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Real-Time In Situ Water Quality Monitoring: Experimental Validation using Unmanned Surface Vehicle (USV)

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ABSTRACT

Water is a precious resource and one of the most essential components for life. It is imperative to ensure that water is safe for human consumption and ecosystem sustainability. However, the rapid urbanization and industrial activities have significantly impacted water resources, necessitating an efficient monitoring system. Traditional methods of water quality monitoring are labor-intensive, time-consuming, and provide limited coverage and outdated information. This study presents a real-time water quality monitoring system for in situ water sampling that continuously assesses key parameters such as pH, temperature, and electrical conductivity, through a web-based user interface for data storage, visualization, future analysis as well as remote and multi-user collaboration. The system utilizes unmanned surface vehicle (USV) prototype, embedded locomotion system, sensors for pH, temperature, and electrical conductivity with an ESP32 microcontroller. The sensors collect data at several sampling points and different depth from water surface, which is wirelessly transmitted to Web-based application. The data is then processed, stored, and visualized in real-time, enabling continuous monitoring. Data collected over a specified period showed significant variations in water quality parameters, which were effectively captured and analyzed in real-time. The result demonstrates that there are distinct trends for each parameter at 10 cm and 20 cm depth under the water surface. Deeper waters (20 cm depth) tend to have more stable conditions, as they are less directly impacted by external factors. This experimental validation at Universiti Teknologi Malaysia (UTM) lake provides insights into the environmental dynamics affecting water quality at different depths as well as the usability and autonomous navigation of our USV platform.

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1. Introduction

Monitoring the quality of water in natural bodies such as streams, rivers, and lakes is critical for environmental protection, public health, and regulatory compliance. Traditional water quality monitoring methods involve manual sampling and laboratory analysis, which are labour-intensive, time-consuming, and provide only periodic data. The advent of the Internet of Things (IoT) has revolutionized water quality monitoring by enabling continuous, automated, and real-time data collection. Traditional methods for monitoring water quality typically involve manual sampling, static monitoring station and subsequent laboratory analysis. These methods, although accurate, come with several limitations. Manual sampling requires significant human resources and is time-consuming, as laboratory analyses can take days or even weeks to yield results. Additionally, these methods often provide data only for specific locations and times, resulting in limited coverage and potential gaps in the data as discussed by several authors [1-4].

Jo *et al.,* [5] has highlighted the implementation of real-time water quality monitoring, which includes the turbidity, temperature and pH sensor for water quality measurement. Their study demonstrates the sensor's ability to provide accurate, real-time data critical for monitoring water quality at retention pond. Ridolfi *et al.,* [6] and Castellini *et al.,* [7] further emphasize the role of sensors in indicating water quality and pollution levels, showcasing advanced sensors effectiveness in providing comprehensive, continuous monitoring. These studies underscore the importance of reliable sensors in maintaining water quality and protecting environmental and public health. Applications of unmanned surface vehicles (USVs) can be found in the environmental sector, specifically in the monitoring of water quality and bathymetry surveys. The self-driving capability of USV is another significant feature, enabling it to navigate autonomously and perform tasks such as water sampling and measuring water quality parameters which is not reachable or dangerous. Moreover, the ability to perform environmental monitoring tasks autonomously reduces the need for manual intervention, which can be both time-consuming and labour-intensive. On the other hand, the collected data can be used to understand the physical characteristics of the water body and identify potential areas of concern [8-11].

Recognizing the shortcomings of existing approaches, there arises a critical necessity for an innovative solution capable of transcending the constraints inherent in static monitoring systems and manual methods as supported by other research works [12-14]. Traditionally, the collection of water samples and laboratory analysis is hazardous to the health of workers and often leads to inaccurate and inconsistent data. Furthermore, it is challenging to keep track of the water quality over time and identify any trends that may require attention. Therefore, this study introduces a cutting-edge technology, the "Robotic Marine for Water Quality Monitoring." This innovative system utilizes an unmanned surface vehicle (USV) equipped with several sensors for autonomous navigation as well as in situ water sampling and real-time water quality monitoring system. The objective of this study is to develop a web-based water quality monitoring system with the embedded sensors and IoT devices to measure and store the water parameter data such as electrical conductivity (EC), temperature and pH.

Wang *et al.*, [21] demonstrated an IoT-based water quality monitoring system using Wemos, a portable integrated chip come with ESP8266. Their system provided real-time data through a web interface, integrated with TDS, pH, and temperature sensors that enabling users to monitor water quality remotely. Their system allowed for efficient data collection and transmission, showcasing its effectiveness in such applications. Similarly, Sunarya *et al.,* [22] conducted a study on smart farming, where the ESP32 was used to monitor water quality in irrigation systems. The microcontroller was connected to various sensors to measure parameters such as pH, TDS and temperature. Data collected by the ESP32 was transmitted to a central server via Wi-Fi, and the results were analyzed to optimize irrigation practices. However, all the above-mentioned methods typically provide data limited to specific depths beneath the water surface, leading to restricted coverage and potential data gaps. This highlights the need for more comprehensive water sampling across varying depths. Collecting samples from multiple levels provides a detailed understanding of the vertical water profile, ensuring that depth-related variations in water quality are accurately captured.

2. Methodology

2.1 Web-based Water Quality Monitoring System

The block diagram of the Water Quality Monitoring System as in Figure 1 shows an integration of temperature, pH, and TDS sensors connected to an ESP32 WiFi & Bluetooth MCU. The data collected by these sensors is transmitted to application platform known as Ubidots Cloud Services for real-time monitoring via web-based or mobile phone interfaces. The schematic diagram in Figure 2 illustrates the control signals from the cloud services manage the operation of three water pumps, each powered by a dedicated power supply, to regulate water quality parameters effectively. Based on the sensor data and user inputs, control signals are sent back to the ESP32, which then uses relays to control the operation of three water pumps. Relays act as switches that allow the low-power control signals from the ESP32 to manage the higher-power operation of the pumps. Pump 1 is responsible for sucking water from a depth of 10 cm, Pump 2 from a depth of 20 cm, and Pump 3 is used to expel water out of the water tank. All three pumps are controlled by users via the Ubidots platform and are powered by a 12V power supply.

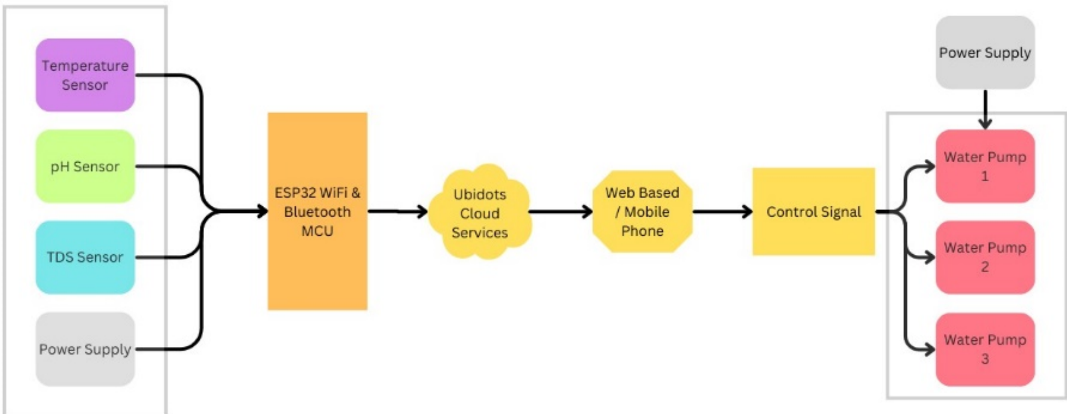


Fig. 1. Overview of components for real-time in situ water quality monitoring system

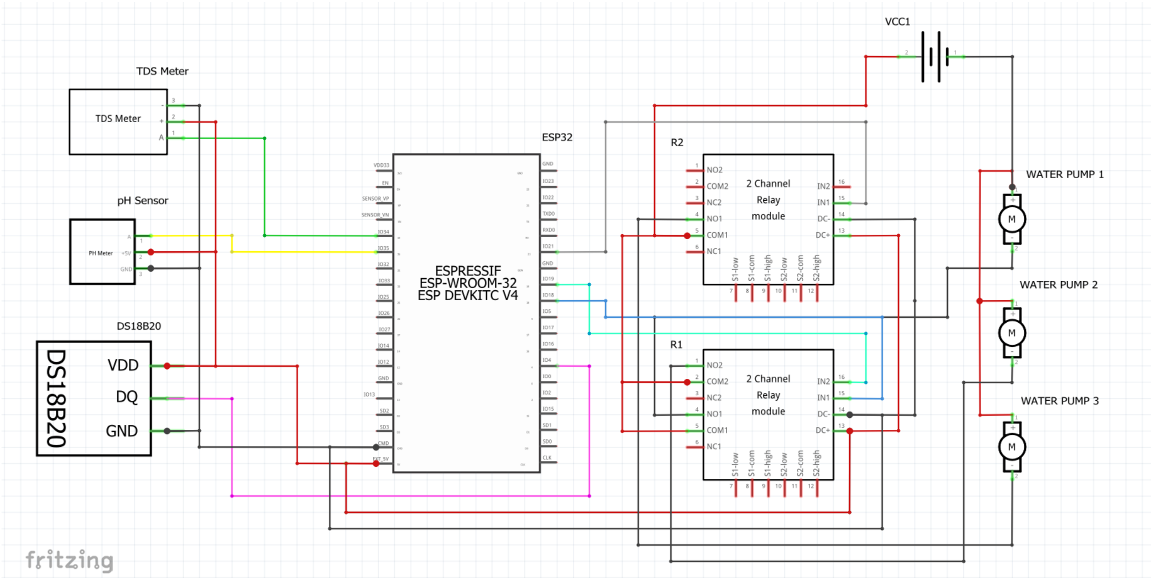


Fig. 2. Schematic diagram for in-situ water quality monitoring system

At the heart of the system is the ESP32 MCU, equipped with WiFi and Bluetooth capabilities. This microcontroller is pivotal in receiving data from the sensors, processing it, and then transmitting the information to a cloud-based platform. The ESP32 is chosen for its robust processing power, low energy consumption, and seamless connectivity options, making it ideal for real-time monitoring applications. Once the ESP32 processes the sensor data, it sends this information to Ubidots Cloud Services using its built-in WiFi functionality. Meanwhile, Figure 3 shows the actual sensors used which are TDS Sensor SEN0244 (left), DS18B20 Temperature Sensor (middle), and DFRobot pH Sensor (right). These sensors provide accurate, real-time data essential for monitoring and managing water quality effectively.

Fig. 3. TDS Sensor SEN0244, DS18B20, DF Robot pH Sensor respectively

The specifications for these sensors as outlined in Table 1 are used in measuring water quality parameters. The DFRobot pH Sensor has an accuracy of ±0.1 pH and a range of 0-14 pH, suitable for determining the acidity or alkalinity of water. The DS18B20 Temperature Sensor has an accuracy of ±0.5°C and can measure temperatures from -55°C to +125°C, crucial for assessing thermal conditions in water bodies. The TDS Sensor SEN0244 measures electrical conductivity (EC) with an accuracy of ±2% over a range of 0-10,000 µS/cm, indicating the concentration of dissolved salts and minerals in the water.

Table 1
Sensor specifications for measuring water quality parameters

Sensor	Parameter Measured	Accuracy	Range
DFRobot pH Sensor	pH	±0.1 pH	0-14 pH
DS18B20	Temperature	±0.5 °C	-55 to ±125 °C
TDS Sensor SEN0244	Electrical Conductivity, EC	±2%	0-10000 µS/cm

As for the water pump, particularly the R385 model as shown in Figure 4, has been widely adopted in various IoT-based water quality monitoring projects due to its efficiency and compatibility with microcontroller systems. This model is noted for its robust performance, capable of drawing water samples at a flow rate of approximately 240 liters per hour, making it suitable for continuous monitoring setups.

Fig. 4. 12V DC Water Pump R385

2.2 Calibration of Sensors

To calibrate each sensor and validate the data in the Web-Enabled In Situ Water Quality Monitoring System, a systematic methodology was employed for each sensor: pH, temperature, and TDS (Total Dissolved Solids). The pH sensor calibration involved the use of two standard buffer solutions with known pH values of 4 and 7 as shown in Figure 5. The sensor probe was immersed in each solution, and the corresponding voltage readings were recorded. These values were then used to establish a linear relationship between the voltage output and the pH value. This relationship allowed for accurate interpolation of pH values across the range from pH 1 to pH 14. The sensor was recalibrated periodically to ensure sustained accuracy. The temperature sensor (DS18B20) calibration was validated through benchmark testing rather than traditional calibration. The sensor was tested in controlled environments such as an ice bath to ensure a 0°C reading and in boiling water for a 100°C reading. These tests confirmed the sensor's accuracy as per the manufacturer's specifications, which claim an accuracy of ±0.5°C over a range from -55°C to +125°C. For the TDS sensor (SEN0244), calibration involved two conductivity standard solutions with known values of 84 µS/cm and 1413 µS/cm as shown in Figure 5. The sensor was submerged in each solution, and the voltage readings were recorded. These readings established the input range for the mapf function, which maps the raw sensor readings to the corresponding conductivity values. This function adjusted the sensor’s output from voltage to EC (Electrical Conductivity) values, ensuring accurate measurement of dissolved solids in the water.

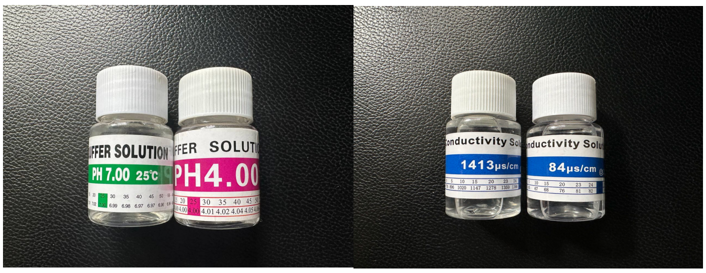


Fig. 5. Buffer Solution for pH and EC for validating the data

2.3 Development of Web Application

The Ubidots web application provides an intuitive interface for real-time monitoring and management of water quality data. As shown in Figure 6, the dashboard displays key metrics such as pH levels, conductivity, and temperature, alongside control options for water pumps at various depths. The interface's design includes straightforward push-button controls for each pump, labelled with their specific functions and depths. This intuitive setup ensures that users can easily start or stop each pump with a single click, facilitating seamless operation and real-time adjustments as needed. The visual feedback provided by the interface such as the on/off status indicators, enhances the user experience by providing clear and immediate information about the pumps' operational states. This integration of technology not only streamlines the water monitoring process but also enhances the accuracy and reliability of the collected data.

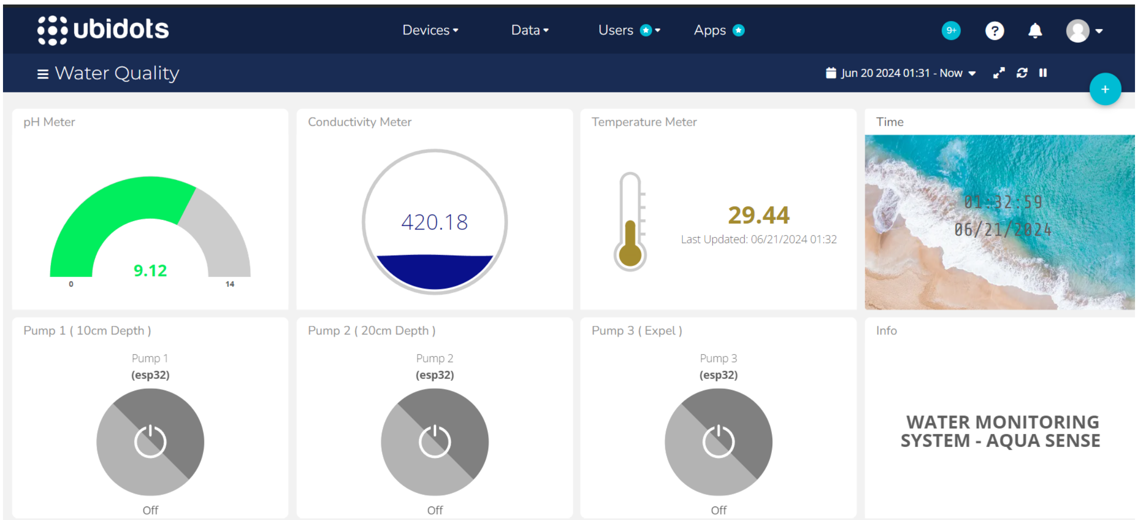


Fig. 6. Web-based user interface to monitor water data collection in real-time

The platform also supports data logging, remote control, and customizable alerts, facilitating efficient water quality management and timely response to any detected anomalies. Additionally, the platform allows users to easily record and track past data, which can be accessed through the history feature. This historical data can be saved as CSV files, enabling users to collect, analyze, and export data for further analysis or reporting purposes. This functionality ensures comprehensive data management and facilitates efficient monitoring and decision-making processes.

3. Results

3.1 Fabrication of Water Tank (3D Printing)

3D printing process of the water tank using an ELEGOO 3D printer with JAMG HE PLA+ filament (1.75 mm diameter), highlighting a balanced 20% infill and support structure for stability. The digital preparation in ELEGOO Cura software involves setting parameters like layer height and print speed for optimal results, with an estimated print time of 17 hours and 43 minutes and a filament weight of 303 grams. The tank is equipped with two inlet tubes, which are used by two separate water pumps to draw water from different depths, specifically at 10 cm and 20 cm. This allows for a more comprehensive sampling of water from varying levels. Additionally, there is one outlet tube connected to a water pump that expels the water after testing. One of the notable features of the tank is its sloped base. This design ensures that water can be efficiently expelled through the outlet tube, preventing any residue from remaining in the tank and facilitating thorough cleaning and maintenance. Figure 7 illustrates this design, showcasing the careful consideration given to the functionality and efficiency of the water tank. Additionally, Figure 8 and 9 presents the final product, post-processing, ready for water quality monitoring applications, demonstrating a smooth, fully functional water tank.

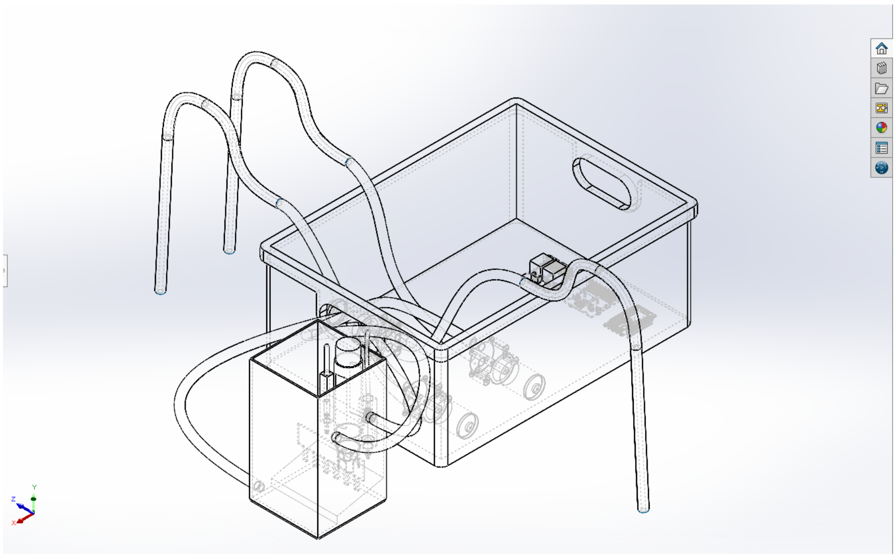


Fig. 7. Design of water tank in wireframe mode (SOLIDWORKS)

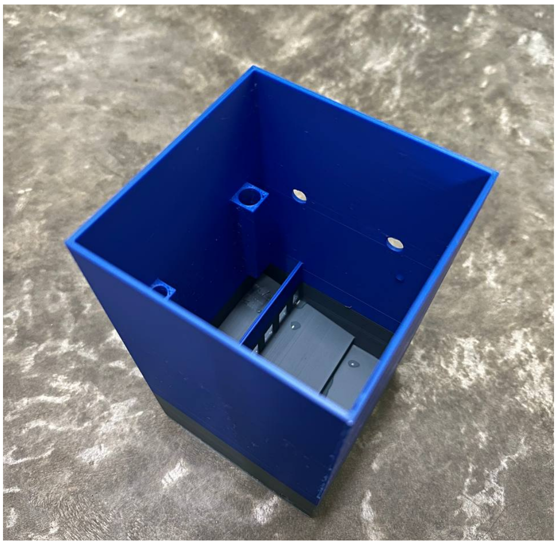


Fig. 8. Final product of water tank

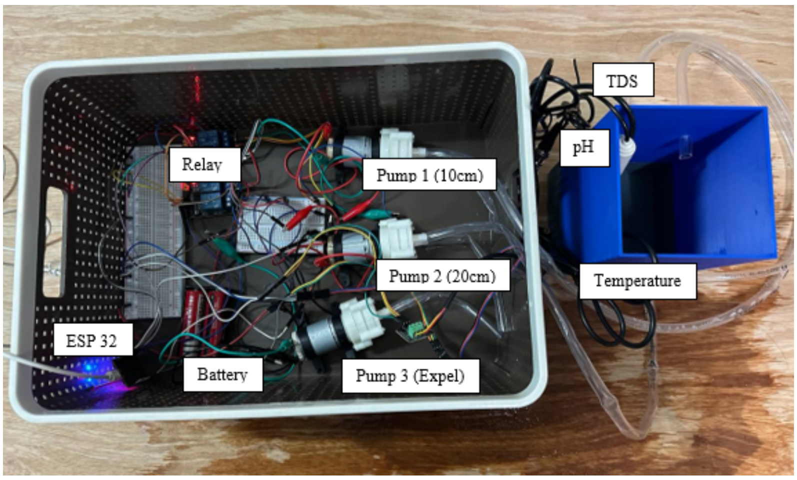


Fig. 9. Full setup of prototype for water quality monitoring system

3.2 Analysis on Water Covered at Probe Sensor

The analysis of the temperature probe, as depicted in Figures 10, demonstrates how submersion affects temperature data collection. In Scenario 1 (left), the partially submerged probe with a 20 mm gap shows temperature fluctuations between 27.03°C and 27.37°C over 30 seconds due to exposure to air, leading to less consistent readings. The probes which are not fully submerged can be influenced by ambient air temperature, resulting in inaccurate readings. Conversely, Scenario 2 (right) shows that a fully submerged probe maintains stable readings around 27.50°C, indicating higher accuracy and consistency. Since partial submersion does not affect pH and TDS probes, this analysis focuses on the temperature probe. Full submersion is crucial for accurate data collection, highlighting the importance of maintaining an appropriate water level to ensure probe accuracy and system reliability.

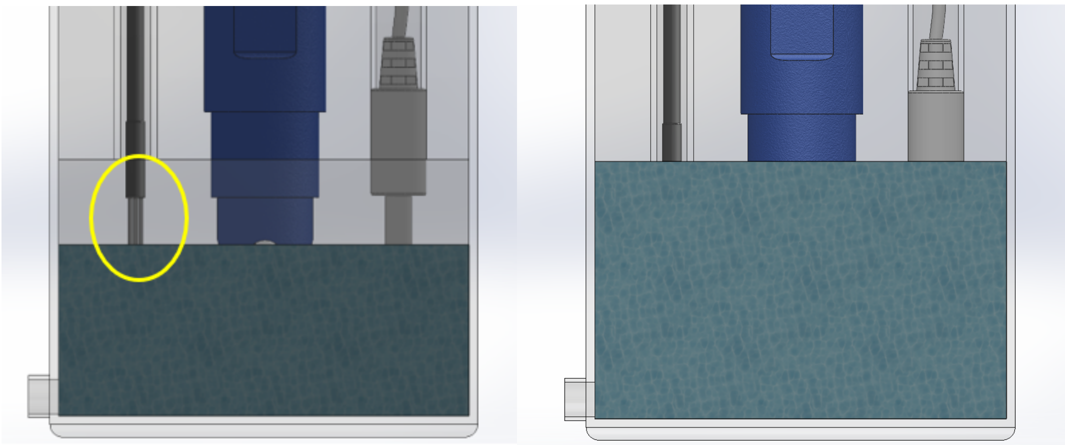


Fig. 10. Partially (left) & Fully (right) Submerged Temperature Probe

Table 2 and Figure 11 compare the temperature readings of partially submerged and fully submerged probes over 30 seconds. The partially submerged probe, with a 20 mm gap, shows temperature variations between 27.03°C and 27.37°C, while the fully submerged probe maintains stable readings around 27.50°C. This demonstrates that the fully submerged probe provides more consistent and accurate temperature measurements compared to the partially submerged probe, which is affected by minor air temperature fluctuations.

Table 2
Comparison of temperature readings for partially and fully submerged probes

Time (seconds)	Partially Submerged Temperature (°C)	Fully Submerged Temperature (°C)
0	27.03	27.39
5	27.20	27.50
10	27.15	27.50
15	27.37	27.50
20	27.22	27.50
25	27.09	27.45
30	27.30	27.50

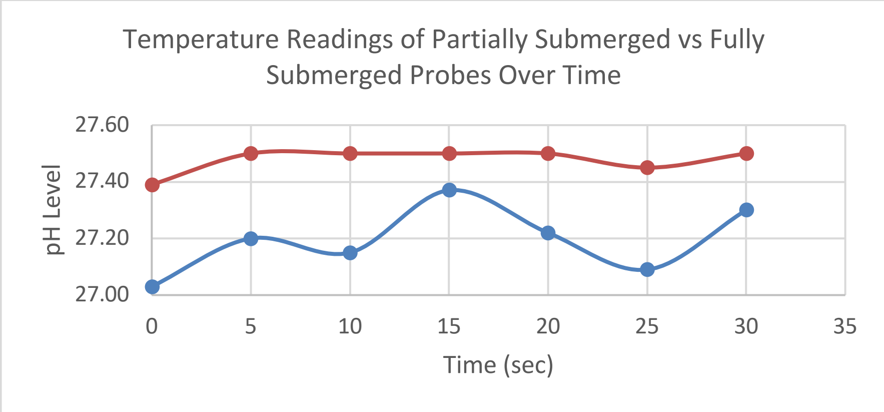


Fig. 11. Temperature readings of Partially Submerged (Blue) vs Fully Submerged (Orange) probes

3.3 Location of Water Sampling

The final phase of testing took place at the UTM lake, where we aimed to validate the in situ water quality monitoring system using our developed autonomous navigation system of USV in real-world conditions. Figure 12 illustrates two sampling points navigated by our USV shown in Figure 13. At each location, samples were taken from two different depths, 10 cm and 20 cm, using 12V water pumps. The samples were analyzed for key water quality parameters, including pH, temperature, and electrical conductivity (EC). This crucial test encompassed the entire system's functionality, ensuring the boat could navigate to a single destination point, pause for a pre-defined time, and return to the home location just as it would in an actual deployment scenario. This test was very important in demonstrating the boat's capability to autonomously navigate within a larger and more complex water body, where external environmental factors could influence its performance. Additionally, the analysis focused on three key parameters: pH, temperature, and electrical conductivity (EC). PH measures the acidity or alkalinity of the water, temperature influences chemical reactions and biological processes, and EC indicates the concentration of dissolved salts and minerals. Collecting samples from different depths provides a detailed understanding of the water's vertical profile, capturing any variations in water quality. This comprehensive dataset helps analyze environmental conditions and their impact on aquatic life and overall water quality [15-16]. The data will be processed and analyzed to identify trends, detect anomalies, and inform water management decisions.

Fig. 12. Home and destination points describing the water sampling and in situ quality monitoring

Fig. 13. Unmanned Surface Vehicle (USV) prototype used for in situ water quality monitoring

3.3.1 Average Data for two different sampling locations

Average data for pH, temperature (Temp), and electrical conductivity (EC) measured at 10 cm and 20 cm depths over a 60-minute period, with readings taken at 5-minute intervals. The pH levels at 10 cm depth range from 7.61 to 7.84, while at 20 cm depth, they range from 7.54 to 7.69, indicating slight acidity variations between the depths. Temperature measurements at 10 cm depth vary from 27.34°C to 28.08°C, and at 20 cm depth, they range from 27.34°C to 27.37°C, showing minimal differences between the two depths. Electrical conductivity (EC) at 10 cm depth fluctuates from 110.2 µS/cm to 126.2 µS/cm, and at 20 cm depth, it ranges from 109.7 µS/cm to 118.8 µS/cm, with more noticeable variations observed in EC values.

The data presented in the Figure 14, 15 and 16 for pH, temperature, and electrical conductivity (EC) over a 60-minute period at depths of 10 cm and 20 cm show distinct trends for each parameter. In Figure 14, the pH levels at 10 cm depth fluctuate between 7.61 and 7.84, with notable variations indicating a dynamic environment possibly influenced by surface interactions, such as photosynthetic activity or organic matter decomposition, as supported by Zainurin *et al.,* [17]. In contrast, the pH levels at 20 cm depth are more stable, ranging from 7.54 to 7.69, reflecting less influence from surface activities and a more buffered environment. Figure 15 shows the temperature trends have a similar pattern, with temperatures at 10 cm depth ranging from 27.34°C to 28.08°C, exhibiting more pronounced fluctuations due to direct exposure to atmospheric conditions and solar radiation. This is consistent with findings from Salam Abdul [18] and Prapti *et al.*, [19] who noted that surface water temperatures are more susceptible to external temperature changes. At 20 cm depth, the temperature remains relatively stable, between 27.34°C and 27.37°C, indicating minimal influence from external temperature variations and a more consistent thermal environment.

For electrical conductivity (EC), the 10 cm depth shows a range from 110.2 µS/cm to 126.2 µS/cm, with noticeable fluctuations as illustrated in Figure 16. This variability can be attributed to surface runoff, which introduces varying amounts of dissolved solids and minerals. In comparison, EC at 20 cm depth ranges from 109.7 µS/cm to 118.8 µS/cm and exhibits less fluctuation, indicating a more stable ionic composition at this depth, likely due to reduced influence from surface runoff and mixing.

These trends align with research indicating that surface waters are more susceptible to environmental changes and human activities, leading to greater variability in water quality parameters. Deeper level of water depth tend to have more stable conditions, as they are less directly impacted by external factors. This analysis provides insights into the environmental dynamics affecting water quality at different depths and underscores the importance of continuous monitoring to capture these variations [20].

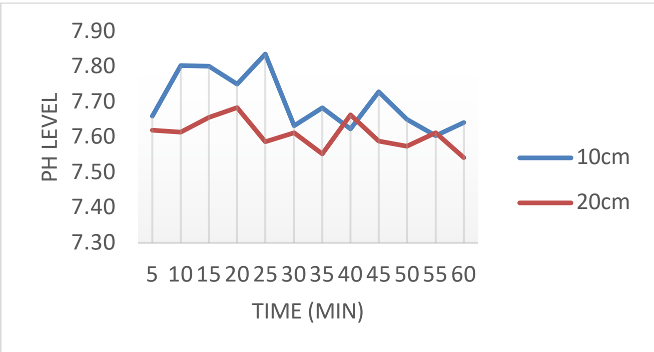


Fig. 14. PH level at two different water depth 10cm and 20cm

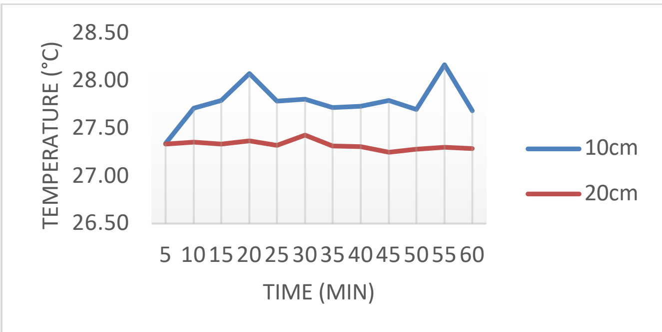


Fig. 15. Temperature readings at two different water depth 10cm and 20cm

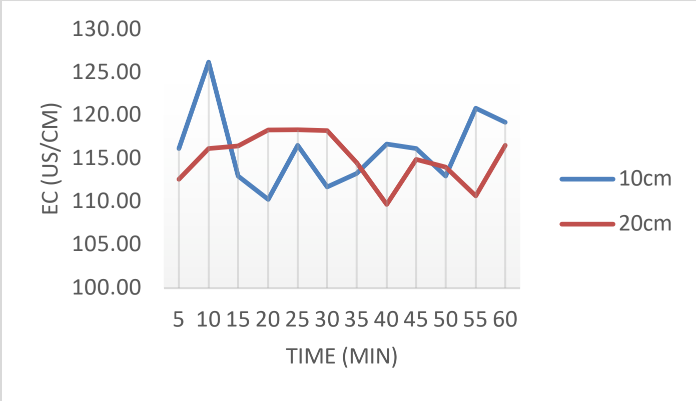
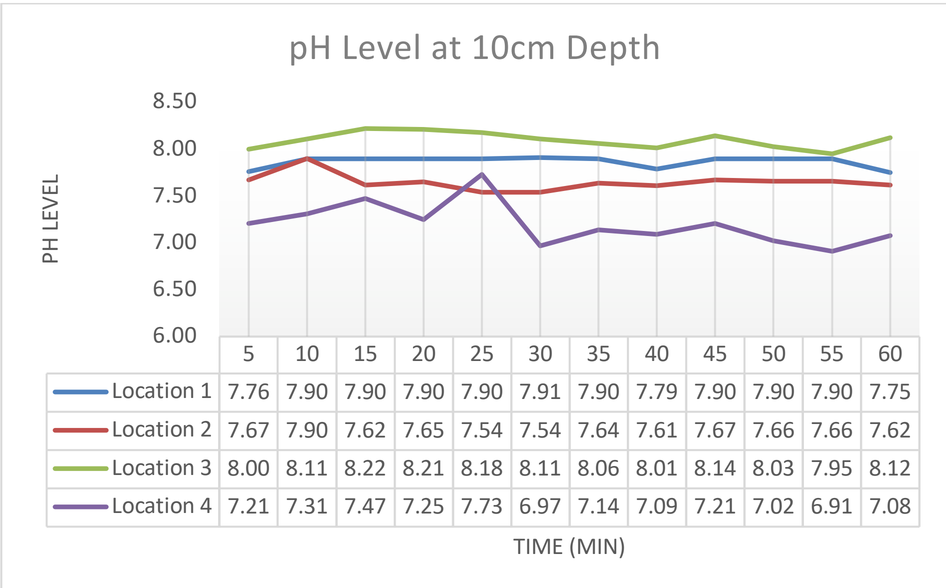


Fig. 16. Comparison of electrical conductivity (EC) at water depth 10cm and 20cm

In this study, the water quality data collected at UTM lake also was compared with the water quality data at Temoh Lake, Perak. For example, Figure 17 and 18 show the pH data for both lakes at 10cm as well as 20cm below the water surface respectively. Overall, the pH levels at each location and depth remain relatively stable over the hour, with only minor fluctuations. Locations 1 and 2 at Temoh Lake describes higher and more consistent pH levels compared to Locations 3 and 4 at UTM Lake, where Location 4 exhibits the lowest and most variable pH levels. The consistency of pH levels at both 10 cm and 20 cm depths indicates minimal vertical pH stratification. Considering the optimal pH range for most freshwater aquatic life is between 6.5 and 9.0, all measured pH levels fall within this range, suggesting that the aquatic environment in both lakes is suitable for sustaining aquatic life. The minor fluctuations observed do not indicate any immediate concern for water quality.



	5	10	15	20	25	30	35	40	45	50	55	60
Location 1	7.76	7.90	7.90	7.90	7.90	7.91	7.90	7.79	7.90	7.90	7.90	7.75
Location 2	7.67	7.90	7.62	7.65	7.54	7.54	7.64	7.61	7.67	7.66	7.66	7.62
Location 3	8.00	8.11	8.22	8.21	8.18	8.11	8.06	8.01	8.14	8.03	7.95	8.12
Location 4	7.21	7.31	7.47	7.25	7.73	6.97	7.14	7.09	7.21	7.02	6.91	7.08

Fig. 17. pH Level at 10cm depth

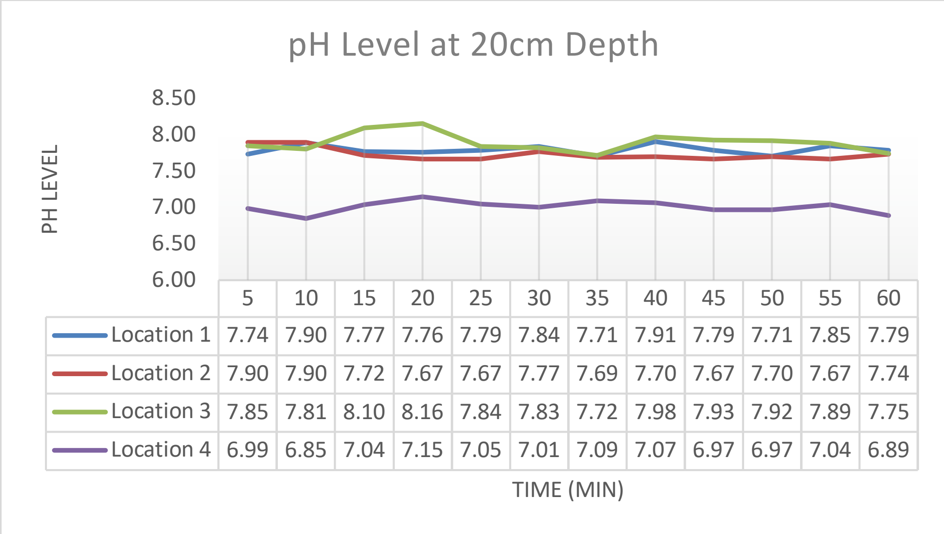


Fig. 18. pH Level at 20cm depth

4. Conclusions

For the objective of monitoring water quality around UTM Lake in real-time using an IoT system, these findings highlight the importance of integrating in situ water sampling at several depth under the water surface. This ensures regular, time-sensitive data collection to capture dynamic variations in water quality, enabling more comprehensive and accurate assessments. By continuously monitoring and recording these parameters, we can detect potential issues early, maintain the health of aquatic ecosystems, and make informed decisions for effective water resource management. The experimental data show that pH levels are stable and within the optimal range for freshwater species, underwater temperatures reflect variations with higher readings in the evening and cooler temperatures at night, meanwhile EC values are consistent with acceptable limits for freshwater bodies.

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