Water level monitoring by using magnetic optical sensor

Monitoreo de nivel de agua mediante sensor óptico magnético

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KEYWORDS:

Liquid level measurement, tank draining, optical-magnetic sensor

ABSTRACT

Measurement of the water level, derived from inherent problems inherent in the nature of the liquid, represents one of the most recurring challenges in both an industrial and a residential context. In this work, a real-time water level measurement system using an optical-magnetic sensor with high linearity, low cost, high reproducibility, and easy installation is proposed. Firstly, mathematical modeling of the water level measurement in a tank using differential equations is described. This system comprises a printed circuit board (PCB), a novel float mechanism, an optical sensor, a microcontroller, and a visualization stage. The proposed float system solves the common problems of corrosion and calcareous sinter, optimizing the functionality of the device for long-term applications. The microcontroller is used to calculate the distance between a reflective cross section and the optical transmitter of the float mechanism correlated to the water level. Certainly, the proposed design offers a key advantage; it prevents direct contact between water and vapor with the sensor device. This separation helps maintain sensor accuracy and longevity. Ten experiments were carried out to measure the water level in a tank manually and automatically and were compared with the mathematical calculation. The preliminary results of the proposed system have an approximate difference of 5% with respect to the analytical calculation.

PALABRAS CLAVE:

Medición de nivel de líquido, drenado de tanques, sensor óptico-magnético.

RESUMEN

La medición del nivel del agua, es un problema inherente a la naturaleza del líquido, representa uno de los desafíos más recurrentes tanto en el contexto industrial como en el residencial. En este trabajo se propone un sistema de medición de nivel de agua en tiempo real, mediante un sensor óptico-magnético de alta linealidad, bajo costo, alta reproducibilidad y fácil instalación. En primer lugar, se describe el modelo matemático de la medición del nivel de agua en un tanque mediante ecuaciones diferenciales. Este sistema consta de una placa de circuito impreso (PCB), un novedoso mecanismo de flotación, un sensor óptico, un microcontrolador y una etapa de visualización. El sistema de flotador propuesto resuelve los problemas comunes de corrosión y adhesión calcárea (sarro), optimizando la funcionalidad del dispositivo para aplicaciones a largo plazo. El microcontrolador se utiliza para calcular la distancia entre una sección transversal reflectante y el transmisor óptico del mecanismo de flotación correlacionado con el nivel del agua. Ciertamente, el diseño propuesto ofrece una ventaja clave; Evita el contacto directo entre el agua y el vapor con el dispositivo sensor. Esta separación ayuda a mantener la precisión y la longevidad del sensor. Se realizaron diez experimentos para medir el nivel de agua en un tanque de forma manual y automática y se compararon con el cálculo matemático. Los resultados preliminares del sistema propuesto tienen una diferencia aproximada del 5% con respecto al cálculo analítico.

• **Recibido: 20 de julio de 2024** • **Aceptado: 7 de noviembre de 2024** • **Publicado en línea: 1 de febrero de 2025**

ProgMat, 2025, 17, 1; https://progmat.uaem.mx/progmat

DOI: 10.30973/progmat/2025.17.1/3

1. INTRODUCTION

Currently, due to the major problems with water supply, both in industrial applications and at home, the measurement of this liquid represents a critical point [1]. There are several specific industry applications that require optimal measurement of the water level, such as: food, chemical, pharmaceutical, electricity generation, purification, reactors, distillation columns, evaporators and mixing tanks, among others [2].

There are several ways to measure water in tanks. Generally, they can be divided into 2 categories: continuous point level measurement and fixed-point level measurement; which can be intrusive and nonintrusive [3]. Many techniques used for water level measurement are based on visual inspection, hydrostatic pressure, floating or mechanical displacement systems, bubblers, load cells, electrical properties, thermal conductivity, capacitance, radiation-based level measurement, microwaves, ultrasounds, optics, etc. [4],[5],[6]. Likewise, there are new non-intrusive and low-cost techniques for level measurement such as the use of cameras and image processing; however, the performance of these systems is inherent to the lighting conditions, and there is a measurement error in float-based systems when the float is outside the range of view or when the object is liquid-like [1], [7],[8].

The development of time-domain reflectometry (TDR) technology has been designed to measure multiple levels of water; however, this technology does not function adequately when there is agitation in the water [9]. Similarly, the development of fiber optic sensors has progressed in recent decades, in terms of water level measurement, fiber-based sensors are used for fixed point measurement, employing the reflection and transmission properties of the light [10], [11]. But many of these systems are not useful in practice, so capacitive sensors are proposed, which have certain advantages of low energy consumption, linearity, adjustability, and use in extreme conditions [12].

Although there are several technologies for measuring water level, both for industrial or home applications, there are problems related to the properties of water, as well as transportation and storage systems. Corrosion and mineral calcareous incrustation are two of the most common problems in this type of systems. These problems can lead to measurement errors, sensor decalibration, reduced useful life, and no operation in the short term. In addition to the above, the end user requires visual feedback of the water level, and most systems do not meet this requirement. To overcome the problem of practical use, this work proposes a water level measurement system based on a printed circuit board (PCB), a novel floating mechanism, an optical sensor, a microcontroller, and a visualization stage.

2. WATER LEVEL CALCULATION

Let $h(t)$ the initial height of a liquid in a tank at any instant t, $V(t)$ the volume of water in the tank at that instant, a the area of the water outlet hole located at the bottom (Figure 1), g the gravity, c the discharge coefficient, and $A(h)$ the cross-sectional area of the tank [13].

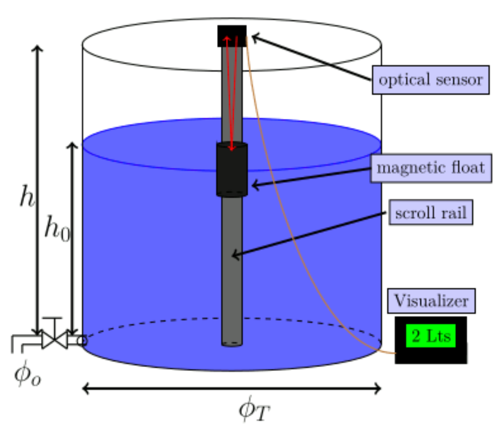

Figure 1. Functional diagram of level measurement system.

The differential equation to model the liquid level of a tank is the following:

$$A(h)\frac{dh}{dt}=-ac\sqrt{2gh} \quad (1)$$

If, in addition, the tank is being filled, the differential equation is given by:

$$A(h)\frac{dh}{dt}=Q-ac\sqrt{2gh} \quad (2)$$

where, Q is the filling factor. Equation 1, can be solved using the method of separable differential equations, conditioned to the initial condition of the height $h(0)$, to obtain the variation of the height depending on time. So, separating variables, we have:

$$\frac{A(h)}{-a\sqrt{2g}}\frac{dh}{\sqrt{h}}=-dt \quad (3)$$

If we consider that for a cylindrical tank like the one used in this work (Figure 1), $A(h)$ is constant and integrating both sides we obtain:

$$\frac{A(h)}{-a\sqrt{2g}}\sqrt{h}=t+k \quad (4)$$

where k is the integration constant. Finding k with the initial condition, then the height as a function of time as:

$$h(t)=\left[\frac{(t+k)(-a\sqrt{2g})}{2A(h)}\right]^2 \quad (5)$$

3. EXPERIMENTAL SETUP

The experimental configuration shown in Figure 2 consists of a floating mechanism, an optical sensor, a microcontroller, and a visualization stage.

3.1. Floating mechanism

The floating mechanism consists of a magnetic float and a sliding rail (Figure 3a). The magnetic float is made up of 3 segments of hydraulic polyvinyl chloride (PVC) tube, arranged as seen in Figure 3b, whose diameter is 0.0508 m.

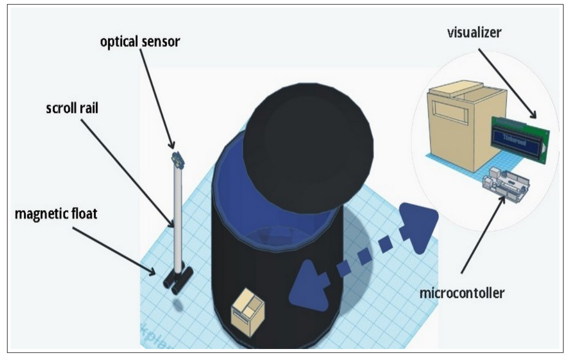

Figure 2. System elements, optical sensor, magnetic float, displacement rail, display and microcontroller, for water level measurement.

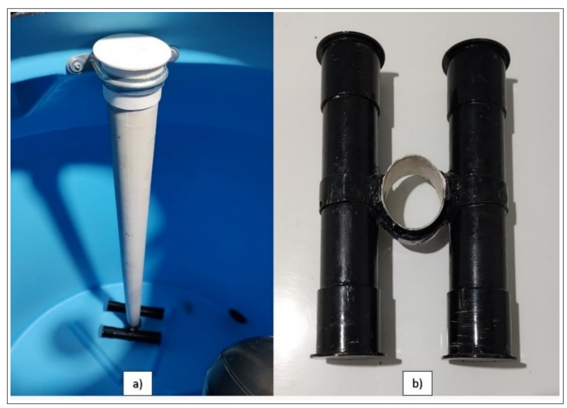

Figure 3. a) Scroll rail and b) magnetic float of the float mechanism.

The magnetic float uses neodymium magnets for its movement, which are arranged on the internal part of the float (Figure 3b) and at the base of the reflective surface. The magnetic characteristics of the magnets are useful for the displacement objective proposed in this work [14]. The hermetic sealing of the structure prevents the entry of water and promotes the rise and fall of the float along the lifting rail through magnetic attraction.

The other component of the flotation mechanism is the displacement rail, whose length is $h=1.2m$, which is attached to the tank through a coupling at its upper end and is completely sealed. The internal part of the rail contains a reflective flat surface (Figure 4b), which is related to (h_0) depending on the water level.

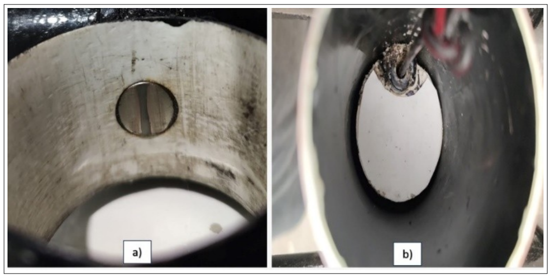

Figure 4. a) Flat reflective surface and b) internal section of the coupling with a neodymium magnet.

|The display cables and the sensor PCB are connected to the coupling at the upper end, as seen in Figure 5. To secure the PCB, two washers were used, one placed on the internal part of the coupling while the other is located on the PCB.

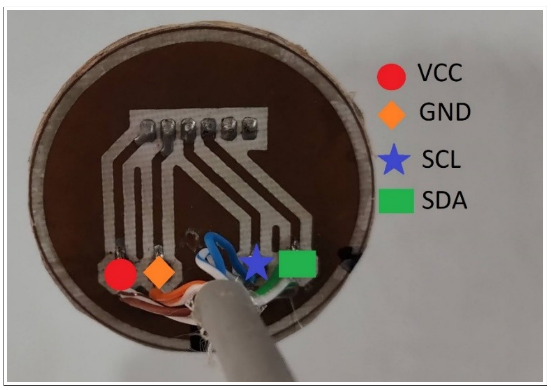

Figure 5. PCB for connection of the VL53LX0 sensor.

3.2. Visualizer

An 8-bit ATmega328P microcontroller [15] and a liquid crystal display (LCD) were used for the visualizer. In this case, an analog input was used for the sensor output and six digital outputs for the display. The integration of the elements of the level measurement system is seen in Figure 2.

The display used in the system allows the visualization of the liquid level in the tank in real time and continuous. For an optimal visualization of the values, the contrast and response time parameters were considered. Table 1 shows the values for the display at room temperature (25 °C) and with nominal voltage (3.3 Volts).

Table 1. LCD contrast and response times.

Item	Common	Maximum	Unit
Contrast	10	-	lm
Image (visible)	200	250	ms
Image (no visible)	300	350	ms

3.3. PCB of the Sensor VL53L0X

We manufactured a PCB using CAD software to connect the VL53LX0 sensor and the output terminals, which consists of 6 pins for the female connectors. The terminals correspond such as VCC: supply voltage, GND: Ground, SCL: Reference signal and SDA: data signal (Figure 5) and are connected to the inputs of the microcontroller. Its circumference has a diameter of 48mm due to the internal diameter (50mm) of the scroll rail tube.

To prevent the optical sensor from coming into contact with the water and mineral waste that is generated, it was placed inside a hermetically sealed plastic tube. This tube has a mobile element on the inside with a flat reflective surface, which moves in sync with the magnetic float. Subsequently, the distance between the reflective flat surface and the optical sensor is measured to correlate it with the quantity in liters of the tank by the microcontroller using Equation (5).

3.4. VL53LX0 optical sensor

The VL53L0X sensor uses a $940\,mm$ infrared laser to emit pulses of light towards the reference object, in this case the flat reflective surface. Its operating principle is based on measuring the Time-of-flight (ToF), The VL53L0X sensor can measure distances ranging between $30\,mm$ and $1.2\,m$ in its default operating mode, and up to 2m in its long-range mode, making it useful for various applications that require accurate distance measurement at close range. and medium distance. Likewise, the average measurement time is $30\,ms$, which allows acquisition and visualization in real time [16].

Table 2. Measurement ranges with different targets [16]

Reflectance	Conditions	Indoor	Outdoor
White target	Typical	200 cm	80 cm
White target	Minimum	120 cm	60 cm
Gray target	Typical	80 cm	50 cm

Table 2, describes the typical performance in different colors on targets and conditions such as where the sensor is located: This information was used to find the white color of the reflective flat surface and the operating distance.

Table 3. VL53L0X sensor operating modes [16].

Profile	Time	Performance	Application
Default	30 ms	1.2 m	Standard
HighRes	200 ms	1.2 m +/- 3%	Accurate
High Range	33 ms	2 m	Long-range
High Speed	20 ms	1.2 n+/-5%	High speed

To obtain better resolution in the level measurement readings, the different profiles of the VL53L0X sensor can operate were analyzed (Table 2). The high-resolution mode is the one with maximum precision (1.2m +/-3\%) in the data using a white object (Table 3).

4. RESULTS AND DISCUSSION

To validate the experimental level measurement system proposed in this work, the mathematical calculation of tank emptying was carried out and compared. First, substituting real values into equation 4, we find the value of the integration constant k, where the diameter $\Phi=1.01\,m$ (open valve at 100%, the diameter of the exit orifice $\Phi_o=0.0508\,m$, and the initial height $h(0)=1\,m$. Subsequently, substituting the value of k and assuming that when the tank is empty $h(t)=0$ in equation 5, the calculated emptying time is 5 min and 20 s.

Subsequently, emptying time measurements were made manually using a digital stopwatch. The average emptying time in this case was $5\,min$ and $36\,s$, which implies a difference of $5\%$of the experimental measurement with respect to the mathematical calculation. Simultaneously, during the same experiments we used the proposed instrumental system with a sampling frequency of 10 s. Figure 6 shows the emptying measurements of the 9 experiments.

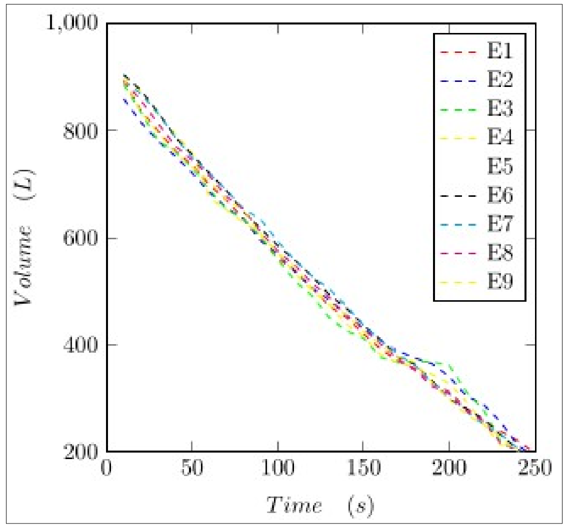

Figure 6. Measurements of the 9 tank emptying experiments using the instrumental system.

As can be seen in Figure 6, the system has high reproducibility, using the alpha of Cronbach [17], its reliability index is 0.999. The average of the 9 tank emptying experiments is shown in Figure 7.

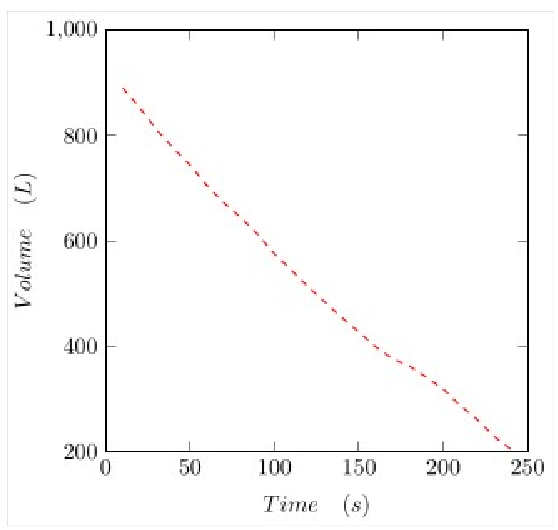

Figure 7. Average of the measurements of the 9 tank emptying experiments using the system.

Likewise, we check the operation of the system in the filling stage, using the same sampling frequency as for emptying. Furthermore, in both stages, the intervals of the tank's full and empty references were 900 l and 200 l, respectively. Figure 8 presents the measurements of the nine experiments in the filling stage.

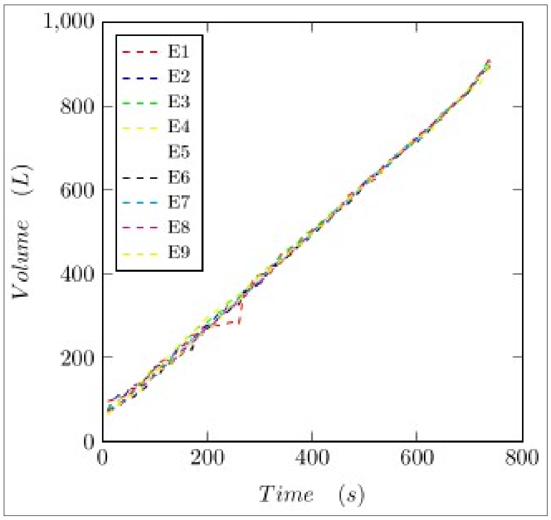

Figure 8. Measurements of the 9 tank filling experiments using the instrumental system.

As can be seen in Figure 8, the nine experiments in the filling stage have reproducibility performance similar to that in the emptying stage. However, it is important to consider that the times in both stages are not the same, because of the difference in diameter in the pipes and the physical mechanisms of both processes. The discontinuity in the measurement signal of experiment 1 (E1) is due to an intentional desenergization of the pump at a time. Figure 9 presents the graph of the average emptying time.

The average filling time was approximately $12\,min$. and 10 s. In this case, the reliability coefficient was 0.996, which means high reliability.

4.1. Scaling problems in liquid level sensors

Scale, a buildup of mineral deposits on surfaces and equipment, represents a significant challenge for various types of liquid level sensors. These deposits, which ate commonly composed of calcium and magnesium, can adversely affect sensor performance and accuracy [6].

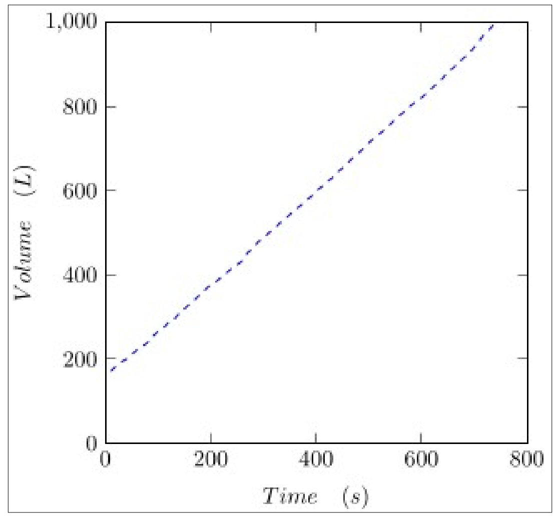

Figure 9. Average of the measurements of the 9 tank filling experiments using the system.

4.2. Ultrasonic Level Sensors

Ultrasonic level sensors operate by emitting ultrasonic waves that bounce off the surface of the liquid and return to the sensor. Scale can adversely affect these sensors in several ways. First, mineral deposits inside the tank can alter the propagation of ultrasonic waves, resulting in inaccurate liquid level readings. Furthermore, if scale builds up on the surface of the sensor or on the transducers, it can scatter the ultrasonic waves and decrease the quality of the reflected signals. As a result, the sensor may have difficulty obtaining clear readings, affecting its accuracy and reliability [6].

4.3. Float level sensor

Float level sensors rely on the movement of a float that rises or falls with the liquid level. Scale can cause problems if it builds up on the float or on the moving parts of the sensor. Mineral deposits can increase the weight of the float, making it less sensitive to changes in liquid level, or even block the entire float movement. In addition, scale can cause friction on moving parts, reducing sensor life and affecting reliability [6].

5. CONCLUSIONS

In this work we have presented the development of a water level measurement system based on a magnetic optical principle. The proposed measurement system, both in the emptying stage and in the filling stage, obtains precise measurements in relation to the real values, so it can be used in both stages. In both stages, high reproducibility can be determined since the reliability coefficient was greater than 0.99. The difference between the mathematical calculation and the manual and instrumental experimental measurement had a variation of 5%, which represents a good result at this stage of the project.

On the other hand, the main contribution of this work is the magnetic flotation mechanism and the real-time optical sensing system. The system is precise, high linearity, low cost, high reproducibility, and easy installation, without contact with water, avoiding problems of corrosion and calcareous sinter, optimizing the functionality of the device for long-term applications, both industrial and home. Although the preliminary results show good performance of the system, it is possible to improve the precision, energy efficiency and level of integration.

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