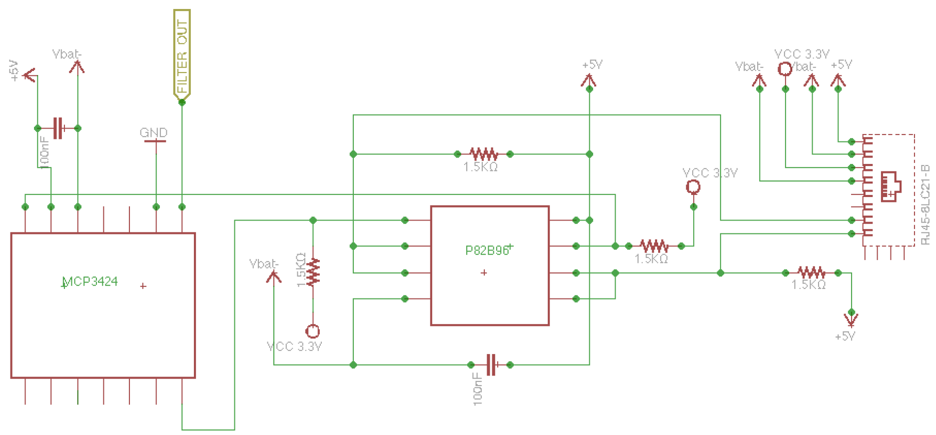


Figure 3.22: MCP3424 read the output voltage.

The MCP3424 ADC provides an 18-bit digital output, with I^2C protocol implementation, which is compatible with the I^2C serial communication that is needed to be set to connection with the data-acquisition system board. 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. Techniques such as the wireless transmission or the employment of industrial communication interfaces, such as the 4-20 mA 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 the design complexity of the overall data acquisition system are increased. The Alix 3d2 system board is used as a data acquisition unit in the target application under study and comprises an I^2C port, which is available for data transmission/reception purposes. 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 by using the Python programming language, is presented in (Figure 3.23). 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, F (Volts) according to the following equation:

$$L = C_1 * F + C_2 \tag{3.4}$$

C_1 and C_2 are the calibration constants of the system. 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

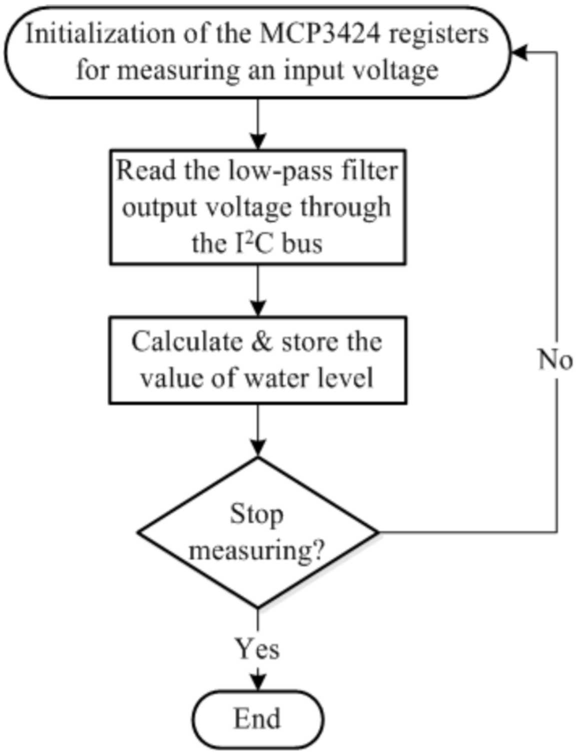
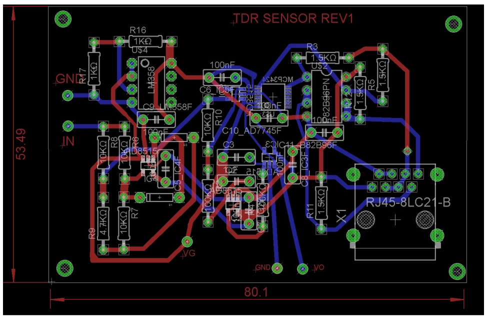
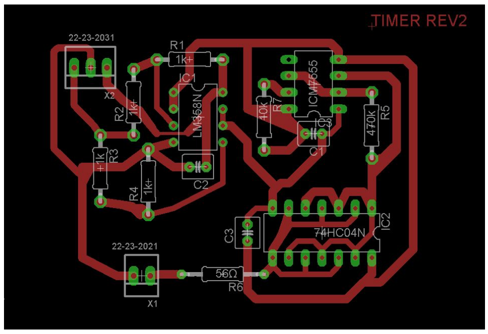


Figure 3.23: A flowchart of the algorithm for the TDR-based sensor.

MCP3424 chip devotes for connecting with other I^2C compatible devices over the I^2C bus. The bus can handle several sensors if the chips operate in a different address. For example, an external humidity sensor can also be connected to the measurement system, providing additional data. A benefit of using the MCP3424 ADC is that it includes dedicated address pins on its package, for providing different I^2C addresses, making address flexible. Thus, more than one water level sensors can be connected with the same terminal data-acquisition unit through the same I^2C bus if it is required by the target application (e.g. in case that the water storage tank under monitoring comprises multiple, isolated water storage segments). In the target water level measurements application of this study, the signal-conditioning circuits are power-supplied by the Alix 3d2 system board, which is powered from an external power source. This source can be either a renewable energy source, such as photovoltaics, or a standard DC power supply. For establishing a safe communication between the two ends of the communication link, a standard Unshielded Twisted Pair (UTP) cable is used. In order to extend the communication distance supported by the I^2C protocol beyond the 5 m limit, the P82B96 I^2C bus 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 easily enables to adapt to the typical installation requirements of environmental water level monitoring applications. The signal-conditioning and communication distance extension circuits were designed using Eagle CADsoft (Figure 3.24 and Figure 3.25).



(a) TDR-based sensor circuit board



(b) Timer circuit board

Figure 3.24: The circuit boards of the TDR-based sensor: (a) signal-conditioning circuits and (b) timer circuit.

Using construction materials from the local market, the total manufacturing cost of the TDR-based experimental prototype sensor, which has been developed, is 20.36 €, whereas the cost of the signal-conditioning circuits is 11 €. Similar with the capacitive sensor, these costs have the potential to drop substantially in case that large quantities of the required materials and devices are purchased within the framework of an industrial implementation. The total cost of the proposed water level data-acquisition system (i.e. sensor and signal-conditioning circuit) is much lower than that of commercially-available ultrasound water-level sensors

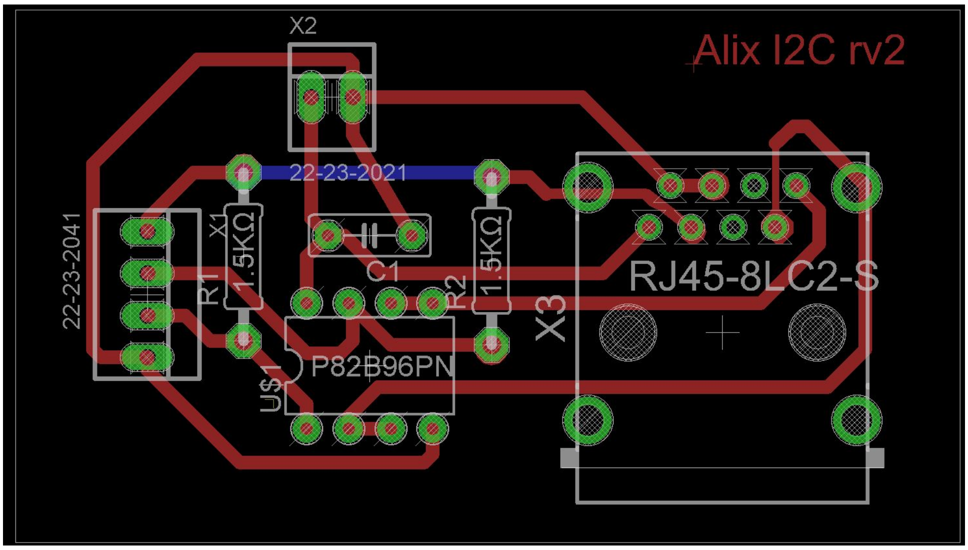


Figure 3.25: The extender circuit board design on Eagle CADsoft.

(typically higher than 300 €). Simultaneously, as will be demonstrated by the experimental results, the proposed sensing system achieves an equivalent performance with an industrial ultrasound sensor.

3.3 Self Calibration of Proposed Water Level Sensor

A significant problem in the installation process of every water-level sensor is the calibration that is required to be done in each tank that the sensor is installed in. Calibration of any sensor is a considerable problem in many sensor monitoring applications. In [46], the problem consists of orienting a network of sensor nodes deployed in a scene at unknown locations and unknown orientation angles. This self-calibration problem was solved by placing a number of source signals with known locations. Then each of these sources sends a calibration signal and a subset of sensor nodes in the network measures the time of arrival and direction of arrival of the signal emitted from that source. An application of self-calibration in water level sensors is presented in [7] , where the sensors are calibrated by using predefined points, where the water level is known. Self-calibration algorithms are also used in [47, 48, 49] to convert the output voltage of sensor systems that have linear relationships with the liquid level. Therefore, the liquid level could be calculated by developing a linear approximation. Several parameters such as piecewise linearisation can be adopted to improve accuracy. For instance, in [48] the authors suggest that a number of fixed points can form an optimal data set for linearisation and self-calibration of a water level sensor. They select a random set of nine points ranging from 51 cm to 59 cm as basic points on the sensor to develop a linear equation. The experimental values of measured liquid level and non-linearity error demonstrated that this method is an effective approach in linear sensors.

Since the sensors developed within the framework of this thesis will be installed in different water level tanks, where factors such as temperature, water salinity, humidity and water depth vary a proper calibration process must be followed for every sensor after the installation. During the various installations in Chania municipality area, the proposed sensors were calibrated manually, by using the pre-installed ultrasound sensors as a reference. In addition to the known properties (length, temperature), each sensor was monitored to verify the correct measurement results. As a result, the sensors were tested in different water level depths, where the measurement system provided the corresponding results. The goal for the proposed system is that the end-user of the sensor array can easily use the auto-calibration software that was implemented. The flowchart in Figure 3.27, demonstrates how the self-calibration algorithm uses known points on the sensor and the software generate a proper calibration equation for the sensor. The algorithm uses the Numpy library of Python programming language to implement the necessary mathematical processes, which provides several mathematical functions similar to those of Matlab. It generates a line equation, which can be followed by the measurement system in order to get accurate results. The generated equation must be calculated from at least three predefined points on the sensor probes. If the points are not inserted correctly, for example the three points are not imported in increasing, or decreasing order of water level values, the self-calibration algorithm requires a new set of values. Following this pattern, the generated equation exploits the linear properties of the sensor. Figure 3.26 illustrates the results of water level sensing with the calibration equation created from multiple water level measurements (i.e. "Expected" in Figure 3.26) and the calibration equation derived by the self-calibration algorithm (i.e. "Values" in Figure 3.26). For linear sensors such as the capacitive and TDR-based sensors proposed in this thesis, this self-calibration algorithm can produce the necessary calibration equation with a measurement error of less than 1 %.

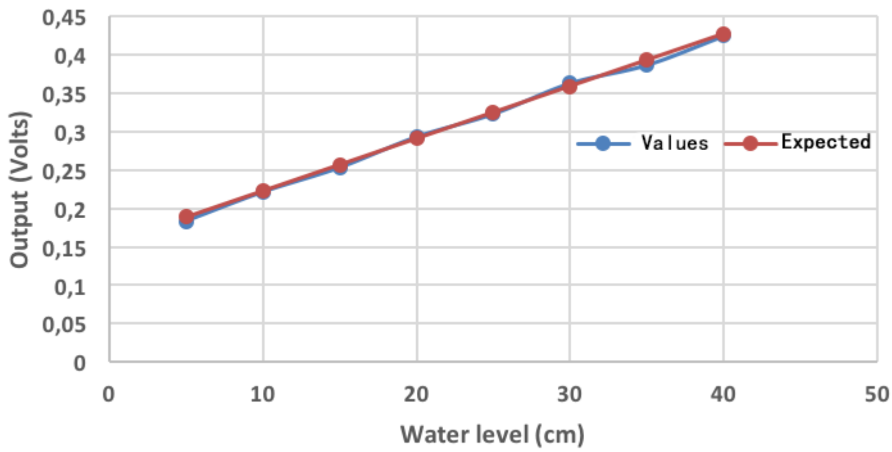


Figure 3.26: Results with self calibration algorithm.

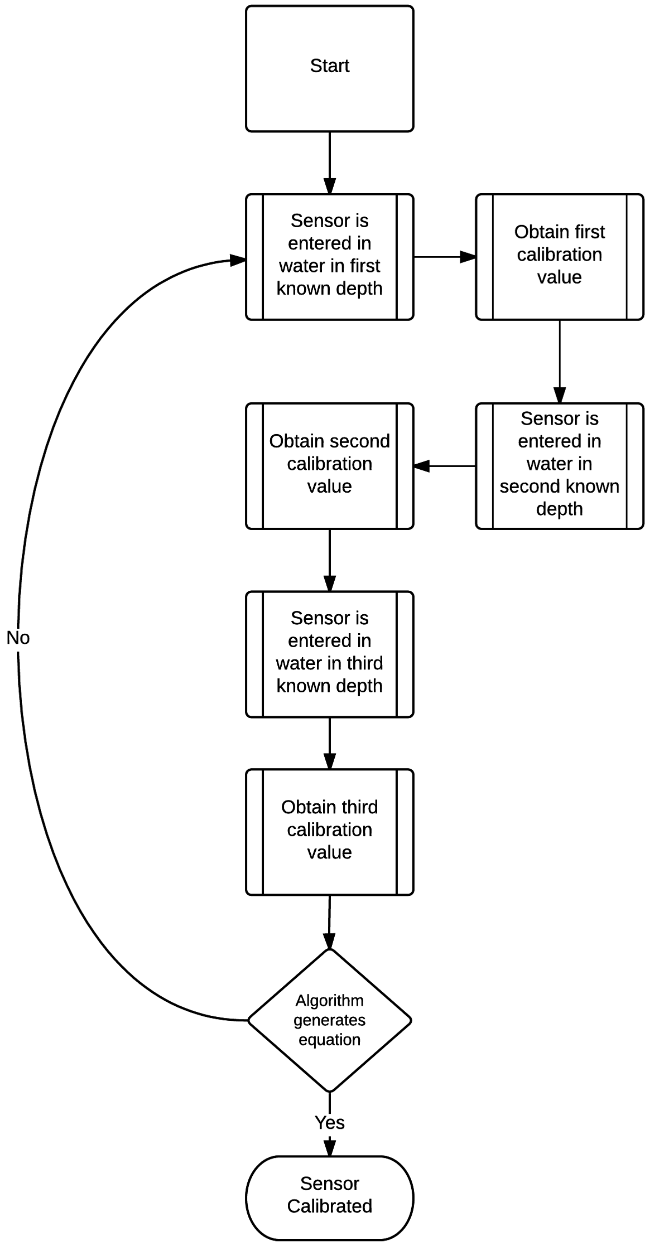


Figure 3.27: The flowchart of the self calibration algorithm.

Chapter 4

Prototype Implementation

In this chapter, the implementation of the signal-conditioning circuits boards and the packaging of the proposed sensors is described. In order to ensure proper system operation inside the water tanks, proper packaging of the circuits and the sensor is essential. Also, the various installations in the different water tanks required proper management in order to protect the sensor system from damage and ensure successful long term operation. The support structure of the sensor, together with the correct packaging of the circuits is vital for stable operation of both proposed systems. The proposed sensors were installed in multiple water tanks of the Municipal Enterprise for Water and Sewage of the city of Chania.

4.1 Capacitive Sensor

After a long testing period in the laboratory and in water tanks, the results of the capacitive sensor measurements against the operation of the pre-installed ultrasound system, proved that the proposed systems could be a great alternative for measuring water level in the water tanks. Nonetheless, to actually develop a proper sensor system, many properties of installation must be properly selected. An essential part for the proper installation of the sensor in the water tanks was the sensor base and ideal sensor placement location. Since the capacitive sensor could be affected from contact with any metallic object, that would create a parasitic capacitance, the sensor base was constructed using Teflon (Polytetrafluoroethylene-PTFE). Also, in every water tank that the system was installed, the PTFE base was placed in an area as far as possible from metallic platforms or guardrails (Figure 4.1). Additionally, the sensor coaxial configuration protects the sensor probes from external interferences.

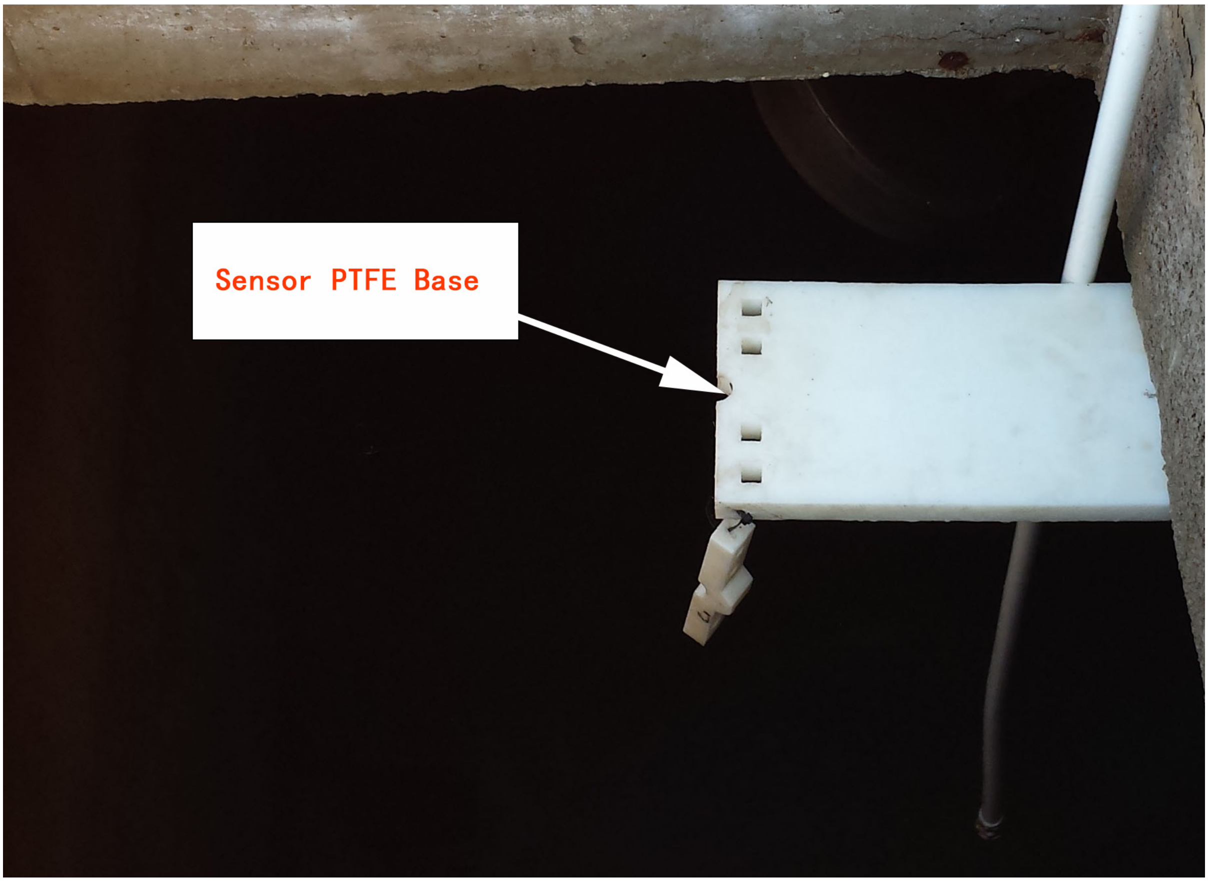


Figure 4.1: The installed PTFE base in the Mournies water tank of the Municipal Enterprise for Water and Sewage of the city of Chania.

The proposed sensor based on the flexible material that was developed, was prepared in an easy to transfer package (Figure 4.2). The folded multi-layer pipes, are also light and easy to be straighten at the installation site. The sensor probes were first transported to the installation site and then unfolded in the tank area to ensure that the sensor would not be damaged during the transferring procedure.

Figure 4.2: The sensor packaging before transfer to the desired installation location.

The capacitive sensor was straighten next to the water tank, since the height or these sensor varies and can extend to over six meters. After the sensor had been inserted into the water with the use of the special PTFE screws, its position was stabilized. Because of the PTFE material properties, the material expands due to the humidity and keeps the sensor even more stable, against the water flow in the tanks. Often in these water tanks several other sensors were pre-installed, thus it was vital to place the sensor in a location that would not affect other sensor measurements and vice versa (Figure 4.3). The sensor probes must be straightened properly to achieve the maximum linearity in water level measurements. The cables that are connected with the sensors inner and outer metallic layers plug with the circuit board using collars on these layers. The collars that were placed on the pipe to implement the connection were made of INOX in order to avoid corrosion due to humidity. This configuration was implemented since during early prototyping it was observed that the collars used to attach the cable that where made of galvanized metal were completely destroyed from corrosion within one month of operation in a water tank.

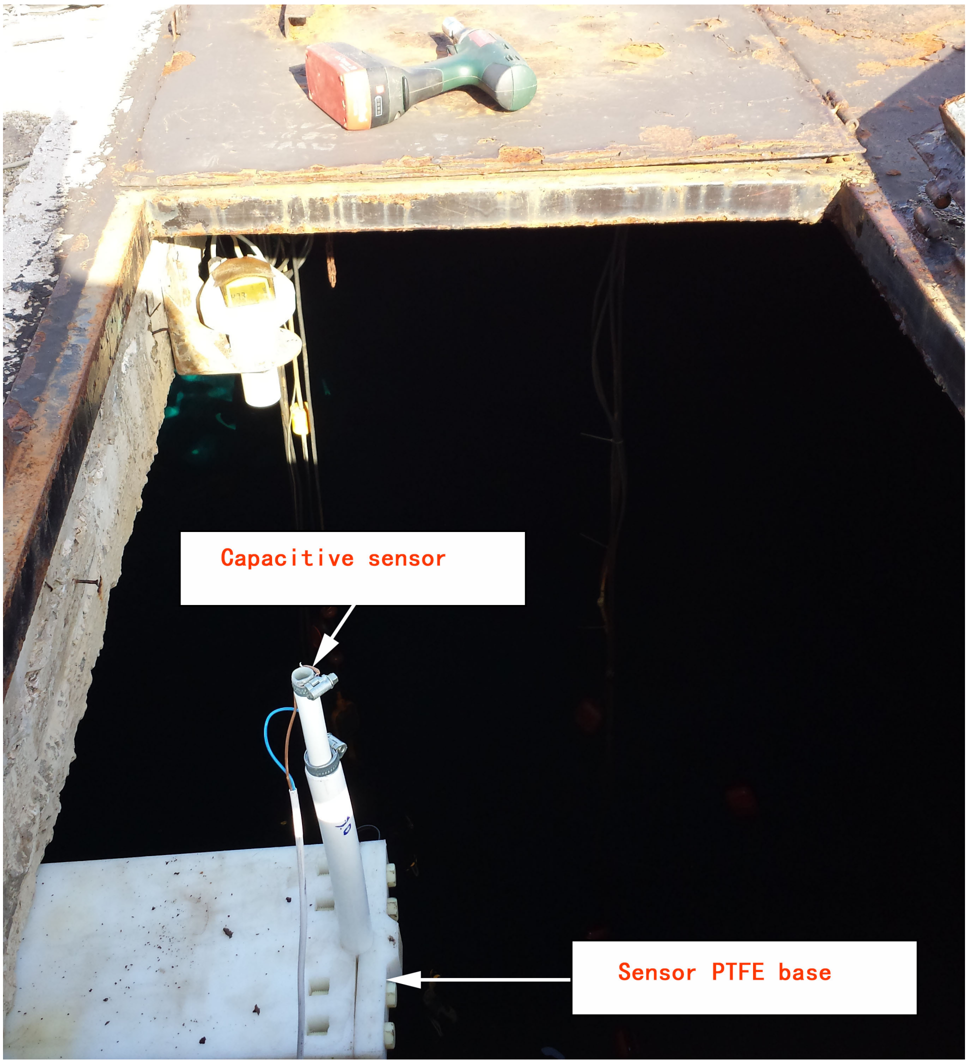


Figure 4.3: The capacitive sensor placed inside the water tank in Korakies.

The experimental prototype of the proposed water-level sensor for measuring a 2 m water level is shown in (Figure 4.4). 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). As mentioned in Chapter 3, 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 fulfils 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 easily folded, for transferring it to remote locations, where frequently the drinking water storage tanks of water distribution networks are installed. Additionally, this flexibility enables to easily eliminate the tubes bending, during installation of the proposed sensor, thus improving the linearity of its response.

The signal-conditioning circuits were also installed inside the tanks, placed in appropriate boxes (Figure 4.5). The used boxes, which are certified with the code IP 65, offer protection against dust ingress, as well as protected against high pressure water jets from any direction. IP is an international code that describes the endurance of protecting boxes [50]. These protective boxes are used in harsh outdoor environments, where the protection of IP 65 guaranties the operation of the enclosed electronic circuits [51, 52]. The outside parts, namely connector and sensor cables of the enclosure, should be IP 65 compliant to make the whole system IP 65 compliant. The right choice of protective material and electronics provides safe operation for the system in an environment where the operating temperature ranges from -40 to +85^oC.

The circuit board was installed next to the sensor to avoid any unwanted capacitance interference from the cable and also acquire ambient temperature measurements close to the sensor environment (Figure 4.6). The two outputs of the box are the cables that connect the sensor board with the sensor probes and the Ethernet cable that is used to transfer the signal of the sensor circuit to the Alix system board, through the extender circuit. The wires that were used for the connection between the sensor and the system board do not require the standard Ethernet configuration. However, the cables configuration follows the regular Ethernet configuration, in order to work with the standard commercial Ethernet cables. The type of cable (UTP or STP) also does not matter, however the Unshielded Twisted Pair (UTP) is much easier to be installed because it is flexible and bendable [53]. The Shielded Twisted Pair (STP) cable protects from interference caused by power lines, radar systems or other high power electromagnetic signals. This happens because STP cables have a conducting shield made of metallic foil encasing the twisted wire pairs, which blocks electromagnetic interference, allowing it to carry data at a faster rate of speed. Additionally, STP cables are more expensive than UTP cables, and have are of larger size. Finally, they are more fragile than UTP cables, as the shield must be kept intact in order for them to work properly.

The connection with the Alix 3d2 system board was completed with the use of the I^2C bus extender circuit. This is connected with the I^2C headers of the system board and it is powered using the +5 V and +3.3 V power supply lines of the Alix board. Also, the ground of the Alix board should be connected with the ground of I^2C bus. To check proper connection and communication of the device with the system board the following command was used:

```
i2cdetect -y 0
```

Moreover, in order for the Linux distribution to recognize the outer device as safe, the module must be named as such in the proper location. Otherwise, the system would not be able to locate the device and the communication channel would stay down permanently. The AD7745 chip operates in the address 48 of the I^2C bus and it can remain active continuously.

If for any reason the communication has problems, the bus alert is triggered and the user can inspect the problem (Figure 4.7).

The sensor circuits were evaluated in different versions, in order to develop a properly operating prototype. The circuits were designed with Eagle CADSoft and all the work involving the development and testing of the circuit boards was performed in the laboratory. Subsequently, the circuits were evaluated for their long-term performance in two main water-storage tanks of the Municipal Enterprise for Water and Sewage of the city of Chania. After constant monitoring of the measurement system properties and validation of the acquired data, the final version of the circuit board was installed in the water tanks (Figure 4.8).

As stated above, the sensor circuits were installed in an IP 65 protected box and the extender circuit was connected with the Alix system board. The communication via the I^2C bus was proven reliable when the UTP cables connected the sensors. Every UTP cable was also installed in a protective cable tube. The cables are often exposed to sun or high humidity in the water tanks and the use of protective cable tubes is inevitable in order to have a reliable measurement system without been affected by external interference.

4.2 TDR-based Sensor

The installation of the TDR-based sensor was limited only in one water tank. The main reason was the cost difference this type of measurement system had against the capacitive sensor. However, testing of the TDR-based sensor in the tank proved that it can also be a great alternative against ultrasound sensors that are frequently used in existing water monitoring systems, as it has equivalent performance and it has a significantly lower price. The initial tests of the TDR-based sensor were conducted in the laboratory with the use of an Agilent oscillator. Several experiments were conducted using various materials, in order to find a stable version of TDR-based sensor probes. In order to construct the TDR-based sensor and avoid the problem of corrosion of the sensor electrodes, the use of the multilayer pipes was promoted again, similarly to the capacitive-type water level sensor. With the one end of the circuit inside the tank, protected from a layer of PTFE, the metal parts of the proposed probes would never contact the water together. Thus, the phenomenon of electrolysis cannot take place. After testing several configurations of multilayer pipe and 304 L Stainless steel rods, the optimum results were tested with the 26 mm multilayer pipe and the 16 mm 304 L Stainless steel. The main problem of the TDR-based sensor is that the used inner stainless pipe cannot be easily transferred because of the sensor significant length. After the development of the laboratory prototype, a 4 m sensor was transferred to the water tank at Ag. Mathaios by truck. The signal-conditioning circuit boards that were designed and constructed (Figure 4.10), were also placed into an IP65 protective box and the connection with the probes and the T-BNC connector was performed with a coaxial cable (Figure 4.9). The circuit was also designed to connect with an I^2C extender circuit via UTP or STP Ethernet cable. For the same reason as the capacitive sensor, the channel of I^2C must be properly installed in every Linux distribution.

4.3 Cross Sensor Testing

Before the implementation of the water level measurements in the water tanks of the Municipal Enterprise for Water and Sewage of the city of Chania, the probes of both sensors were tested in the laboratory. The materials used for developing the sensor probes have the proper certification and can remain in constant contact with drinking water without harming the water quality. The signal-conditioning circuits developed have a relatively small size (Figure 4.11) and can be used without interfering with other electronics that were previously installed in the area of testing. In order to test both sensors and evaluate their performance, both experimental prototypes were tested at Ag. Mathaios water tank of the Municipal Enterprise for Water and Sewage of the city of Chania (Figure 4.12). The sensors were also calibrated and tested against a pre-installed ultrasound water level sensor. The experimental results indicated that the developed sensors were of equal performance as the commercially available sensors. From the evaluation of the sensors, it was proven that both prototypes can be seen as competitive solutions for water level measurement applications.

Figure 4.4: Experimental prototype of 2 meter length.

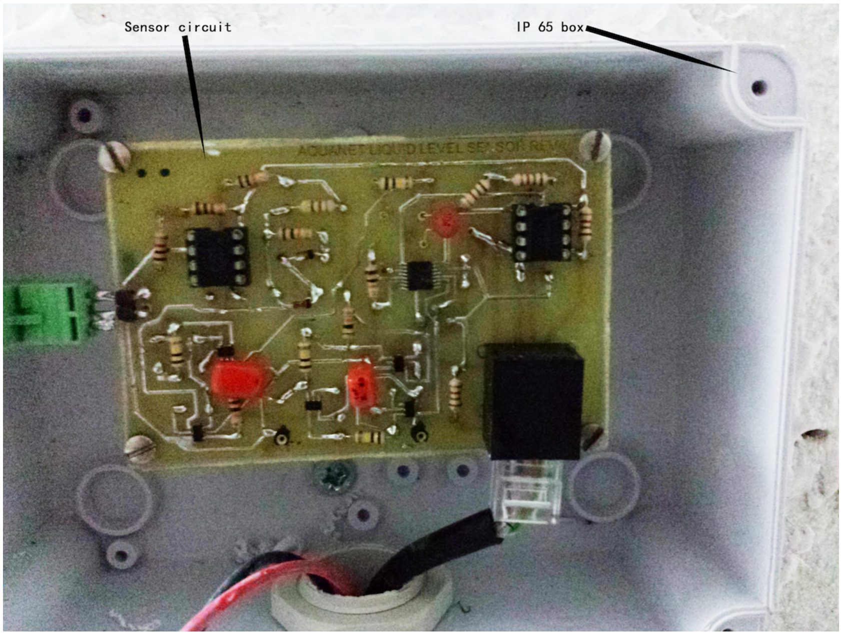
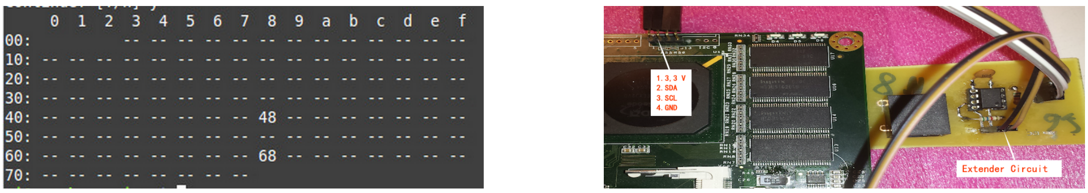


Figure 4.5: The capacitive sensor circuit installed in the IP box 65 in Ag. Mathaios water tank.

Figure 4.6: The capacitive sensor circuit installed next to the sensor probes in Ag. Iwannis water tank.



(a) **(b)**

Figure 4.7: (a) Communication through the I^2C bus with the sensor located in address 48, (b) The Alix 3d2 board connected with the extender circuit.

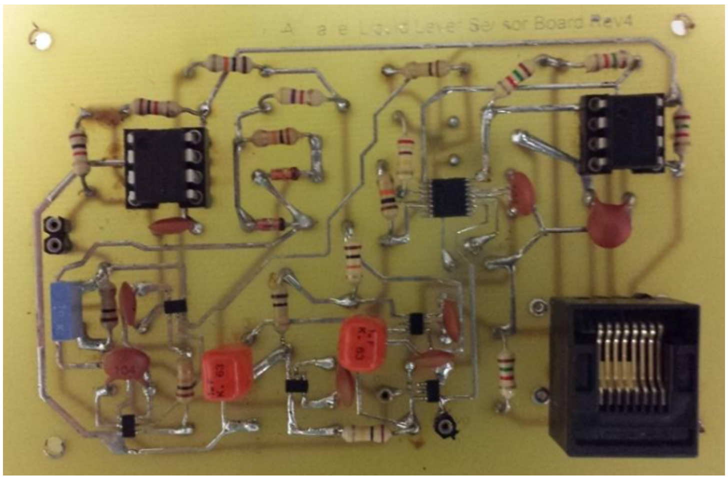
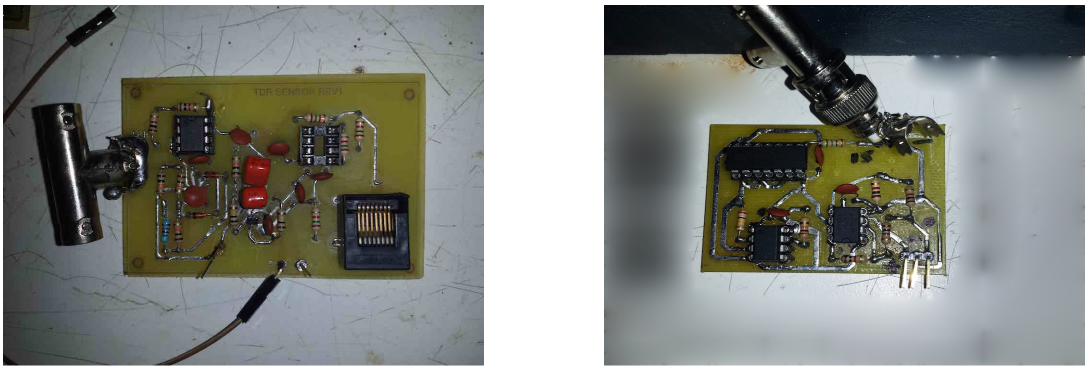


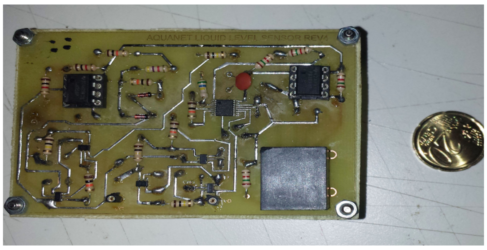
Figure 4.8: Circuit prototype.



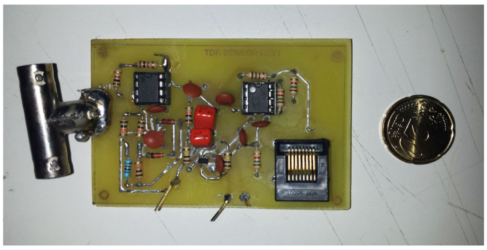
(a) (b)

Figure 4.9: The signal-conditioning circuit boards of the TDR-based sensor, in (a) Pulse measurement circuit for TDR and in (b) the TDR-timer circuit

Figure 4.10: The TDR-based circuit boards connected on operation.



(a)



(b)

Figure 4.11: : The size of the signal-conditioning circuit boards of the two types of sensors developed in this thesis. In (a) Capacitive sensor size demo and in (b) TDR-based sensor size demo.

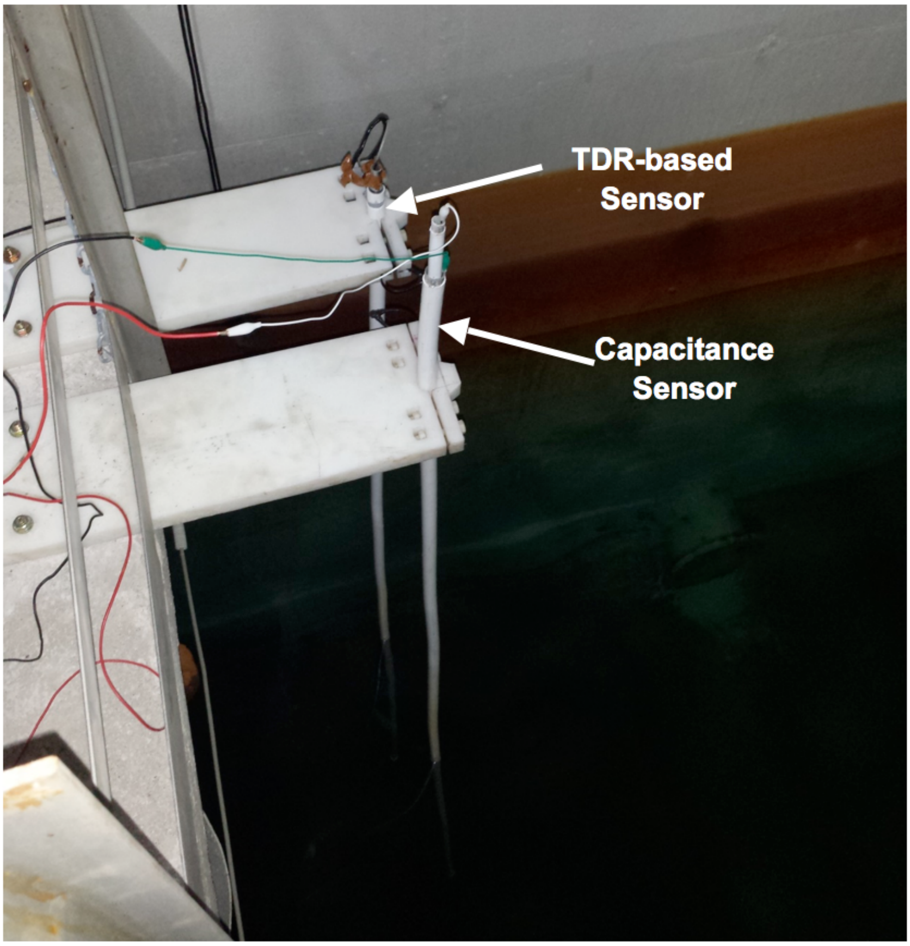


Figure 4.12: Parallel sensor testing in a water tank of the Municipal Enterprise for Water and Sewage of the city of Chania.

Chapter 5

Experimental Results

In this chapter, the experimental results of the proposed water level sensors testing are presented. The various tests that were performed during the development process are analysed, from the initial testing in the laboratory, to the final measurements at various water storage tanks of the Municipal Enterprise for Water and Sewage of the city of Chania. The work that is described in this chapter emphasizes on the process of developing a working prototype to a measurement system that is ready to use, in the harsh environment of water storage tanks.

5.1 Laboratory Testing

To develop a stable water level sensor, a series of tests were required. The initial testing was implemented on the capacitive sensor, which was easier to be tested with the laboratory equipment. The capacitive sensor has the advantage of more available information, since capacitive sensors are becoming more and more popular in liquid measurements. On the other hand, developing a TDR-based sensor was more challenging, since the applications of this sensor type are limited and of higher cost. In order to develop the experimental prototype, the state of the art of TDR research [5, 21, 22] was studied thoroughly. However, all studied applications used an external measurement system to obtain water level values (i.e. TDR measurement instruments). This limitation creates a challenge for developing the measurement system in order to support the proposed TDR-based sensors. The proposed system had to be simple and operated without the use of external equipment in order to reduce the cost and maintain a low power consumption. Additionally, the information must be transmitted to the system board through a communication channel provided. All external instruments for TDR measurements do not offer this capability, since they are display units and cannot be operated with embedded boards.

5.1.1 Capacitive Sensor

The first experiments during the capacitive sensor development process were conducted in the laboratory by immersing the sensor inside a plastic container and using an LC-Meter (HM8018) to measure the capacitance of the sensor. Measurements were conducted with different materials (brass pipes, stainless steel and multilayer tubes). For evaluating the performance of the proposed sensors, the Root-Mean-Square (RMS) and the Mean Absolute Error (MAE) metrics were calculated using the experimental measurements. The experiments where separated from the initial stages of parallel probes and the following stage of the coaxial configuration. The use of the coaxial configuration for the sensor, solved the problem of installation and external noise interference. The experimentally measured total capacitance of the proposed sensor at various water levels is shown in (Figure 5.1). The non-linearity Root-Mean-Square (RMS) error is 0.81 % and the Mean Absolute Error (MAE) is 0.75 %. Moreover, 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. The charge amplifier circuit is affected only from the changes in capacitance of the probes and neglects the additional resistance of the water.

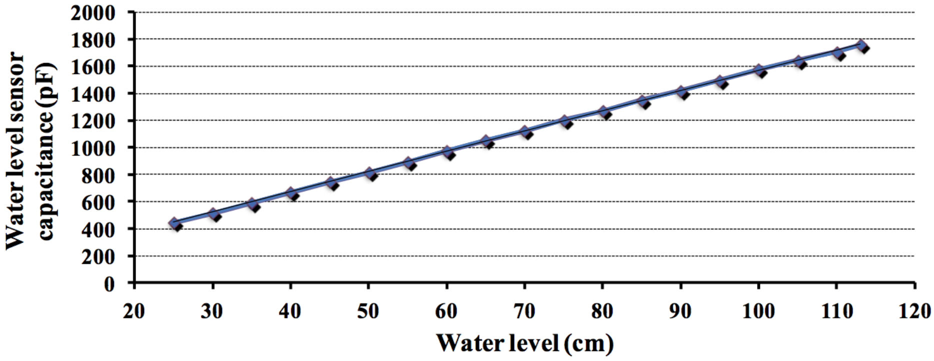


Figure 5.1: Measured capacitance in the laboratory tests.

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 has already been 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 has 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 Figure 5.2. 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.

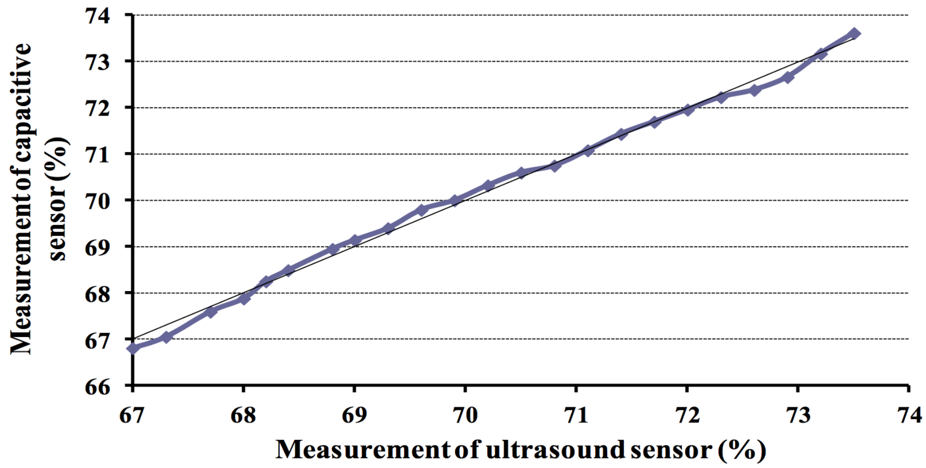


Figure 5.2: Measurement of the proposed sensor against the pre installed ultrasound.

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. In order to get the level measurement result, the algorithm computes the voltage output of the circuit and then receives the temperature measurement from the integrated sensor of the AD7745 chip. In order to receive this information, the program sets appropriately the registers of the sensor after every measurement. This creates a lag time for the final output. However, temperature measurements are essential to be measured in order to get a calibrated value of the sensor measurement. From several laboratory experiments it has been proved that when temperature drops, the capacitance of the sensor system slightly increases. The capacitive sensor system was thoroughly tested in several water tanks. It was also verified that it can operate properly under the rough conditions of the water tank environment. Figure 5.3 displays the experimental measurements acquired by the proposed water level sensor at the water storage tank of Ag. Mathaios during four consecutive days. It is observed that the level of water in the storage tank exhibits 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. The capacitive sensor installation in the remaining tank of the water distribution network was preferred from the TDR-based sensor, because it is of lower cost and can be easily transferred.

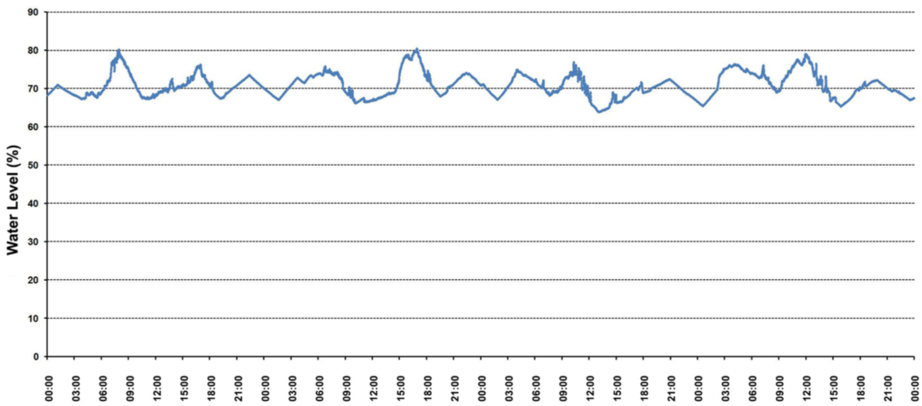


Figure 5.3: A four days timeline of water level measurements.

The capacitive sensor installation in the remaining tank of the water distribution network was preferred from the TDR-based sensor, because it is of lower cost and can be easily transferred.

5.1.2 TDR-based Sensor

An experimental prototype of the proposed TDR sensor with a length of 1.8 m was initially constructed as analysed in Chapter 3 and tested in the laboratory. It comprised a TP304/304 L 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 Figure 5.4. The non-linearity Root Mean Square (RMS) error is 0.65 % and the Mean Absolute Error (MAE) is 0.62 %.

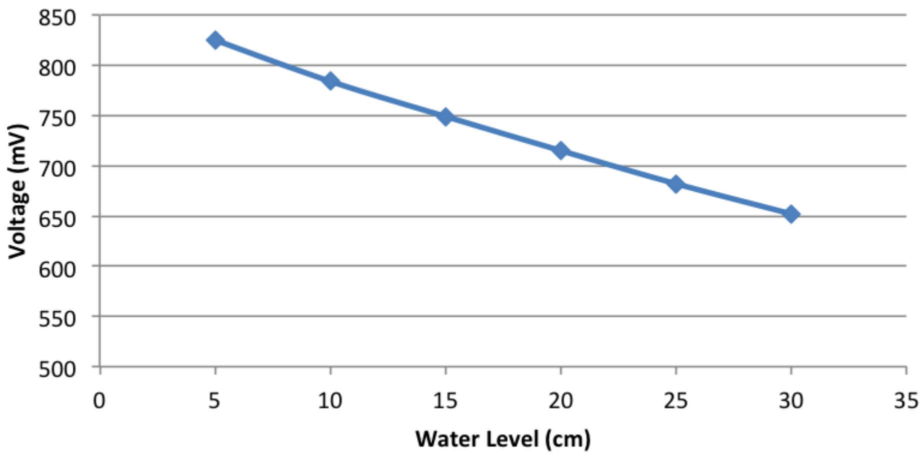


Figure 5.4: Measurements with the proposed TDR-based sensor in the laboratory.

Then, the performance of the TDR-based 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 Figure 5.5.

In the same water storage tanks, 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 for evaluating its performance as well. These two different types of sensors were set to operate concurrently in the same storage tank for a time period of six 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 Figure 5.6. 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.

5.2 Field Installation and Testing

For the capacitive sensors to operate correctly, without been affected by the environmental conditions, required proper installation, protection and extensive testing. The locations of water tanks in Chania have several differences. The IP boxes that contain the sensor circuit were installed close to the sensor probes and secured on the walls of the tanks or on the PTFE bases. All the cables that transfer signals between the sensor and the system board were also secured with the use of a protective tube. Since the IP boxes protect the circuit from humidity, all the open holes in every box were also covered with silicone to ensure safe operation (Figure 5.7).

5.3 Measurements in Water Tanks

The measurement system was fully deployed in water tanks in the Chania municipality area. After the installation of the sensors in these remote tanks, water level measurements were obtained. Every node, connected with the Alix 3d3 or Alix 3d2 system board, received the measurements from the installed sensors. The two versions of Alix system boards that were used, have different sizes but the same overall operational characteristics. The I^2C bus pins are also located in different positions, but operate in the same way. Furthermore, the sensors after proper calibration provided the measurements from several water level tanks. The update on water level is immediate since the sampling rate can reach 1 measurement per second. The information obtained from the system board is the level of water in the tanks and the temperature of the sensor. In Figure 5.8 a demonstration of measurements from Ag. Mathaios tank is presented. Additionally the same measurement system is also installed in the other seven water tanks location. Ag. Ioannis in Figure 5.9, DEI-Moter water tank in Figure 5.10, Malaxa water tank in Figure 5.11, Mournies water tank in Figure 5.12, Korakies water tank in Figure 5.13, Tsikalaria water tank in Figure 5.14 and in Vantes water tank in Figure 5.15.

Figure 5.5: The prototype of the TDR-based water level sensor before the installation in the water tank of Ag Mathaios.

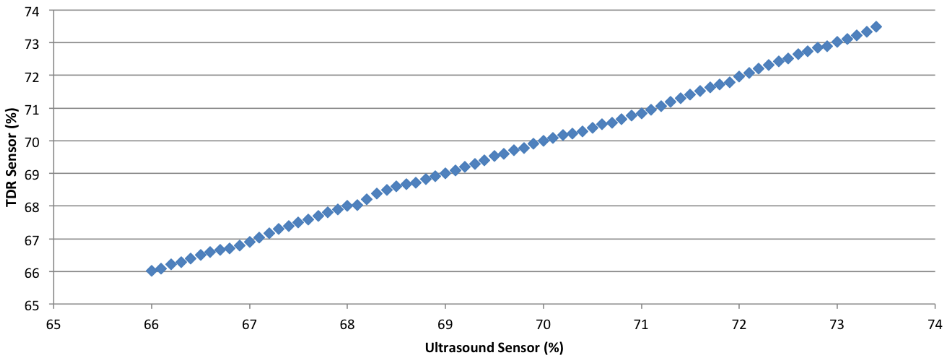


Figure 5.6: TDR-based sensor installed in the water tank.

(a)

(b)

Figure 5.7: Installation of the system in the water tanks of Ag Ioannis(a) and Ag. Mathaios(b).

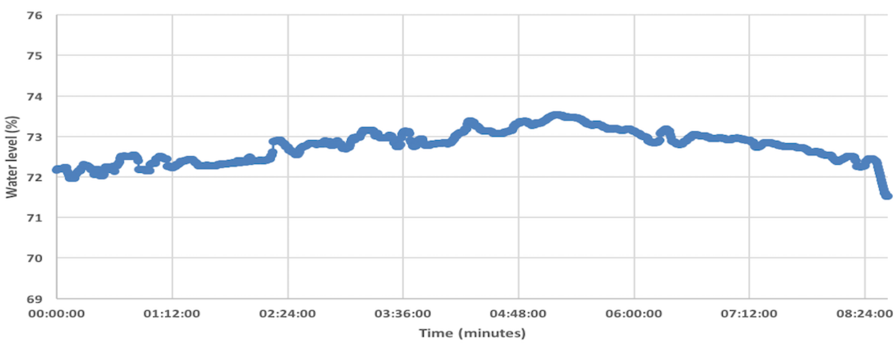


Figure 5.8: Water level data obtained from the measurement acquisition system from Ag. Mathaios tank.

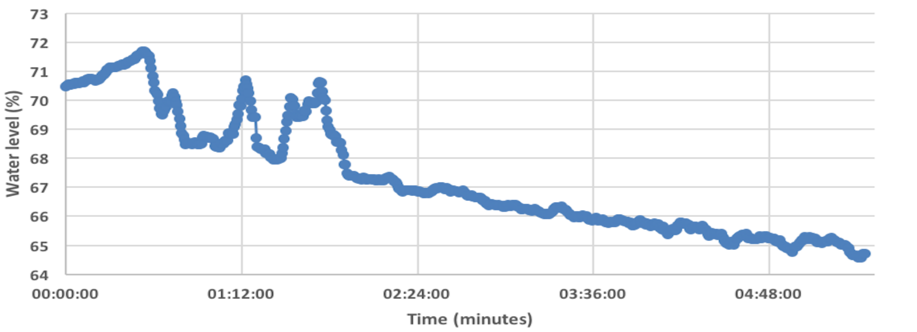


Figure 5.9: Water level data obtained from the measurement acquisition system from Ag. Ioannis tank.

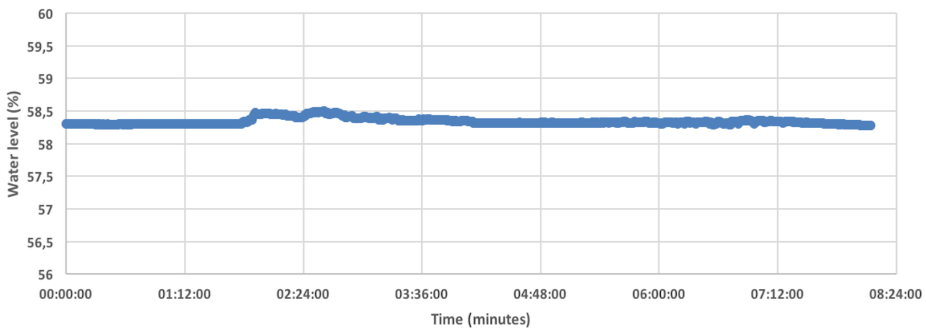


Figure 5.10: Water level data obtained from the measurement acquisition system from DEI-Moter tank.

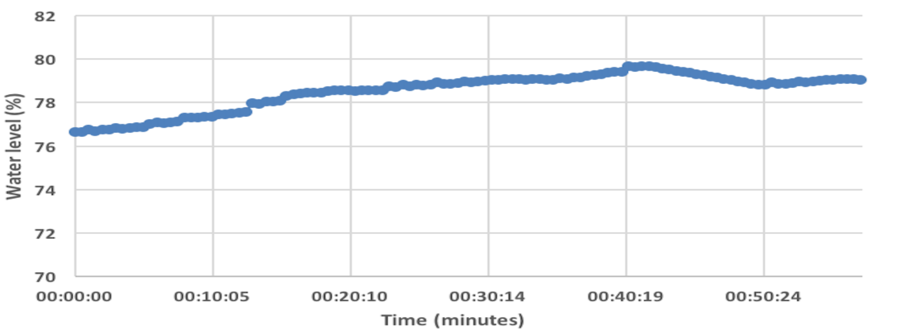


Figure 5.11: Water level data obtained from the measurement acquisition system from Malaxa tank.

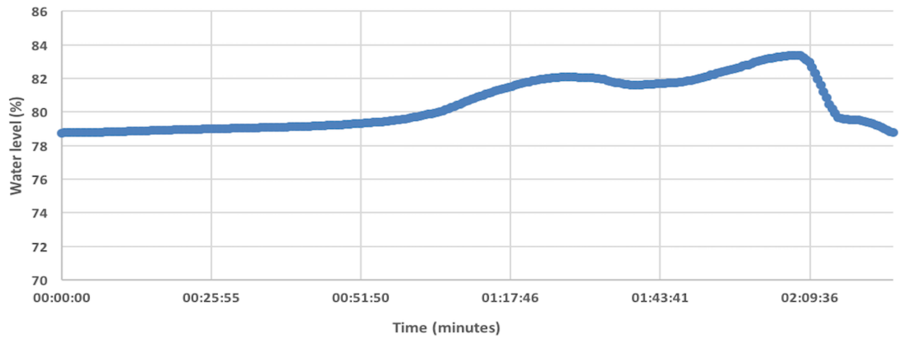


Figure 5.12: Water level data obtained from the measurement acquisition system from Mournies tank.

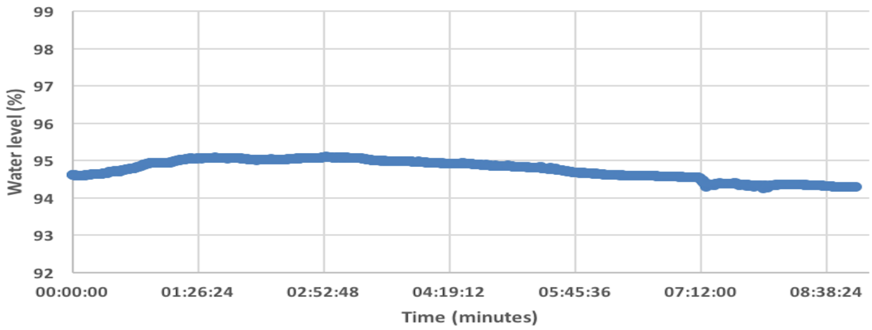


Figure 5.13: Water level data obtained from the measurement acquisition system from Korakies tank.

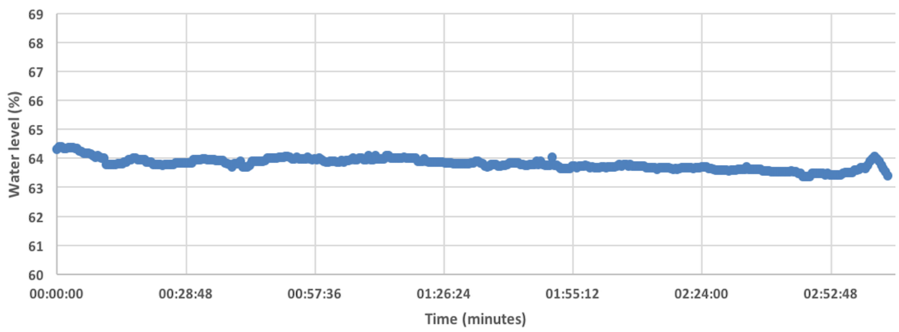


Figure 5.14: Water level data obtained from the measurement acquisition system from the Tsikalaria tank.

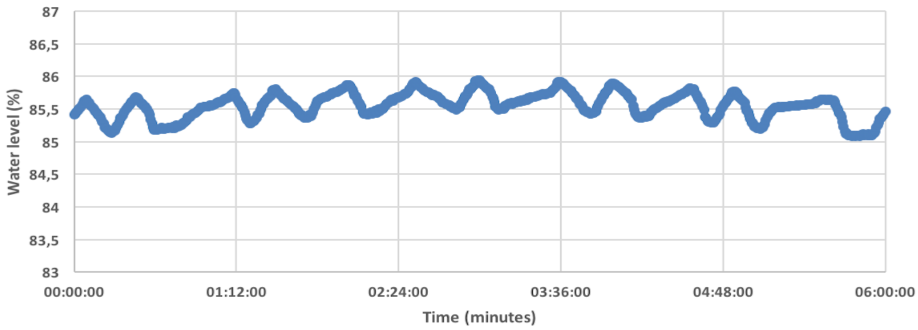


Figure 5.15: Water level data obtained from the measurement acquisition system from Vantes tank.

Chapter 6

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 thesis, a review of the past-proposed techniques for liquid level sensing has been initially 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 signal processing. Additionally, the studied sensors 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. Subsequently, the development of two different types of novel water level sensors, which are suitable for measuring the level of drinking water in large scale storage tanks has been presented: a capacitive-type water level sensor and a water level sensor based on the Time Domain Reflectometry (TDR) technique. Both of the proposed sensors comprise sensing probes constructed using low cost and widely available multilayer and stainless steel tubes. With these low-cost materials, the sensors probes are stable and can be constructed everywhere. To operate each of these two water level sensors, low cost and low power consumption signal-conditioning circuits were also designed. The acquired measurements are interfaced to a digital data-acquisition device through the I^2C communication bus. These features favour the incorporation of the proposed sensors in RES power-supplied WSNs, which are employed in various environmental and industrial applications. The operational characteristics and performance of the proposed sensors have been investigated through simulations, as well as experimental tests conducted in water storage tanks of a city-scale water distribution network. It has been demonstrated experimentally that the proposed capacitive and TDR-based water level sensors achieve equivalent performance with that of a commercially-available ultrasound sensor and simultaneously exhibit a much lower manufacturing cost. Comparatively, although the capacitive and TDR-based sensors exhibit equivalent performance characteristics in terms of measurement accuracy and power consumption, the capacitive water level sensor is of lower cost.

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