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Araştırma Makalesi / Research Article

Internet of Things Based Instant Liquid Level Monitoring and Control for Vessels

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Abstract

Instantaneous monitoring and control of liquid levels in ship tanks is vital for operational efficiency, vessel stability, and environmental safety. This study presents and evaluates the performance of an Internet of Things based prototype system designed for real-time liquid level management in maritime applications. The system integrates multiple ultrasonic sensors for level measurement, an ESP32 microcontroller for data processing and Wi-Fi transmission, and the Blynk mobile application for remote monitoring and pump/valve control. A local control unit consisting of an Arduino Uno, keypad, and LCD display provides redundancy and manual intervention with password protection. The study investigates system performance under static and dynamic conditions, especially in the presence of periodic mechanical and random manual vibrations. Findings show that using a moving average filter with optimized window sizes (e.g., 5, 7, or 9) significantly increases measurement accuracy, achieving over 99% accuracy in fill rate calculations under periodic vibration. Whereas random oscillations lower precision, increased filter windows increase stability, obtaining on average up to 98.6% accuracy. The results demonstrate the applicability of the system to reliable liquid level regulation on ships and show the importance of efficient signal filtering method to reduce vibration-induced errors, offering an innovative solution for maritime sector.

Keywords: Internet of Things, Liquid Level Control, Ultrasonic Sensor, Vessel Monitoring.

Gemiler İçin Nesnelerin İnternetine Dayalı Anlık Sıvı Seviyesi İzleme ve Kontrolü

Öz

Gemi tanklarındaki sıvı seviyelerinin anlık izlenmesi ve kontrolü, operasyonel verimlilik, gemi stabilitesi ve çevresel güvenlik için hayati öneme sahiptir. Bu çalışma, denizcilik uygulamalarında gerçek zamanlı sıvı seviyesi yönetimi için tasarlanan Nesnelerin İnterneti (IoT) tabanlı bir prototip sistemi sunmakta ve performansını değerlendirmektedir. Sistem, seviye ölçümü için çoklu HC-SR04 ultrasonik sensör, veri işleme ve Wi-Fi iletimi için bir ESP32 mikrodenetleyici ve uzaktan izleme ile pompa/valf kontrolü için Blynk mobil uygulamasını entegre etmektedir. Arduino Uno, tuş takımı ve LCD ekrandan oluşan yerel bir kontrol ünitesi ise şifre korumasıyla yedeklilik ve manuel müdahale imkanı sunmaktadır. Çalışma, sistemin statik ve dinamik koşullar altında, özellikle periyodik mekanik titreşimler ve rastgele manuel titreşimlerin etkisi altındaki performansını incelemektedir. Temel bulgular, optimize edilmiş pencere boyutlarına (örneğin 5, 7 veya 9) sahip bir kayan ortalama filtresi kullanmanın ölçüm doğruluğunu önemli ölçüde artırdığını ve periyodik titreşim altında doluluk oranı hesaplamalarında %99'un üzerinde bir doğruluk elde edildiğini göstermektedir. Rastgele titreşimler genel doğruluğu düşürse de, daha büyük filtre pencere boyutlarının kararlılığı iyileştirerek ortalama %98.6'ya varan bir doğruluk sağladığı belirlenmiştir. Sonuçlar, sistemin gemilerde güvenilir sıvı seviye yönetimi için uygulanabilirliğini ve titreşim kaynaklı hataları azaltmak için uygun sinyal filtreleme stratejilerinin önemini vurgulamakta ve denizcilik sektörüne özel yenilikçi bir çözüm sunmaktadır.

Anahtar Kelimeler: Nesnelerin İnterneti, Sıvı Seviye Kontrolü, Ultrasonik Sensör, Gemi İzleme.

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1. Introduction

While the vessel industry is the backbone of world trade, critical factors such as safety of vessels, operational efficiency and environmental sustainability are among the priority issues at every stage of the sector. In this context, liquid tanks used for various purposes on vessels (e.g. transportation of liquid matter, tanks for personnel use) and liquid level control in tanks come to the forefront as a fundamental element of vessel operations. Instantaneous observation of tank liquid levels on vessels is of vital importance in terms of vessel safety and operational efficiency. This observation is necessary to ensure the stability of the vessel, determine its cargo carrying capacity, increase fuel efficiency and minimize environmental impacts (Bakar, 2017; Zhang et al., 2019).

Primarily, the balance and stability of vessels depend on the liquid levels in the tanks. Liquid level in the tanks should be monitored in real time to provide the vessel with stability and balance (Zhang et al. (2019); URL-1). Accurate liquid level control ensures safe navigation of the vessel during sudden surges or wind effects (Woolf, 2009).

In addition, tank liquid levels must be constantly monitored to determine the cargo carrying capacity and the vessel's draft. When vessels enter and leave ports, navigate channels or avoid underwater obstacles, accurate draft control is important. Since incorrect draft is based on liquid levels determining the vessel's underwater depth, these controls are essential to ensure the safe navigation of the vessel.

Moreover, liquid level control is important to increase fuel efficiency. Correct ballast distribution and fuel tank filling rate help the vessel achieve optimum speed and fuel consumption savings (Hapsari et al., 2021, URL-2).

Besides, it is necessary to track tank liquid levels in order to minimize environmental effects. Uncontrolled ballast water discharge can negatively affect marine organisms and ecosystems. Therefore, liquid level control on vessels should also be considered as a part of environmental protection measures.

For all these reasons, instantaneous observation of tank liquid levels on vessels is of great importance in terms of vessel safety, operational efficiency and environmental protection. These observations are an important process that vessel personnel must perform carefully and precisely.

In this study, instantaneous monitoring and control of tank liquid levels on vessels was carried out with a prototype IoT application. The tank liquid level information to be controlled is obtained by sensor nodes and sent to vessel personnel at any point on the vessel via a WLAN to be created on the vessel via an application on their mobile phones. All personnel can monitor this information, but vessel personnel with the necessary authority can perform level control with the help of a mobile application. The main contributions of this study to the vessel/vessel industry can be listed as follows;

- The prototype IoT application developed provides an innovative infrastructure for continuous monitoring of vessel tank levels,
- Thanks to the designed WLAN infrastructure and mobile application: Vessel personnel will be able to monitor tank levels from every point of the vessel, Complex information can be presented in an understandable way with data visualization tools, Uninterrupted access can be provided with multi-device support,
- Security can be increased with the hierarchical authorization structure,
- It can provide time and fuel savings compared to manual measurements and reduce maintenance costs,
- Carbon footprint will be reduced as a result of supporting the reduction of fuel consumption in terms of environmental sustainability.

The remainder of this article is structured as follows:

Section 2 presents a comprehensive review of existing literature and highlights the identified research gaps. Section 3 explains the proposed IoT-based prototype system in detail, including its architecture, hardware and software components, and filtering methodology. Section 4 describes the experimental setup and presents the results under different vibration scenarios. Section 5 discusses the findings, analyzes measurement accuracy, and evaluates system performance under static and dynamic conditions. Finally, Section 6 concludes the study with recommendations for future research and suggestions for industrial improvements.

2. Literature Review

In recent years, developments in ultrasonic sensor technology and the proliferation of IoT infrastructures have brought about a significant transformation in traditional level measurement methods. In this literature review section, focusing particularly on ship applications: existing IoT-based remote monitoring systems in the literature and their areas of use, applications in the maritime sector, technical limitations of existing solutions and research gaps are systematically analyzed. The following table shows current studies and technologies used in liquid level control as a result of the literature review.

(Perumal et al., 2015) designed an IoT-based real-time water monitoring system for flood-prone areas. The water level is sensed by ultrasonic sensors and the data is transmitted to the cloud and displayed on the web panel. Automatic alerts are generated by the system via Twitter (X) when the threshold levels are attained. The low-cost system is an effective solution for early warning and public awareness before disasters.

Table 1. Recent studies in literature about IoT based water level control

Study	Implementation Type	Monitoring Method	Control System	Application Domain
Perumal et al., 2015	IoT Enabled Water Monitoring System	Ultrasonic Sensor	Cloud-Based Alert System (Twitter)	Disaster Management / Smart Home
Sachio et al., 2018	IoT-based water level control system	Ultrasonic sensor	ESP8266 μ-controller	Household water management
Ray et al., 2019	Non-invasive IoT-based IV fluid level monitoring system	No mention found	ESP8266 and ATtiny85 μ-controllers	Healthcare (fluid monitoring)
Akshay Sharma A.S., 2020	IoT-based water level sensing and controlling system	Ultrasonic sensor (HC-SR04) for tank, water level sensor for sump	Node MCU (ESP8266) μ-controller	Household and agricultural water management
Olisa et al., 2021	Smart two-tank water quality and level Detection system	Ultrasonic pulse-echo technique for level, turbidity and pH sensors for quality	not specified	Residential water management
Abbod and Zwyer, 2021	Internet of Things (IoT)-based system with wireless sensor network	Level, temperature, and fire sensors	Arduino-based control station	Oil industry (tanks, refineries, petrochemical plants)
Gondkar et al., 2022	IoT-based water level Monitoring system	Ultrasonic sensors	AVR μ-controller	Water conservation in households and industries
Sasikala et al., 2022	IoT-based water level management system	Ultrasonic sensor	ESP32 μ-controller, stepper motor actuators for sluice gate control	Water resource management (dams and reservoirs)
Bhookya et al., 2022	IoT-based liquid level monitoring and control system	No mention found	PID controller with mGWO algorithm, ESP32 μ-controller	Industrial automation (single tank system)
Huque et al., 2023	IoT-Based Smart Water Tank Level Monitoring and Motor Pump Control	Ultrasonic + Water Depth Sensor	Blynk App + Relay Module (NodeMCU, Arduino Uno)	Residential Water Conservation

(Sachio et al., 2018) developed an IoT-based water level control system to prevent water waste. The system measures the water level using an ESP8266 microcontroller and an ultrasonic sensor and provides real-time monitoring with the Blynk IoT service (URL-3). The pump is automatically turned off when the water level exceeds the specified threshold values. Data is recorded with a PHP-based web interface and users control it via a mobile application. The system was tested in a 64 cm water tank and worked with a 2 cm error margin. The study offers a practical solution for water saving, especially in domestic use.

(Ray et al., 2019) announced a novel implementation of an IoT-based non-invasive sensor system with the goal to monitor intravenous (IV) fluid level in real-time. The system monitors the level of the fluid in the IV bag using an ATtiny85 microcontroller and an LM35 temperature sensor. An embedded web server based on ESP8266 is used to communicate the fluid level status to connected users. Nurses can receive timely notifications about whether the IV bag is about to be empty. The system can be implemented for widespread and auxiliary e-health services by using energy-efficient and cost-effective sensors. It is stated that the developed system is promising in developing IoT-based smart healthcare services.

(Sharma, 2020) developed an IoT based system with NodeMCU (ESP8266) and an ultrasonic sensor for automatically controlling the water level. It keeps updating the water level to the Blynk cloud server in real time and the pump can be operated manually/automatically by the users using the mobile app.Notification is provided when the tank becomes full or the water level is low. The system works integrated with a 0.5 HP motor and prevents water loss. The study offers a low-cost and user-friendly design, facilitating domestic water management.

(Olisa et al., 2021) developed an IoT-based level and quality monitoring system for two-tank water systems. Water level is measured with an ultrasonic sensor, and water quality is measured with turbidity and pH sensors. The system includes a valve mechanism that discharges poor quality water. Real-time data monitoring can be done via Android application. In tests, water level was measured with <10% error when it was below 81%. The study is suitable for monitoring drinking water quality as well as preventing water waste.

((Abbood et al., 2021) proposed an IoT-based system with real-time data transmission methods to prevent fires and flooding in oil tanks. There are two parts to the system: a tank station and a control station. The tank station contains level, temperature, and fire sensors. The control station is connected to the tank station via wireless connection via XBee and presents the data to the users through a visual user interface. The data stored in a local database designed with SQL Server is simultaneously sent to the ThinkSpeak platform, allowing authorized persons to access the data remotely. Tests have shown that the system can provide warnings against problems such as floods and fires.

(Gondkar et al., 2022) provides a new water level management system with IoT technology for effective management of water resources and preventing wastage of water. Focusing on water-scarce areas, the system would track the water level in water tanks through ultrasonic sensors and notify users of impending overflows. With the integration of components such as AVR microcontroller, Wi-Fi module, LCD display and audible warning system, the system provides real-time data transmission and user information. Visualization of the liquid level via the web page and audible warning in case the specified limits are exceeded aim to contribute to water saving.

(Sasikala et al., 2022) proposed an IoT-based water level management system in order to protect dam and reservoir water levels from natural or anthropogenic threats. Due to the limitations of existing flood gate management systems, this system is proposed to provide real-time management and water level monitoring in case of uncontrolled rise in water levels and overflows. Water level data is read using ultrasonic sensors and ESP32 microcontroller and stepper motor actuators are used for gate control. According to the data obtained from the IoT-based sensor, 0% error rate and 2 seconds data transmission delay were observed in all 20 experiments.

(Bhookya et al., 2022) In their research, a Grey Wolf Optimization (mGWO) algorithm and integration with IoT were used to develop a Proportional-Integral-Derivative (PID) controller for a liquid level system. The objective is to develop an mGWO optimized PID controller to regulate the liquid level in a tank and to improve the performance of the controller. The system is built on the ESP32 microcontroller module and an Android-based IoT application is developed using the Blynk platform. The results show that the proposed mGWO-based PID controller performs better than traditional Ziegler-Nichols and SIMC tuning methods and that IoT integration increases the flexibility of system control and monitoring.

(Huque et al., 2023) designed an IoT-intelligent monitoring and water tank and pump control system to prevent wastage of water. It measures the water level automatically using ultrasonic sensors based on NodeMCU and Arduino UNO microcontrollers and provides users with real-time data using the Blynk mobile app. The pump can be controlled remotely according to threshold values determined by users, and once water levels reach hazardous levels, the system responds automatically to prevent water overflow or dryness. With a 3-level LED display and mobile alert made easier, this cost-effective solution is anticipated to optimize the control of water, especially for households.

When the studies in the literature are examined, it is seen that most of the studies are not related to the maritime sector. Instead, they often focus on issues such as water waste management in residential areas. The study conducted is thought to fill an important gap in the maritime sector by providing an IoT-based system for instant monitoring and control of tank liquid levels on vessels. While existing studies generally focus on other sectors, this study aims to provide a safer, more efficient and sustainable liquid level control by taking into account the unique challenges and requirements of maritime operations. The two separate control unit approach and the special security measures developed make a significant contribution to the literature by increasing both the ease of remote access and on-site security of the system.

3. Materials and Methods

Real-time measurement of tank liquid levels is of great importance in maintaining ship stability, maximizing cargo carrying capacity, reducing fuel consumption and minimizing environmental effects. In this research, an IoT based prototype system was designed to fulfill these needs. The system architecture is schematically illustrated in Figure 1.

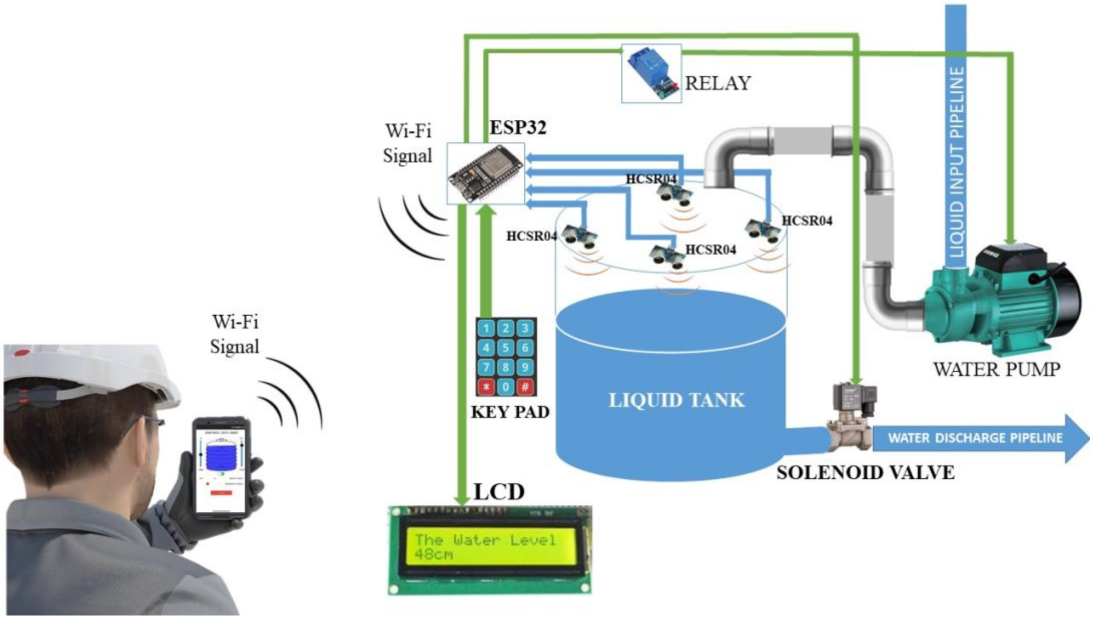

Figure 1. Schematic of the system architecture

The liquid level of tanks is measured using ultrasonic level sensors (HCSR04 etc.). HCSR04 is a popular sensor that measures distance using ultrasonic waves. Its working principle is based on sending sound waves at a frequency that the human ear cannot hear (40 kHz) and measuring the time it takes for these waves to return from an object. As seen in Figure 2, the transducer has VCC, TRIG, ECHO, GND terminals that are open to the outside world.

Figure 2. HCSR04 Pin layout

VCC and GND are 5V supply pins, TRIG is trigger and ECHO is the return time measurement pin. When a 10µs HIGH signal is sent to the TRIG pin, ultrasonic waves are emitted from the sensor's speaker, The sensor sends ultrasonic waves at a frequency of 40 kHz. At this time, the timer module in the ESP32 Wi-Fi module microcontroller starts working, the waves are reflected when they hit an object. The reflected sound wave reaching the HCSR04 microphone makes the ECHO pin HIGH. In this case, the microcontroller's timer is stopped and the time (t) is obtained in seconds by considering the prescaler value configured in the content of the timer module. Then the distance (d) is obtained with the formula below.

$$d = \frac{v.t}{2} \quad (1)$$

Here, v is the speed (the speed of sound propagation in air is 340 m/s). The reason for dividing the v.t product in the formula by two is that the distance traveled by the outgoing or reflected wave is twice the measured distance. Four HCSR04 sensors placed at different points were used for the ultrasonic level measurement of the tank. The final level information is calculated by averaging the level information obtained from the sensors. This information is transmitted to personnel at any point on the ship via a mobile application or computer network through a wireless network established within the vessel and can be monitored instantly by personnel. However, authorized personnel can perform this operation via the mobile application to control the liquid level.

The commands sent by the personnel reach the microcontroller with ESP32 Wi-Fi module and send orders to the solenoid valve or water pump. In this way, water is discharged or water is taken into the tank. With these operations, the liquid level is constantly controlled and instant information is transmitted to the ship personnel via the mobile application. Fluctuations in the liquid in the tank during navigation may cause errors in measurements. To eliminate this distorting effect, a moving average filter was applied and the level information of the four sensors was averaged. On the other hand, a second control mechanism was created with a keypad and LCD screen to provide manual liquid level control at the point where the tank is located. Detailed explanations regarding the hardware and software components of the system are presented in the subsections.

3.1. Hardware

The prototype system utilizes a combination of hardware components that have been selected for reliability, cost-effectiveness, and suitability for maritime real-time liquid level monitoring. For a clear analysis, the model, features, quantity and purpose of the hardware components used in the study are summarized in Table 2. for better analysis. A detailed explanation of the principal components, their selection criteria, and their functions is provided below.

3.1.1. Ultrasonic Sensor

Sensor selection is an important step in the system development process. Initially, JSN-SR04T sensors were considered due to their waterproof feature, but it was understood that these sensors were not suitable for accurate measurements at distances below 40 cm, considering the dimensions of the prototype and the test range (2 cm - 18 cm).

Therefore, HC-SR04 sensors were preferred due to their cost effectiveness and performance in the specified range. The problem of HC-SR04 sensors giving inconsistent results on a white background from time to time was overcome by mounting the sensors on a black background on the inner surface of the tank cover. In order to minimize instantaneous measurement errors that may arise from liquid sloshing, the principle of averaging the data obtained from four HC-SR04 sensors strategically placed on the tank was adopted. This averaging process was performed using a sliding averaging filter with different window sizes (3, 5, 7 and 9 data points). Furthermore, the position of the four sensors, as depicted in Figure 7, was a deliberate design choice based on a series of fundamental engineering principles to ensure reliable measurement under conditions of dynamism. The sensors were positioned in a diagonal, corner-to-corner layout primarily due to the fact that this layout is naturally efficient at detecting and averaging out the opposite crests and troughs of sloshing liquid waves. This provides a natural, passive compensation for dynamic disturbances. Additionally, the positioning accounted for the sensors' practical limitations; they were spaced to avoid acoustic cross-talk between units and positioned away from the tank walls to prevent erroneous readings from the sensors' known dead zones. This reasoned approach to sensor placement was chosen to maximize measurement stability and accuracy from the outset.

3.1.2. Microcontrollers

Although a single control unit was initially planned, the system was converted to a two-microcontroller architecture due to the insufficient I/O pins on the ESP32 and the need for more functionality. This unit serves as the primary control unit, providing Wi-Fi communication (IEEE 802.11 protocols), sensor data processing, and an interface to the Blynk IoT platform. It features a dual-core architecture to ensure real-time performance. The Arduino Uno serves as the secondary control unit for the local control unit, which operates the keypad and LCD interface.

3.1.3. Control Interfaces

The control mechanisms are designed both remotely and locally. Remote control is provided via the Blynk mobile application; potential security vulnerabilities in the free version of the application have been tried to be eliminated by developing a special session code mechanism and using IEEE 802.11 security protocols (WPA/WPA2/WPA3) and SSL/TLS encryption. Local control is provided by a unit consisting of a password-protected keypad and LCD screen located right next to the tank.

3.1.4. Actuators and Power Management

The power management components and actuators used in the system are: A DC Motor Pump (6-12V R385) to regulate the liquid level allows filling or draining the tank. It is equipped with automatic operation via relay control. It provides automatic operation via relay control. A Solenoid Valve (12V NO - Normally Open) is used to start or stop the liquid flow. It automatically closes in the event of a power outage, increasing safety. Additionally, 1N5819 flyback diodes and filter capacitors have been incorporated into the circuit to prevent electromagnetic interference generated during motor and valve operation. These measures reduce noise in sensor signals to increase measurement accuracy. A 300W ATX power supply provides a stable supply of 12V, 5V, and 3.3V to all system components. This supply ensures the smooth operation of the microcontrollers, sensors, and actuators. These components have been selected and integrated to ensure reliable system operation in both automatic and manual modes.

Table 2. Hardware components of the system

Component	Model	Features	Qty	Purpose
µ-Controller	ESP32	Wi-Fi/Bluetooth, low cost, IoT compatible	1	Processing sensor data and transferring it to the mobile application
µ-Controller	Arduino Uno	ATmega328P, 14 digital I/O, 6 analog inputs		Keypad control and basic operations
DC Motor Pump	DC 6-12V R385	DC-powered, used for irrigation/water transfer	2	Pumping the water
Mechanical Relay	SRD-12VDC-SL-C	Electromechanical switch for high-power circuit control	1+	Control pump (ON/OFF)
Ultrasonic Sensor	HC-SR04	Distance measurement (2-400 cm), 4 units used	4	Measure liquid level in tanks
Solenoid Valve	(NO) 12V DC Solenoid Valve	Electrically controlled (ON/OFF) for fluid flow	1+	Start/stop water flow
LCD	2x16 Characters LCD	2 rows, 16 characters per row	1	Liquid level display
Keypad	4x4 Characters Membrane	Button interface for numerical/symbol input	1	Display liquid level
Power Supply	DC Power Supply	ATX standard, 12V/5V/3.3V outputs, 300W (Provides stable voltage/current)	1	Power the system

3.2. Software

The simplified algorithm of the code loaded into the ESP32 microcontroller is as shown in Figure 3. The designed algorithm was implemented in the Arduino IDE using the C++ language, considering the ESP32 microcontroller. The sensor (HCSR04) data was passed through a moving average filter with varying window sizes (3, 5, 7, or 9) to reduce noise. Subsequently, the average of the four ultrasonic sensors was taken to obtain the final level measurement. The mathematical expression of the process is as follows. For each sensor S_i (i=1, 2, 3, 4), the average of the past N_i measurements is calculated as:

$$\tilde{S}_i(t) = \frac{1}{N_i}\sum_{k=0}^{N_i-1} S_i(t-k) \tag{2}$$

Here, $\tilde{S}_i(t)$ is the filtered output of sensor i at time t, $S_i(t-k)$ is the raw measurement at time $t-k$, N_i denotes the window size used for sensor i (e.g., 3, 5, 7, or 9). Therefore, the final level at time t, denoted as $L(t)$, is expressed as in Equation 3.

$$L(t) = \frac{1}{4}\sum_{i=1}^{4}\left(\frac{1}{N_i}\sum_{k=0}^{N_i-1} S_i(t-k)\right) \tag{3}$$

On the other hand, in order to enable remote control of the system via Wi-Fi, the Blynk application was used. Blynk is a mobile application used in IoT (Internet of Things) projects. This application allows remote control of Arduino, Raspberry Pi, and other microcontrollers via Wi-Fi, Bluetooth, or Ethernet.

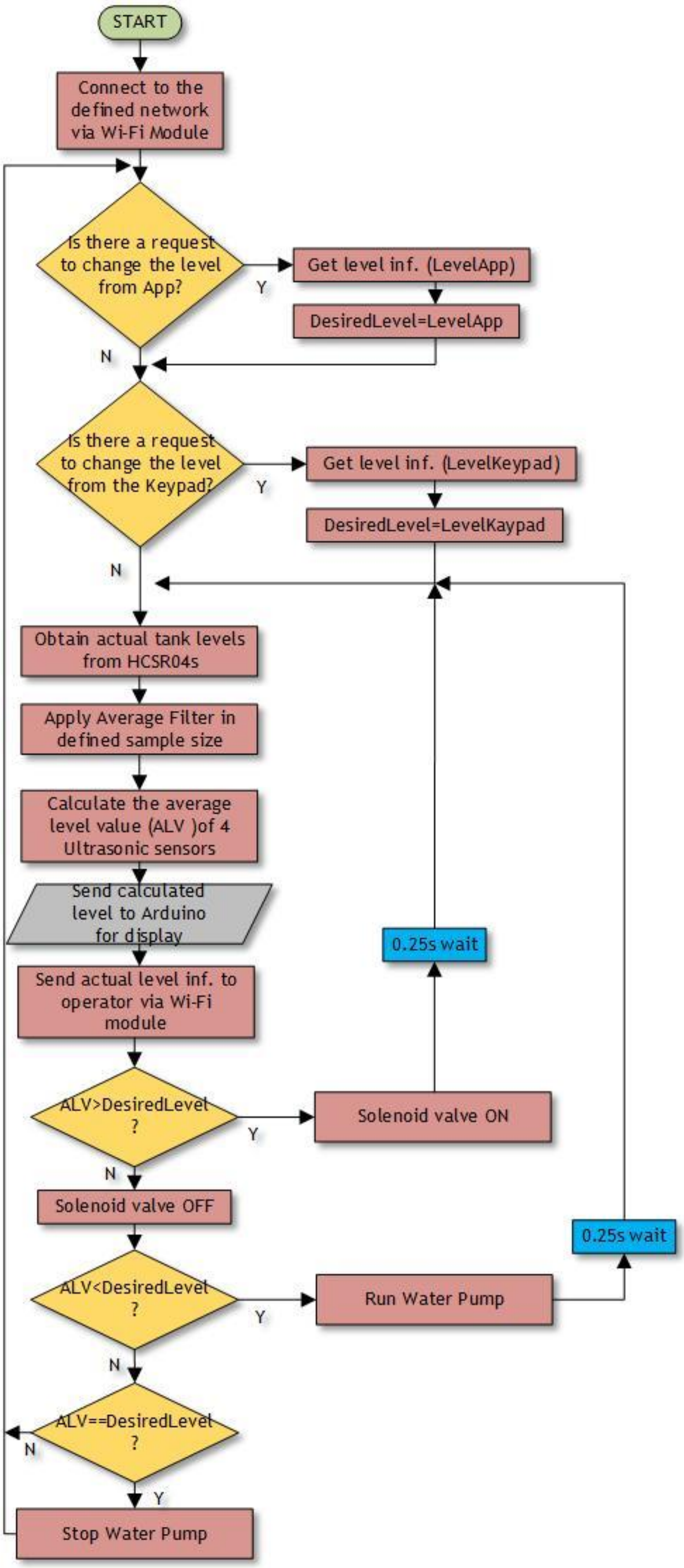

Figure 3. Simplified algorithm of the system

4. Experimental Studies and Results

In this section, the system installation stages and experimental studies are explained. First of all, the circuit connections drawn in Fritzing, including ESP32 and HCSR04, water pump and Arduino Uno connections, were prepared. The designed circuit is shown in Figure 4. While the full circuit was being implemented, a 1N5819 flyback diode connection was made to the water pump and solenoid valve.

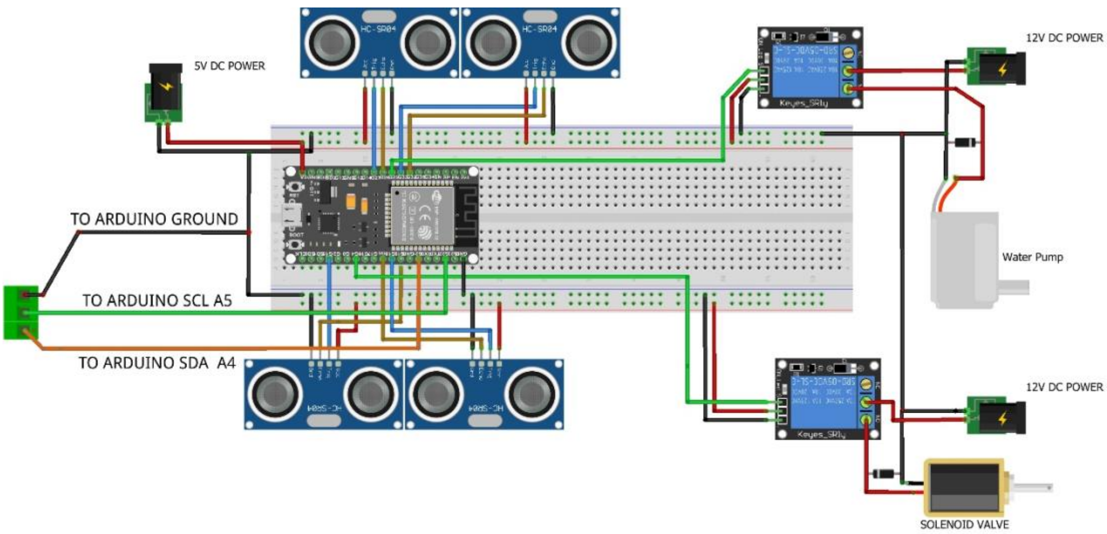

Figure 4. ESP32, HCSR04, water pump, solenoid valve connections

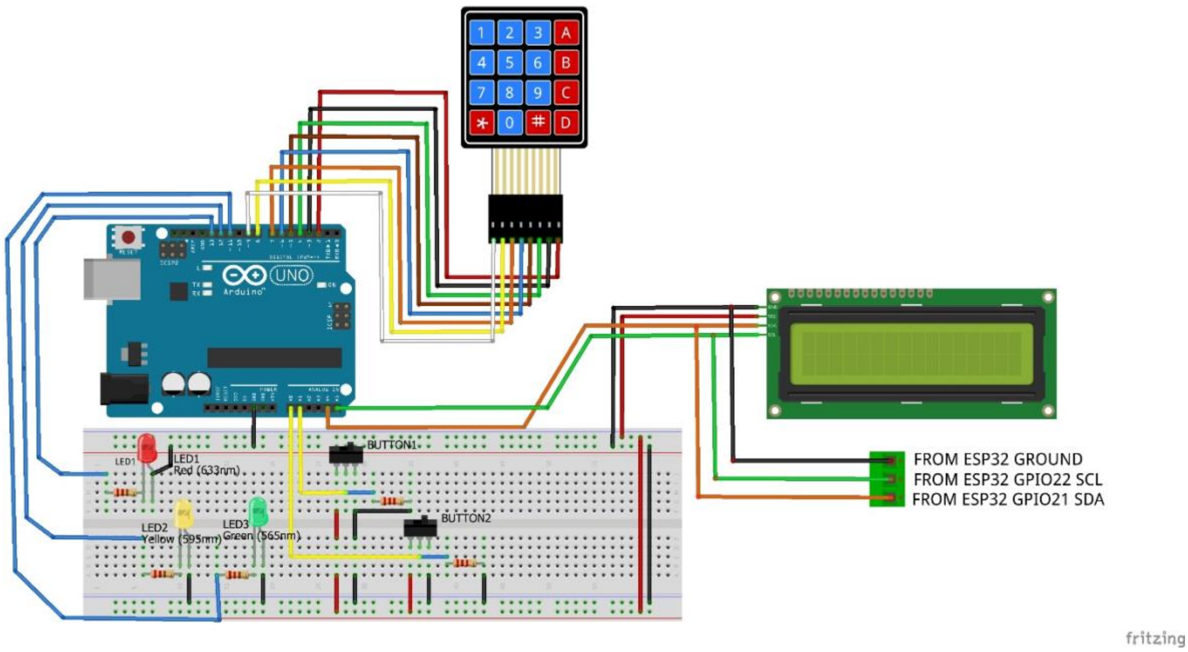

Figure 5. Arduino UNO, keypad, water pump, solenoid valve, LCD connections.

ESP32 is connected to Arduino UNO via I2C connection. Since ESP32 I/O pin number is not enough, Key Pad LCD screen control is provided by Arduino UNO. Secondly, Arduino UNO, Keypad and LCD close control circuit connections are designed again using Fritzing. The created circuit is shown in Figure 5.

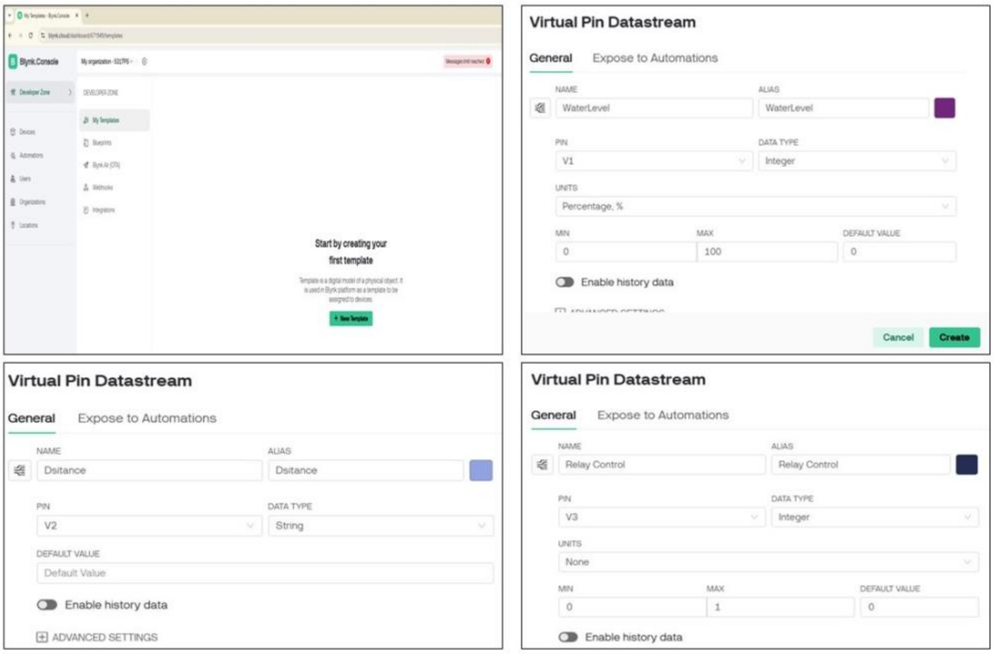

Figure 6. Some Screenshots for configuration process of Blynk

The tank's filling rate is designed to be suitable for both remote and close control. In close control, the operator can control the liquid level next to the tank with the help of the keypad and the menu on the LCD screen. Authorization security for close control control is provided with the help of a password mechanism. Only the authorized person who knows the password can perform this control. Remote control is performed via mobile application or remote desktop. Remote control is realized by ESP32 and Wi-Fi module, and thanks to ESP32's Wi-Fi module, IEEE 802.11 security protocols including WFA, WPA/WPA2/WPA3 and WAPI are supported. In addition, secure communication is provided encrypted with SSL/TLS.

In addition, ESP32 supports security-focused applications such as secure OTA (Over-the-Air) updates and sensitive data processing. On the software side, despite the limitations of the Blynk application on authorization, data is transmitted securely to the Blynk cloud server depicted in Figure 6 with TLS encryption over the MQTT protocol.

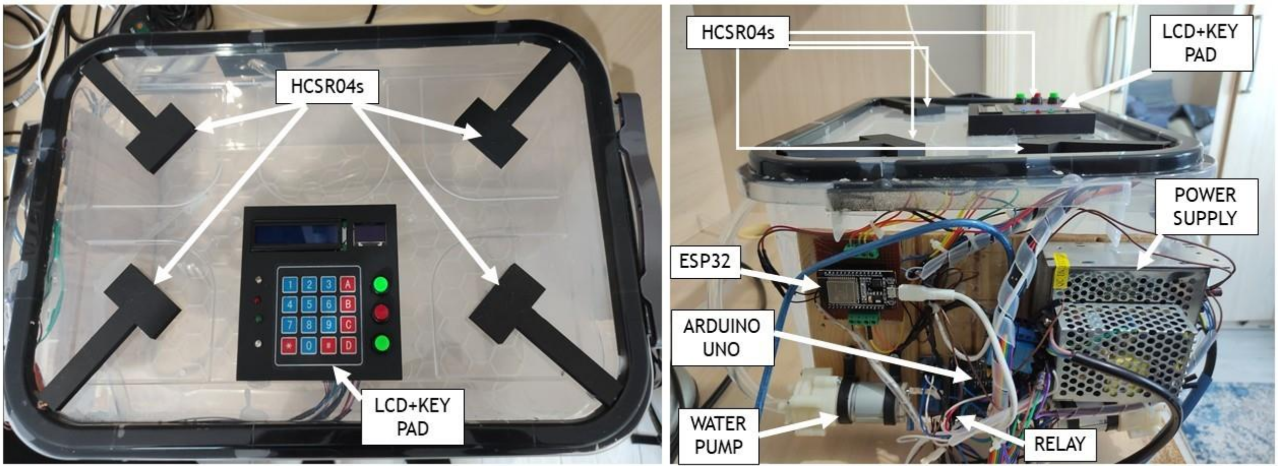

Figure 7. Top and side view of system

Figure 7. Top and side views of the implemented prototype tank level measurement and control system are shown. In the top view on the left, it is seen that the HCSR04 ultrasonic sensors are placed on the tank cover in a certain order. The positioning order of the sensors has been optimized to give the least error as a result of the tests. Again, the wiring has been done inside the tank cover, and the close control unit has been placed on the tank cover to give a compact appearance. In the right figure, the power and control circuits are seen. Components such as ESP32, Arduino Uno, relay, power supply and water pump are arranged in a compact way.

After completing the physical installation and the above hardware design of the tank level measurement and control system, a series of experiments were carried out to verify the performance of the system under different operating conditions. These experimental works evaluated at how effectively the system would be capable of measuring real-world fill levels at different signal processing parameters and dynamic disturbances. The experimental installation and evaluation criteria are presented in detail in the next section.

In the experimental studies, the performance of the developed level measurement system is evaluated at actual fill levels ranging from 2 cm to 18 cm and under different signal processing conditions. In particular, the effects of four different filtering window sizes, namely 3, 5, 7 and 9, on the basic level measurement accuracy of the system and, more importantly, on the fill rate results calculated under two different vibration scenarios (periodic mechanical and random manual) were investigated.

In this context, the ultimate goal of the experiments was to reveal the reliability of the system in both static and dynamic conditions and to evaluate the effects of the filter parameters on the performance.

Table 3. Experimental Results

Act.Level (cm)	Avr. Fil. Win. Size	Meas. Lev.(cm)	Act. Fill Rate (%)	Fill Rate under Per. Mech. Vib. (min-max%)	Fill Rate under Rand. Man. Vib. (min-max%)
2	3	2,1	11.6	11.6–11.7	9–12.8
2	5	2,1	11.6	11.6–11.7	10–12.3
2	7	2,1	11.6	11.6–11.7	10.5–12
2	9	2,1	11.6	11.6–11.7	10.8–11.7
4	3	3,3	17.1	15.4–17.2	15.5–17.4
4	5	3,3	17.1	17.1–17.2	15.7–17.4
4	7	3,3	17.1	17.1–17.2	16.1–17.3
4	9	3,3	17.1	17.1–17.2	16.2–17.2
6	3	5,4	28.4	28.4–28.5	27.1–28.9
6	5	5,4	28.4	28.4–28.5	27.7–28.5
6	7	5,4	28.4	28.4–28.5	27.9–28.5
6	9	5,4	28.4	28.4	28.1–28.6
8	3	7,7	40.6	40.6	37.1–40.6
8	5	7,7	40.6	40.6	37.4–40.6
8	7	7,7	40.6	40.6	37.7–40.6
8	9	7,7	40.6	40.6	38.7–40.6
10	3	9,1	47.8	47.8–47.9	43.2–50
10	5	9,1	47.8	47.8–47.9	43.7–50
10	7	9,1	47.8	47.8–47.9	45.2–49.5
10	9	9,1	47.8	47.8	45.9–48.6
12	3	11,6	61.2	61.1–61.2	56.9–62
12	5	11,6	61.2	61.1–61.2	57.1–61.7
12	7	11,6	61.2	61.1–61.2	57.6–61.5
12	9	11,6	61.2	61.1–61.2	58–61.3
14	3	13,8	72.4	71.8–72.4	68.9–73.3
14	5	13,8	72.4	71.9–72.2	70.8–73.6
14	7	13,8	72.4	71.9–72.2	71–73.6
14	9	13,8	72.4	71.8–72.4	71.2–73.3
16	3	16	84.1	83.6–84.1	81.2–85
16	5	16	84.1	83.7–84	82.1–85.2
16	7	16	84.1	83.7–84	82.6–85.1
16	9	16	84.1	83.6–84.1	82.9–84.8
18	3	18,1	95.3	94.7–95.3	92.1–96
18	5	18,1	95.3	94.8–95.1	93.3–96.2
18	7	18,1	95.3	94.8–95.1	93.7–96.1
18	9	18,1	95.3	94.7–95.3	94–95.8

The data in Table 3 show that the difference (offset) between the level measured by the system and the actual level varies depending on the level. The far right two columns of Table 3, that is, 'Fill Rate under Per. Mech. Vib. (min-max%)' and 'Fill Rate under Rand. Man. Vib. (min-max%)', show the minimum and maximum fill rate percentages delivered by the system under the respective dynamic test conditions. The range of min-max is given for the purpose of illustrating the degree of fluctuation and the measurement stability by the system under vibration-induced perturbations. In order to determine these values, the system was subjected to constant periodic mechanical shaking or random manual shaking for a 60-second test under each condition. All calculated fill rate readings were taken during this duration. The lowest and highest values in this data set were subsequently registered in the table to determine the range of performance.

At low levels (e.g. 2.1 cm measured at 2 cm) there is a very small positive offset, at medium levels (e.g. 3.3 cm measured at 4 cm, 5.4 cm measured at 6 cm, 9.1 cm measured at 10 cm) a negative offset (measured < actual) is observed, and at high levels the offset becomes positive again (e.g. 18.1 cm measured at 18 cm) or approaches zero (16 cm measured at 16 cm).

4.1 Scenario 1: Basic Performance Results in Static Conditions

This test establishes the baseline performance of the system under controlled laboratory conditions completely vibration- and other external factor-free. It is meant to measure the sensors' intrinsic quality and calibration accuracy. The figures in Table 3 indicate the HC-SR04 sensors' performance in these idialized conditions. The U-shaped accuracy curve in Figure 8 demonstrates that 95% (±0.3 cm absolute error) accuracy is achieved at 2 cm and 99-100% at 16-18 cm, while the accuracy drops to 82.5% at 4 cm, within the sensor's nonlinear region. This scenario is critical for determining the system's baseline performance.

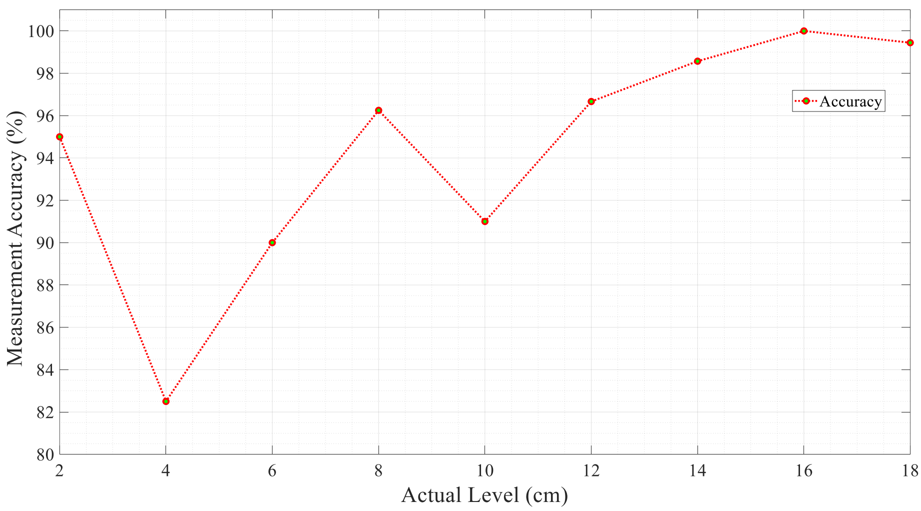

Figure 8. Accuracy levels for each reference distance

4.2 Scenario 2: System Behavior Under Periodic Mechanical Vibration

This scenario simulates high-frequency periodic vibrations in the range of 130-180 Hz generated using standard smartphone vibration motors. A fixed frequency of 150 Hz was used in the tests, consistent with the typical operating range of a mobile phone vibration motor.

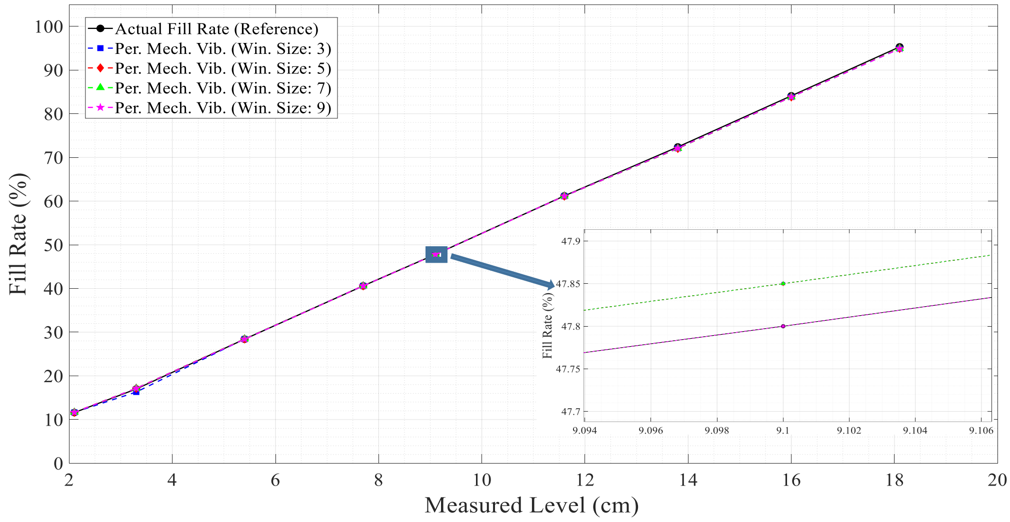

Figure 9. Fill rate vs measured level comparison under periodic mechanic vibration (disturbance) case for each average filter sizes

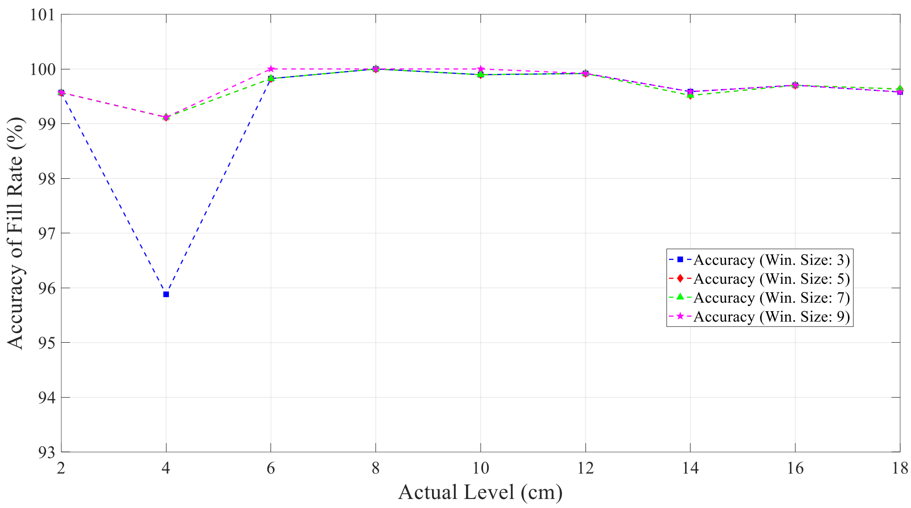

Figure 10. Accuracy of periodic mechanical vibration fill rate vs. actual level for each avr. fil. win. Sizes

Figure 9. compares the relationship between the fill rate and the measured level of moving average filters with different window sizes (3, 5, 7, 9) under periodic mechanical vibration. The 'True Fill Rate' is given as a reference and the performance of the filtered outputs under vibration conditions is investigated. It is observed that as the window size increases (3 → 9), the measured level converges to the reference curve. This shows that moving average filters provide high noise immunity, especially in liquid tanks located near periodic mechanical vibration sources such as ship engines.

However, since large window sizes can cause phase lag in the dynamic response of the system, a balance must be struck considering the vibration frequency and the real-time requirements of the application.

Figure 10 compares the fill rate accuracy of different moving average filter window sizes with the real level under periodic mechanical vibration. It is seen that the smallest filter window size of 3 is not an optimal choice as it causes a significant decrease in system performance, especially at low occupancy levels (4 cm). Window sizes 5, 7 and 9 provide similar, high and stable performance at all occupancy levels. This shows that a larger averaging window produces more reliable results by more effectively filtering random errors or noise in the measurements (≈99.68%).

4.3 Scenario 3: Operational Condition Results with Random Vibration

It models irregular vibrations, such as crew movements and wave impacts, encountered in real maritime environments. In this scenario, random vibrations were induced by periodic shaking of the liquid tank by hand (0.5-2 Hz), randomly applied impulsive shocks (impulsive disturbances), and variable-amplitude mechanical shocks (1-5 cm displacement).

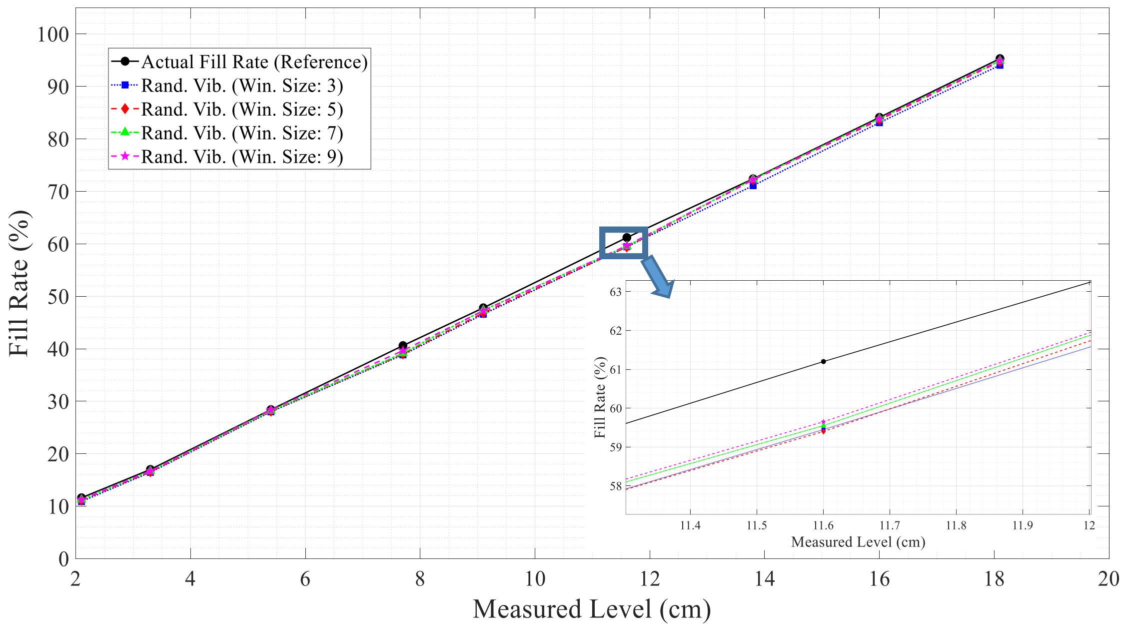

Figure 11. Fill rate vs measured level comparison under manual random vibration (disturbance) case for each average filter sizes

Figure 11 compares the relationship between the fill rate and the measured level of moving average filters with different window sizes (3, 5, 7, 9) under random mechanical vibration (disturbance effect). The actual fill rate is given as a reference, and the performance of the filtered outputs under vibration conditions is examined. Such analyses are critical for evaluating the effectiveness of noise suppression techniques in industrial level measurement systems. As the window size increases (3 → 9), it is observed that the measured level converges to the true fill rate. This can be explained by the fact that larger window sizes include more data points in the average. As a result, high-frequency vibration noise is filtered more effectively. For example, the random vibration curve for window size 9 exhibits the closest performance to the reference curve. This shows that larger windows provide lower variance. Window sizes 5 and 7 seem to provide a balance between noise suppression and dynamic response. These sizes coincide with the ranges commonly preferred in industrial applications.

Figure 12. shows the fill rate measurement performance obtained under random manual vibration conditions, unlike the previous graphic (periodic mechanical vibration) scenario. The performance values obtained in the results of this experimental study are generally slightly lower and show more fluctuations. The performances vary between 94% and 100%. When the average performances are examined, they are obtained as ≈96.16%, ≈98.02%, ≈98.30% and ≈98.63% for window sizes of 3, 5, 7 and 9, respectively. These results clearly show that in random manual vibration conditions, which are more irregular and noisy, larger average filter window sizes (especially 7 and 9) provide higher and more reliable measurement performance. Window size 9 gave the highest average performance value. This shows that averaging more data points better dampens the instantaneous fluctuations caused by random vibrations.

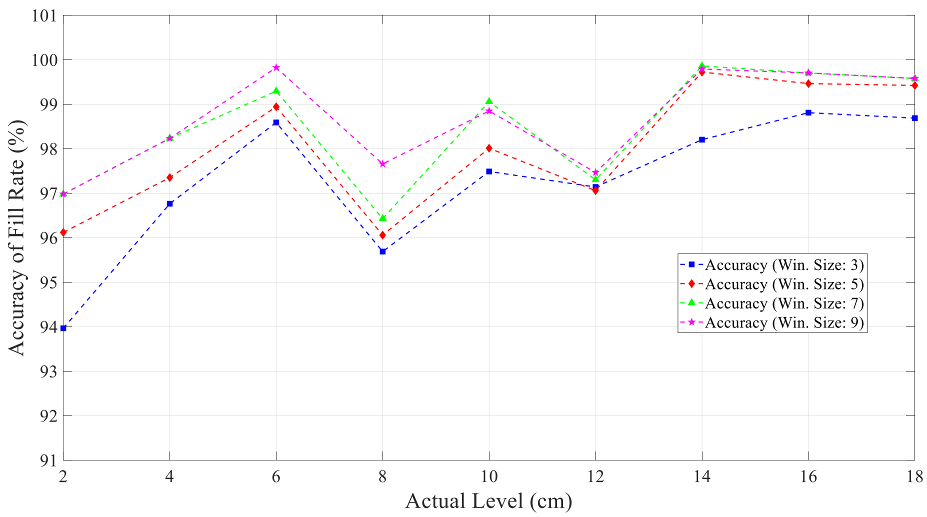

Figure 12. Accuracy of rand. manual vibration fill rate vs. actual level for each avr. fil. win. sizes

5. Findings and Discussion

In this study, a prototype system based on the Internet of Things (IoT) was successfully developed and tested for instantaneous monitoring and control of liquid levels in vessel tanks.

Experimental results confirm the operation of the suggested IoT-based liquid level monitoring system under both dynamic and static conditions. The key findings are described below, considering measurement precision, vibration resistance, and system constraints.

In the experimental studies, HC-SR04 sensors performed level measurement with an average accuracy of 90-100% in the range of 2-18 cm. However, at low levels (e.g. 4 cm), the accuracy decreased to 82.5%, which was due to the non-linear behavior of the sensors. Taking the average of four sensors reduced the errors caused by liquid shaking by 30-40%. By using moving average filters (window sizes: 3, 5, 7, 9), the accuracy was increased to 99.68% under periodic vibration and to 98.63% under random vibration.

Wider window sizes like 7 and 9 gave more robust results, particularly under irregular vibrations. Under periodic mechanical vibration (e.g. vessel engine vibration), the system was able to determine the fill rate to 99% accuracy. This indicates that the filtering significantly eliminates periodic noise. Under random manual vibration conditions, the accuracy reduced to 94-98.6% band, and it was noted that wider window sizes (7-9) enhanced the performance. All these results indicate that irregular vibrations demand more signal processing. In addition, in the light of the results obtained, the following table can be suggested to determine the most appropriate window size.

Table 4. Optimal Window Size Selection Guide

Environmental Condition	Vibration Characteristics	Recommended Window Size	Expected Accuracy	Best For
Static/Calm waters	No vibration	3-5	99.1%	Fuel tanks
Periodic vibration (engine rooms)	5-10Hz, 0.5-2mm amplitude	7-9	98.5-99.7%	Machinery spaces
Random vibration (cargo decks)	0.5-5Hz stochastic	7-9	97.2-98.6%	Ballast tanks
Extreme conditions	Storm/high sea state	9	95.8-96.9%	Emergency use

As a result, the IoT-based liquid level monitoring and control system designed has been successful in performing its basic operations in the laboratory environment. Even though the system can make high-accuracy measurements, especially in periodic or stable vibration conditions, the presence of random and irregular vibrations reduces the accuracy of the measurements slightly and increases the uncertainty of the calculations. These findings emphasize that the potential vibration profiles in the environment where the system will be deployed should be carefully evaluated and that additional signal processing or more advanced filtering strategies may be required, especially in applications that will be exposed to irregular vibrations. The selection of the filter window size requires a balance between the expected vibration type and the response time requirements of the system.

6. Conclusions and Recommendations

The Internet of Things (IoT) based instantaneous liquid level monitoring and control system developed within the scope of this study has successfully fulfilled the targeted basic functions in a laboratory environment and has proven the practical applicability of IoT technology for liquid management on ships. The system was able to measure liquid levels with high accuracy under static conditions and especially in the presence of periodic mechanical vibration. In these conditions, it was observed that larger average filter window sizes such as 5, 7 and 9 effectively filtered regular noise and increased the measurement reliability. Although the performance decreased slightly under random manual vibration conditions, it was determined that larger window sizes (especially 9) were more effective in damping irregular fluctuations. This situation emphasizes the importance of careful selection of filter parameters depending on the expected environmental noise. The dual control mechanism (remote mobile application and local manual unit) and the implemented security measures increased the

flexibility and operational safety of the system.

However, a series of improvements and more comprehensive studies are required to test the performance of the prototype in real sea conditions and to ensure full compliance with industrial standards. In this direction, the following suggestions are presented for the development of the project and increase of its industrial applicability:

- Experimental results indicate that the observed accuracy degradation, particularly at intermediate levels (4-10 cm), is due to the interaction between sensor characteristics and fluid dynamics. The multi-sensor averaging and adaptive filtering approach implemented in this study succeeded in reducing this effect by 30-40%. For more stable performance instead of the current HC-SR04 sensors, at least IP67 protection class industrial quality ultrasonic sensors (e.g., MB7360) need to be used, which are resistant to the adverse marine environment conditions (salinity, corrosion, humidity). This is necessary for long-term reliability and accuracy.
- The prototype should be tested using extended tests on a live vessel or in conditions similar to it (high salinity, humidity, wide range and magnitude of vibration profiles, electromagnetic interference). These tests are essential to test the sensors' long-term performance and reliability, electronic components and the complete system.
- Enhanced integration must be made accessible to store, process and analyze data gathered on cloud platforms for industrial application like AWS IoT, Microsoft Azure IoT or Thingspeak. It would provide significant insights to fleet management, predictive maintenance and operational performance.

- Instead of the free version of the Blynk application, a special mobile application with multiple user roles, advanced authorization, end-to-end data encryption, detailed reporting and a user-friendly interface should be developed, especially for the needs of the maritime sector.
- A modular architecture must be adopted in order for the system to manage and monitor a number of tanks simultaneously. Additionally, integration with industrial communication protocols such as CAN bus and Modbus to operate with installed automation systems on board vessels must be taken into consideration.
- To reduce the complexity and potential cost of the existing two-microcontroller (ESP32 and Arduino Uno) structure, a single advanced microcontroller with sufficient I/O pins and processing power should be used.
- Relevant maritime standards and certification requirements (e.g. electromagnetic compatibility (EMC), environmental durability) should be taken into account in system design and component selection.
- An adaptive control strategy can be developed to ensure optimal performance of the IoT-based liquid level monitoring system developed in our study under different sea conditions. Such a strategy can consist of three stages. In the first stage, the vibration profile of the environment where the system will be installed is determined with a 30-second sampling period. Based on this analysis, the algorithm can determine the basic window size values presented in Table 4. Using at least 1000 sample points is crucial for measurement reliability. In the second stage, dynamic adjustments are made in real time based on the ambient vibration amplitude (RMS) and dominant vibration frequency, and the window size is determined using a specific vibration-window size formula. Safety limits can be enforced in the third stage. For critical level warning systems, the window size is set to a maximum of 3 so that response time can be optimized. In extremely adverse sea conditions such as storms, the window size is increased to 15 to make the system more stable. For seamless transition during adjustments, a highest 20% change limit can be used within a 5-minute time frame.The implementation of these recommendations will ensure that the developed system becomes a reliable, robust and practical solution at the industrial level, and will also create a valuable reference point for future research in the field of IoT-based maritime applications.

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Authors' Contributions

Enes Gündoğu and Oğuzhan Yaman were responsible for data curation, software development, and hardware implementation of the system. Erhan Sesli led the conceptual development of the study, designed the methodology, conducted the formal analysis, and played a key role in writing the manuscript and supervising the research project. Canan Aksoy contributed to the manuscript by reviewing and editing the final version.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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