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Development of Unmanned Aerial Vehicle and IoT System for Water Quality Monitoring and Water Sampling

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Abstract

Regular monitoring of water quality has become increasingly important due to rising pollution levels, which seriously harm human health, aquatic ecosystems, and decrease the performance of water treatment plants. Nowadays, monitoring water quality can be accomplished by traditional methods (e.g., taking samples and analysing them in a laboratory) and by water quality monitoring stations. These methods can only detect pollution as it occurs and spreads to the monitored areas. It is essential to develop a system capable of detecting pollution events early, allowing authorities to respond in a timely manner. Unmanned Aerial Vehicle (UAV) has emerged as an alternative approach for water monitoring for a large scale of reservoirs. The reason lies in the fact that, UAV equipped with remote sensing techniques and sensor nodes can be flexibly deployed to different places to collect water quality data in both spatial and temporal variations and are suitable for early detection of water pollution before it widely spreads. This paper proposed an efficient UAV platform integrated with IoT system to enhance efficacy of water quality monitoring and water sampling. In particular, an effective IoT framework combining LoRa and 4G communication networks improves data acquisition and facilitates control over long distances. Meanwhile, the UAV, with a high payload capacity, ensures the collection of sufficient water samples for laboratory analysis. The water quality data is also transmitted to a web server for storage, real-time visualization, and analysis. To demonstrate the efficacy of the UAV-assisted water quality monitoring system, it is applied to measure pH, total suspended solids (TSS), and temperature parameters, and to collect water samples from an area of the lake. The data collected by the UAV system is compared with the results obtained from laboratory analysis of water samples, revealing that the developed UAV system, while capable of being deployed flexibly over large areas, provides relatively accurate results and significantly reduces labor costs associated with water sampling.

Keywords: Unmanned aerial vehicle, water quality monitoring, water sampling.

1. Introduction

Regular monitoring of water quality has become increasingly critical and is currently facing numerous challenges due to the escalation of water pollution, which poses serious risks to human health, degrades aquatic ecosystems, and reduces the operational performance of water treatment plants [1]. Water pollution arises from various factors, including climate change, industrial contaminants (e.g., microplastics, fertilizers, and pesticides), and the emergence of newly identified pollutants (emerging contaminants, ECs). These ECs, which remain insufficiently investigated and poorly understood, have raised substantial environmental and public health concerns [2]. To ensure the safety of drinking water and to protect landfills, soils, and groundwater resources, it is essential not only to monitor water quality but also to predict trends in water quality variations, thereby enabling early detection of pollution events and enhancing the protection of surface water resources. Recently, water quality monitoring technologies have been developed to assess water quality more accurately with less labour and cost [3]. The traditional method, e.g., sampling water and transporting it to the lab for analysis of water quality, yields accurate water quality parameters, however, it lacks the real-time fashion Moreover, sampling of water usually requires much efforts of labours, and in some areas, human cannot approach for water sampling due to the appearance of harmful events such as algal bloom, natural disasters and emergencies. Along with the traditional water sampling, water quality monitoring stations have been installed at reservoirs for monitoring of water quality. However, only a limited number of stations are placed since the cost of investment for these stations is high. The satellite technologies were also developed for water quality monitoring in the mid-1900s. Such the technique utilizes the mathematical prediction model and the image processing tools for interpreting water quality parameters. The application of satellite is suitable for monitoring the variational trend of water quality for large areas. However, the satellite follows certain orbits and yields low resolution image data [4], which significantly affects the process of image interpretation.

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Unmanned aerial vehicles (UAVs) have recently emerged as an alternative method with flexibility and low cost for water quality monitoring. Deploying of UAV assisted in situ measurements and sample collection may also help to decrease the sample collection duration and cost, and at the same time increase the temporal and spatial features of water quality. About the capacity of investigation, UAVs have been proven to be capable of monitoring water quality for areas covering from several m2 to million km2 [4]. The work in [5] has evaluated a UAV assisted autonomous water sampling for a 1.1ha pond (at LaMaster Pond at Clemson University, Clemson SC) to assess the diurnal changes of dissolved oxygen (DO), electrical conductivity (EC), pH, temperature, and Chloride parameters. For water sampling, a custom-made thief-style water sampling mechanism is mounted on the UAV. The observed results are compared with the manual water sampling method, demonstrating that the differences between the two sampling methods for DO, EC, pH, and temperature are 3.6%, 2.3%, 0.76%, and 0.03%, respectively. Koparan *et al.* [6] designed a hexa-copter with sensor nodes and cartridges to conduct in situ measurements of EC, pH, temperature, and DO, and collect water samples. The UAV can tolerate a payload of 6.4 kg when taking off. For data acquisition, sensor nodes from Atlas Scientific were integrated with a microcontroller ATmega 2560, and the I2C protocol was used for reading sensor data. Data was then recorded on a secure digital SD card. Water samples are taken at depths of 0.5 and 3.0 m by cartridges with a capacity of 130 mL for each one. The developed UAV system has been shown to be practical and reliable for water quality assessment. In [7], the author proposed the UAS-based hardware platform with the DJI Matrice 600 (M600) for water quality monitoring. The water sampling container attached on UAS can sample up to 1000 ml, while Atlas sensor nodes are used to measure EC, pH, and DO parameters. These data are transmitted and displayed in the ThingSpeak Cloud web services using a 4G network. A similar approach is accomplished in [8], where the collected data is directly sent to the server by using a 4G network. However, the network connection sometimes poses a shortcoming as the UAV system is deployed in rural areas or in places where 3G/4G network coverage is limited, and in this situation, collected water quality data may be lost. LoRa has been extensively used in river water monitoring due to its long-range communication capacity for data acquisition and control [9]. However, it has not been applied to UAV data acquisition so far. About water sampling, the work in [10] has indicated that most of the UAV, having designed so far for water monitoring, is just capable of sampling with low volume of water (i.e., up to 330 mL), which may be insufficient in quantity for analysis water quality in laboratory, and that application of high payload UAV for higher volume of water sampling is urgent for the task of water sampling.

The application of UAVs for water quality monitoring and sampling is important, as it reduces labor costs and enhances water quality management. Most existing UAV systems collect data from onboard sensors and either store them on memory cards or transmit them to web servers using 3G/4G networks. However, deploying UAVs in remote areas far from residential regions presents challenges, as 3G/4G network coverage in such locations may be unstable and is often associated with high data transmission latency. Moreover, many existing systems lack a supervision mode for system operation, preventing operators from determining whether the UAV has executed assigned tasks correctly or whether the collected data contains outliers.

To address these issues, this paper proposes an efficient UAV system design capable of high-volume water sampling, thereby ensuring that the collected samples are sufficient and suitable for laboratory analysis. In addition, the combined use of LoRa and 3G/4G networks enables bidirectional communication between the UAV and the ground control station. Through LoRa-based communication, commands and responses are supervised at the ground control station, allowing operators to monitor the investigation process in real time and decide whether measurement and sampling tasks should be repeated. The data are stored on the ground control station computer, while the 3G/4G network is used to transmit data from the ground control station to the web server. The developed UAV can be flexibly deployed to collect data across both spatial and temporal dimensions. Consequently, it can be applied for early detection and warning of pollution events before they become widespread. Experimental results demonstrate that the proposed system ensures reliable UAV operation in water quality monitoring and sampling applications.

2. The UAV Platform and IoT System for Water Quality Monitoring and Sampling

2.1. The UAV System

The complete system of UAV assisted for water monitoring, as shown in Fig. 1, is developed with following components: (i) The UAV frame is integrated with Phantom 3 flight controller; (ii) The datalogger is designed and attached on the UAV; (iii) Sensor node float and water sampling boxes, which can be controlled to enter under the water surface for measurement and water sampling; (iv) The ground control station; (v) Server and Website for data storage, visualization and analysis. The frame and motor of the UAV are chosen to be capable of carrying out a total payload of 20 kg (consisting of battery, sensor nodes, datalogger, and water sampling) with a flight time of approximately 15 minutes under full load.

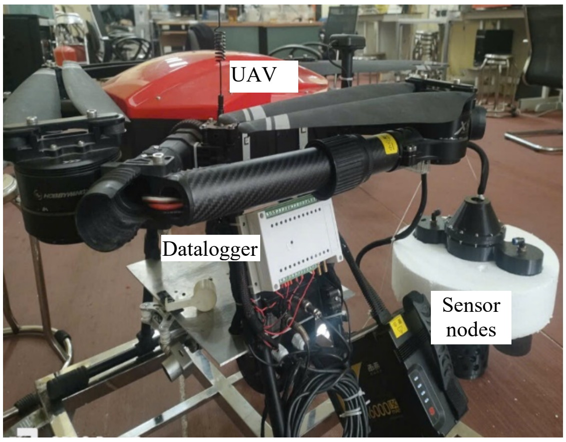

Fig. 1. The developed UAV system assisted water quality monitoring and sampling

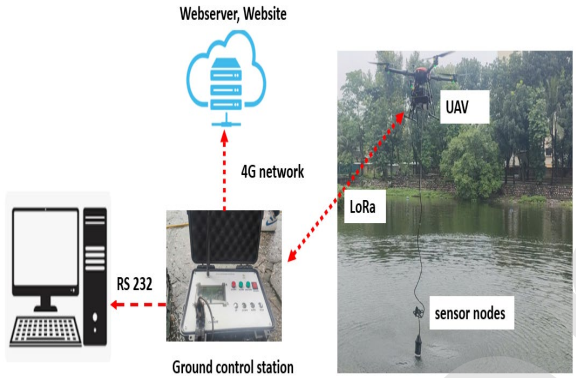

Fig. 2. The hierarchical IoT system based on the UAV platform

The hierarchical IoT system based on the UAV platform for water monitoring is illustrated in Fig. 2. The system comprises three layers: the perception layer, the transmission layer, and the application layer. The perception layer includes the datalogger, water quality sensor nodes, a submersible pump, and a motor. The transmission layer is accomplished through the ground control station, which is responsible for data processing and data transfer between the perception and application layers. In particular, in order to get data from the perception layer, the LoRa network is used, while data exchange between the transmission layer and the application one is carried out through a 4G network. The advantage of this scheme lies in the fact that, with the data transmission speed of LoRa, we can access the data at the ground control station while the UAV is performing its tasks and can modify the task as needed.

The application layer is designed to interface with the transmission layer to support data storage, visualization, and analysis. In the proposed system, sensor data and UAV location information are stored on a web server, and a web-based interface is developed to visualize the collected data.

2.2. Design of the Datalogger and the Ground Control Station

2.2.1. Design of the datalogger

The datalogger is designed and installed on the UAV as a component of the perception layer. It is developed to fulfil several essential functions, including acquiring data from sensor nodes, receiving control commands from the ground control station, transmitting data to the ground station, controlling the pump for water sampling, and operating the motor responsible for either lifting up and lowering down the sensor node float. The schematic design for the datalogger is illustrated in Fig. 3. The fabricated prototype is shown in Fig. 4, where a central microprocessor of STM32F047VET6 is integrated with peripheral modules such as LoRa, 4G SIM, UART–RS485, GPS, digital input/output buffers, and relay modules. Among these peripherals, LoRa is used for long-distance data communication, while the UART–RS485 module, comprising the MAX485 and 74HC14 ICs, facilitates data acquisition from sensor nodes via the Modbus RTU protocol. The digital output modules, which incorporate optocouplers and relays, are designed to drive the pump and motor. In addition, using the Modbus RTU protocol, the datalogger can communicate with up to 32 sensors. The datalogger will send water quality data and the UAV positioning data (including longitude and latitude) obtained from the NEO-M8 GPS module to the ground control station. Based on that, users can monitor the data at the ground control station during the time the UAV is investigating.

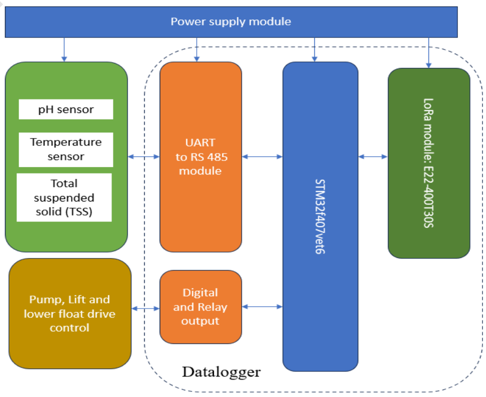

Fig. 3. The datalogger circuit design

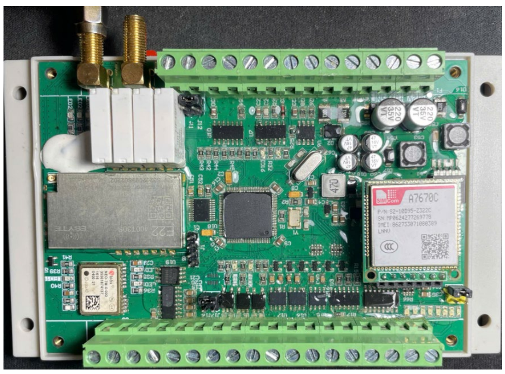

Fig. 4. The fabricated datalogger

2.2.2. Design of the ground control station

The ground control station in the transmission layer is designed to exchange data with the datalogger in the perception layer. The task of this station is to request sensor data from the datalogger, command the datalogger to switch on/off the pump for water sampling, and also command the datalogger to either lift up or lower down the sensor node float. Similar to the hardware of the datalogger, the hardware of the ground control station is designed with the central microcontroller of STM32F047VET6, which is designed to interface with the LoRa module (E22-400T30S), SIM4G module, RS232 module (for connecting to the computer), and an input digital module (for connecting to peripheral buttons). The ground control station is fabricated and arranged in a control box as shown in Fig. 5, and it can be connected to the computer through RS 232 port for direct monitoring of the data, commands, and states of the datalogger and UAV (i.e., percentage of battery), which is convenient for the operation of UAV. In addition, data collected from the ground control station will be automatically sent to the web server using the SIM4G module of Quectel eg800k.

Fig. 5. The ground control station box

2.2.3. Modbus RTU protocol for sensor node communication

The Modbus RTU protocol is used for communicating between the datalogger and sensor nodes for data exchange. The microcontroller is interfaced with the module UART to RS485 through its UART port, enabling communication of Modbus RTU. The strategy of reading data from sensor nodes is accomplished where the datalogger acts as the host (or master) and the sensor nodes act as slaves. The host and slaves operate on the principle of question and answer. In particular, the host requests measurement data from one of the sensors by transmitting a data frame containing the information about the destination sensor (ID) and the code function to the bus line. Only the sensor with a matched ID will receive such data frame, and it will answer the host by sending back a data frame containing its ID and the sensor measurement data contained in data bytes. As a result, in order to collect data from sensor nodes, requests from the host are sequentially sent to slaves. In this system, the data frame from the host (the datalogger) consists of 8 bytes (in accordant with the Modbus standard) in which the first one byte is for assigning slave address (ID sensor address), the second bye is for definition of function code, 4 bytes for data (depending type of sensor), and two bytes for CRC. These bytes, arranged in order in a frame, are continuously sent in accordance with Modbus RTU protocol. In the system, the pH sensor ID is assigned with an address of 0x01, while the addresses of temperature and TSS sensor (IDs) are 0x04 and 0x13, respectively. For example, the data frame of host for pH and temperature sensors sequentially are: 0x01| 0x03| 0x00| 0x00| 0x00| 0x06| 0xC5| 0xC8| and 0x04| 0x03| 0x00| 0x04| 0x00| 0x01| 0xC5| 0x9E. In principle of communication, the sensors (slaves) will respond to the host as received the data frame (from the host) by sending back a data frame with 7 bytes where the data of sensor measurement values are stored in data bytes. The data frame answered from sensor pH and temperature are in forms: 0x01| 0x03| 0x02| 0x02| 0x04| 0x01| 0x84 and 0x04| 0x03| 0x02| 0x03| 0x88| 0xB8| 0xD2. The data bytes (i.e., byte 3rd to byte 5th) in these forms are changed in accordance with different values of measurement.

2.2.4. LoRa network communication between the ground control station and UAV

LoRa network is used for communication between the ground control station and the UAV. The application of LoRa in urban environments may be cumbersome with interference and large obstacles. However, in the application of UAV for water quality monitoring for reservoirs, the environment over the water surface of reservoirs has almost no obstacles. For this reason, the application of LoRa technology for the UAV system is indeed suitable. In addition, many reservoirs that supply water to treatment plants are located in remote areas far from residential regions, where 3G/4G network coverage may be weak, making the use of LoRa particularly advantageous. The ground control station communicates with the UAV for control of measurement and water sampling. In addition, it also receives data from the UAV system and sends it to the web server. Although this communication process introduces additional latency, it is necessary to ensure reliable measurement and water sampling. Specifically, operators are able to monitor the collected data before transmission to the web server and can issue commands to repeat measurements if abnormal data are detected. The two LoRa modules (in the ground control station and the datalogger) are configured to operate in the function mode of fixed point transmission. According to this operation mode, each module is encoded by its address and channel, i.e., to transmit data from a sending module to one received module, its data frame must contain the address and channel of the receiving ones. The general data frame is designed with 19 bytes, in which the first 2 bytes are used for assigning the address and channel of the receiving module, respectively; one byte is used for defining the function code (the 3rd byte), and the 16 bytes are for the data field (i.e., for sensor data, UAV position, Battery information). The communication between two nodes is secured by using the confirmation mode. This means that as one module transmits data to one specified node. This node, as received data, will send back a "confirmation message" to the sending side. With such a communication mechanism, the sending module will know whether the command is received by the receiving module or not. The data frame of the datalogger and the ground control station has the same format of 19 bytes. Depending on the type of data transmission, the 3rd byte and data byte (the 4th byte to the 19th byte) may be different. The 3rd byte is defined as a function code for commanding actions that the received module (i.e., the datalogger) has to carry out. Moreover, the 3rd byte can be used for representing states of actions (success or failure) or classifying feedback data (i.e., sensor data or location of UAV; battery).

2.3. The Sensor Node Float and Pump System for Water Sampling

The sensor nodes are attached to the float system, which both protects the sensor and maintains them floating on the water surface. The float containing sensor nodes is designed as shown in Fig. 6 with three components. The first component is for holding sensor nodes, the second one is for protecting the sensor nodes, and the third one is for containing a pump for water sampling. All components are designed in 3D and fabricated. In this paper, three sensor nodes (RK500-2 for pH, RK500-01 for temperature, and RK500-20 for TSS), from Rika Electronic Tech Co., Ltd (https://www.rikasensor.com/), are chosen for water quality monitoring. For the pH sensor, the measurement range is from 0 to 14, while for temperature, it is from -50 °C to +100 °C, and 0 to 4000 mg/L for TSS.

Fig. 6. The sensor node float

These sensors support Modbus RTU protocol for data exchange with the datalogger. The pump for water sampling is selected as a kind of submersible one (JT500 model) with a pumping flow rate of 10L per minute. As the datalogger received a command for water sampling, it will switch the pump to the power, and the pump will operate to supply water for the water sampling box. Moreover, in order to lift up or lower down the sensor node float, the DC gearbox motor with parameters of 12 V and 155 rpm is used to drive the winding roller as seen in Fig. 7.

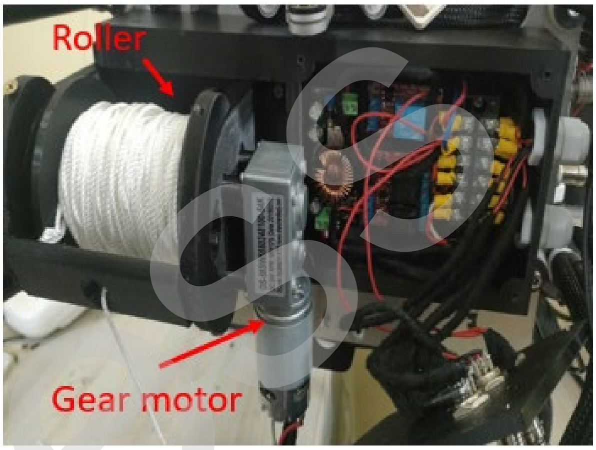

Fig. 7. Winding roller drive system

Several factors that affect measurement accuracy may arise during the measurement process, such as the duration for which sensor nodes remain in contact with the water environment. In the experiments, three industrial-grade sensor nodes are employed, namely pH, temperature, and total suspended solids (TSS) sensors. To ensure accurate measurements, these sensors are calibrated in the laboratory before UAV deployment. In addition, the sensors are securely mounted on a floating platform to prevent movement during the measurement process. Furthermore, when the UAV moves between different monitoring locations, the sensors require a sufficient stabilization period to provide reliable measurements.

2.4. The Algorithm for The Datalogger and The Ground Control Station

To ensure proper data transmission and control, the algorithm for the datalogger is illustrated as in Fig. 8. Specifically, the datalogger continuously listens for incoming commands from the ground control station. Upon receiving a lifting or lowering command, it acknowledges the command and activates the motor to adjust the position of the sensor node float accordingly. Similarly, when a water sampling command is issued, the datalogger activates the pump. When the ground control station requests sensor data, the datalogger sequentially sends data acquisition commands to each sensor.

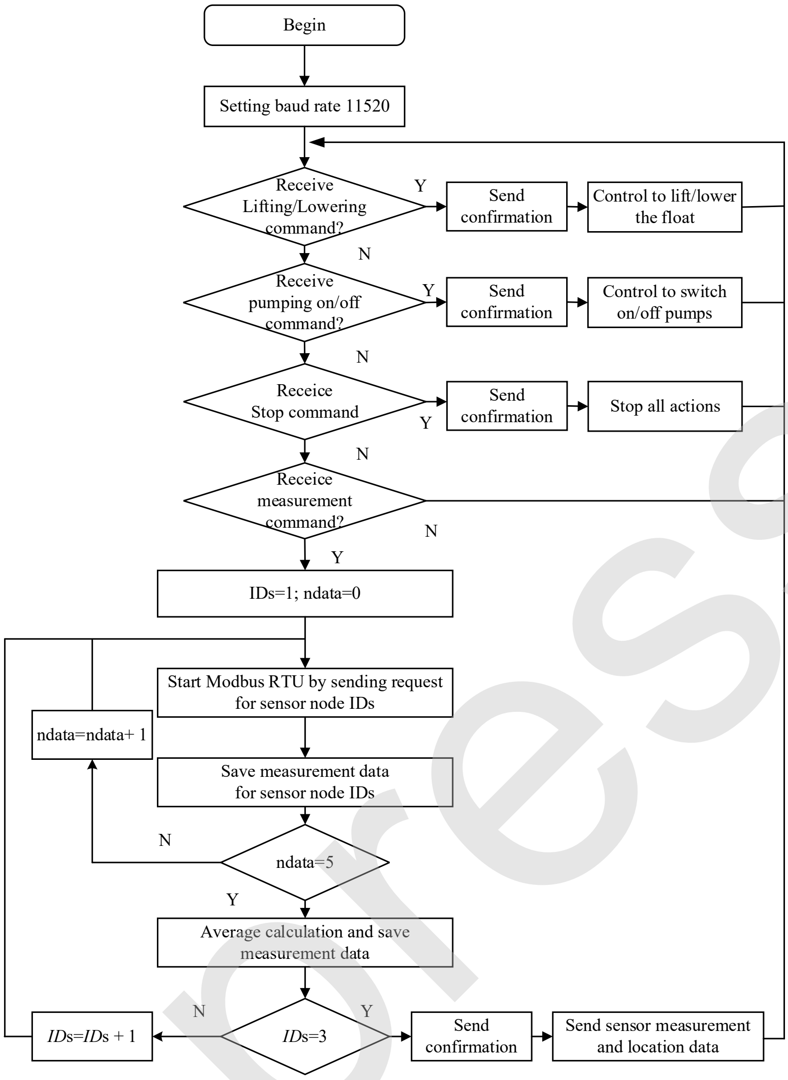

Fig. 8. The algorithm for the datalogger

As seen in Fig. 8, each sensor (assigned by IDs) performs five consecutive measurements (i.e., assigned by *ndata*- number of measurements), and its averaged value is computed to obtain the final result. Once all sensor data are collected, the datalogger will automatically transmit the water quality dataset and the locations of investigation points back to the ground control station. Moreover, in order to check errors or malfunctions, all command executions are continuously observed at the ground control station. If any failure occurs during a sensor request or if any malfunction is detected, the corresponding error information will be recorded and sent to the ground control station. Similarly, the algorithm for the ground control station is illustrated in Fig. 9. Specifically, any changes in the states of push buttons will enable the ground control station to send a respective command to the datalogger. Also, when the data of water quality and the position of UAV are available at the ground control station, it will be sent to the web server.

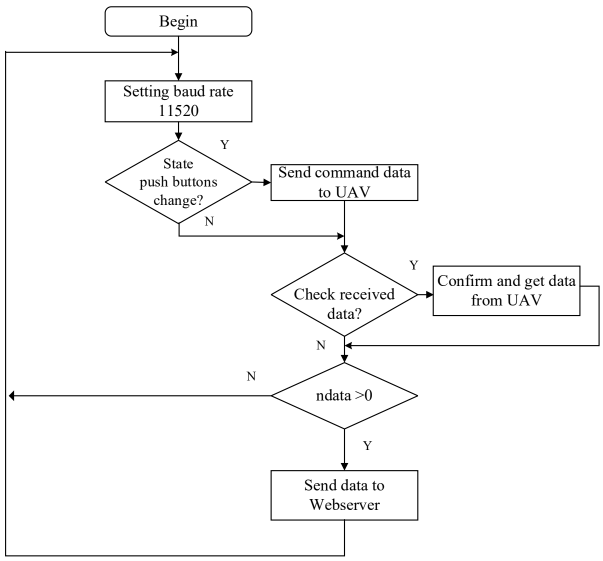

Fig. 9. The algorithm for the ground control station

The flight time of UAV is about 15 minutes. It is well known that the operating time is significantly dependent on the battery, payload, and the UAV frame. For this system, the sampling is carried out by controlling submersible pumps remotely to supply water to the sample bottle. For each time of sampling, and for one litter bottle, the UAV will take about 6 seconds to fill the bottle. In addition, the time for lowering and lifting the pumps is about 20s. Roughly, the time required for one time of sampling is just around 2.0 minutes. In terms of operating time, it can be seen that the use of UAVs will reduce the time for sampling of water as compared with the traditional method. In addition, it requires less labor cost. In terms of coverage, it is due to the fact that the UAV can be deployed flexibly and thus it can investigate water quality for large areas, provided that the energy power for the UAV must be further improved. In addition, the manual sampling approach normally uses boats to travel to the sampling locations, while requiring more labor cost, it exposes personnel to potential risks, such as operating in contaminated or hazardous environments. In future work, to improve the energy of UAVs, a hybrid power may be studied as an alternative to the battery.

Numerous studies have developed UAV systems for water quality monitoring and water sampling. Due to space limitations, two representative UAV systems are selected for comparison with the proposed system, as presented in Table 1. The comparison shows that the proposed UAV system outperforms existing approaches, particularly in terms of its supervisory operation mode. The introduction of this supervision mechanism ensures that both data collection and water sampling processes are carried out correctly and reliably

Table 1. Comparison of UAV systems

	UAV system developed in [6]	UAV system developed in [7]	Our proposed UAV system
UAV frame	Hexacopter; payload: 0.75 kg	Hexacopter; payload: 5.5-6 kg	Quadrotor; payload: 20 kg
Flight	Pixhawk	DJI Matrice 600	Phantom 3S
Sensor nodes	EC, DO, pH, and temperature; Sensor with I2C	pH, EC, and temperature; Wi-Fi	pH, TSS, temperature; Sensor with Modbus RTU
Water Sampler	130 mL	1000 mL	1000 mL
Communication	No	LTE network	LoRa and 3G/4G
Data storage	Memory card	Cloud	Cloud; Computer
Supervisory	No	No	Yes. Supervision of commands and measurement data on the computer.

3. Application of the UAV for Water Monitoring and Water Sampling

The UAV system is deployed to monitor water quality parameters of pH, temperature, and TSS for Thanh Nhan lake. The operation of the UAV as well as the investigation area are shown in Fig. 10 and Fig. 11, respectively. The deployment strategy for the UAV is carried out through several sequential steps. Step 1: The flight waypoints are planned in advance. Step 2: The UAV is controlled to take off and flies to the first waypoint. Once the waypoint is reached, the UAV descends at about 10m above the water surface, and the measurement process begins. At first, the ground control station issues a command to the datalogger to lower the sensor node float approximately 50 cm below the water surface.

Fig. 10. Deployment of the UAV system at Thanh Nhan lake

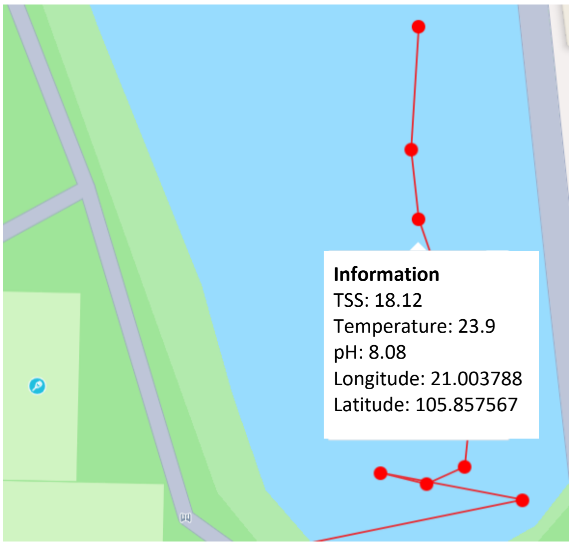

Fig. 11. The investigation points at Thanh Nhan lake

Then, the datalogger initiates communication with the sensor nodes to collect water quality data. Each sensor is required to take five measurements for deriving its average value computation. The sensor float is lowered under the water surface at a distance of about 50 cm, which is suitable in practice for water quality monitoring and sampling. This comes from the fact that water used for a water treatment plant is taken at a depth ranging up to 1.0m below the water surface. For this reason, the water quality should be monitored at an average depth of 50 cm. Step 3: After all measurement values have been collected, the datalogger will automatically transmit the data to the ground control station.

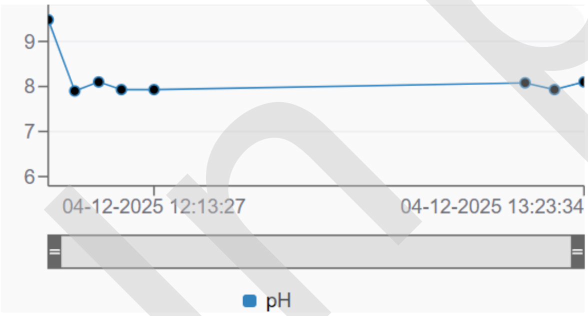

Fig. 12. pH at different locations

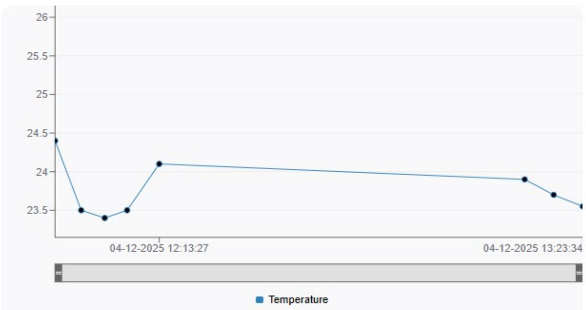

Fig. 13. Temperature at different locations

Step 4: Once the ground control station successfully receives all data, the datalogger lifts the sensor node float, and the UAV continues its flight to the subsequent waypoints. The changes of pH and temperature at different locations are illustrated in Fig. 12 and Fig. 13, respectively (which can be seen on the website). From the investigation, it is seen that the observed temperatures are around 22.4 °C, while the pH levels are around 8.0 pH. These parameters can provide a preliminary assessment of the water quality at Thanh Nhan lake. In terms of accuracy evaluation, the water sampling taken by the UAV system at various locations will be used for verifying the temperature in the field by digital folding probe thermometer (TP-606).

The comparison of temperature parameters is given in Table 2. The testing on the water sampling at the field is shown in Fig. 14. It can be seen from Table 1 that, using our developed UAV system, the resulting temperatures are a bit higher than the ones obtained by testing on the water samples with the thermometer, and the maximum difference is around 1.1 °C. The difference is due to the arrangement of the pumping and sensor nodes, in this case, the pump is placed at a position lower than the sensor node, for this reason, the temperatures from the sensor node are higher. For pH comparison, the water samples taken by the UAV system are analyzed in the laboratory. The comparisons are given in Table 3. It is seen that the UAV system also provides relatively accurate pH levels. The largest deviation is 1.7pH coming from the first point of investigation, other deviations are around 0.4pH. This observation indicates that the sensor nodes (pH) are highly sensitive to changes in the environment (i.e., the sensor comes under the water surface for the first time). This evidence can be seen with the rest of the investigation points, where the maximum error is around 0.4 pH. For these cases, the sensor nodes are familiar with the environment, and the results are relatively accurate. For this reason, in order to get accurate measurement, the sensor nodes should be placed under the water surface in sufficient time before the command of measurement is accomplished.

Table 2. Comparisons of temperature

Longitude	Latitude	UAV system	Thermometer (TP606)
21.003318	105.857488	24.40	22.80
21.003298	105.857584	23.50	22.40
21.00333	105.857656	23.40	22.50
21.003404	105.857664	23.50	22.60
21.00352	105.857664	24.10	22.40
21.003788	105.857568	23.90	22.80
21.003916	105.857552	23.70	22.80
21.004142	105.857568	23.55	22.80

Fig. 14. Testing temperature of water samples in the field

Table 3. Comparisons of pH

Longitude	Latitude	UAV system	Laboratory
21.003318	105.857488	9.48	7.7
21.003298	105.857584	7.90	7.8
21.00333	105.857656	8.10	7.7
21.003404	105.857664	7.93	7.6
21.00352	105.857664	7.93	7.5
21.003788	105.857568	8.08	7.5
21.003916	105.857552	7.93	7.6
21.004142	105.857568	8.10	7.7

Table 4. Comparisons of TSS

Longitude	Latitude	UAV system	Laboratory (±2mg/L)
21.003318	105.857488	25.71	28.0
21.003298	105.857584	25.45	24.0
21.00333	105.857656	23.80	25.0
21.003404	105.857664	19.43	21.0
21.00352	105.857664	20.50	22.0
21.003788	105.857568	21.80	23.0
21.003916	105.857552	18.45	20.0
21.004142	105.857568	18.12	20.0

Similarly, for the TSS comparison, the results obtained by the UAV system are comparable with the ones obtained by analyzing water samples in laboratory, as shown in Table 4. From these comparisons, it can be concluded that the UAV assisted for water quality monitoring and water sampling gives relatively accurate results as compared with those obtained by analyzing in laboratory. The advantage of the application of UAV is due to the fact that it allows fast measurement, fast sample collection, and flexible movement. In particular, the application of UAV can replace the traditional approach, i.e., water sampling.

With the developed UAV system, it is possible to deploy UAV system for fast monitoring of some water quality parameters over a large area to efficiently regulate the pollution of the lake. Although the application of the UAV system gives results primarily, it is required to evaluate the accuracy for other parameters, which are highly sensitive to the environment, such as TDS, DO, and Chlorophyll.

In addition, to demonstrate the efficacy of our proposed data transmission scheme with a combination of LoRa and 3G/4G network, log data on the computer is attained through RS232 communication with the ground control station. The log data, presented in Table 5, includes only pH measurements. The log records reflect the operational status of the UAV system. The status column enables operators to monitor and identify the system's operational conditions.

When a command is transmitted from the ground control station to the UAV, a successful execution is confirmed by a feedback message indicating that the command has been received and completed. For instance, the message "Order Measure Auto" indicates that the UAV has received a command to perform measurements, namely to acquire data from onboard sensors. The message "Data Get 0" signifies that the ground control station has received the first set of collected data. These data are temporarily stored, labeled, and sequentially transmitted to the web server.

As shown in Table 5, the total time required for one measurement cycle is approximately 9.0 s, including about 7.9 s for sensor data acquisition and 1.1 s for communication between the UAV and the ground control station via LoRa. This result indicates that LoRa communication introduces relatively low data transmission latency. For data transmission to the web server, the collected data are indexed. For example, the message "No. data 1" in Table 5 indicates that one data packet is pending transmission to the web server. The time required to transfer this data is approximately 12 s, measured from the appearance of the "No. data 1" message to "No. data 0." These results demonstrate that data transmission over a 3G/4G network exhibits higher latency compared to LoRa communication. Furthermore, the use of LoRa enables bidirectional data transmission, thereby supporting effective command execution, measurement, and sampling operations within the UAV system.

Table 5. The time latency for LoRa and the 4G SIM module

Time	pH	Status
13:13:21	0.00	Oder Measure Auto
13:13:30	8.08	Data Get0
13:13:34	0.00	Oder Pump
13:13:48	0.00	[GET SERVER] No. data 1
13:13:53	0.00	[GET SERVER] No. data 1
13:13:53	0.00	[GET SERVER] Resend...
13:13:56	0.00	Oder Pump
13:13:58	0.00	[GET SERVER] No. data 1
13:13:58	0.00	[GET SERVER] Resend...
13:14:02	0.00	[GET SERVER] No. data 0

For transmission latency comparison, the direct transfer of data from the UAV to the web server (through 3G/4G network) will certainly require less amount of time as compared with the case as the intermediate relay station is used. However, as explained before, without the intermediate relay station, we cannot supervise the operation of the UAV for water quality monitoring and water sampling. For this reason, this study proposes a combination of LoRa and 3G/4G networks for improving the operation of the UAV system. In addition, data is stored in both the computer (at the ground control station through RS 232 connection as shown in Fig. 2) and web server.

4. Conclusion

This paper developed a UAV system for in situ water quality monitoring and water sampling. The IoT architecture, integrated with the UAV, is designed with three layers: perception, transmission, and application. Each layer is designed with appropriate devices and communication methods. In the perception layer, the datalogger requests data from sensor nodes by utilizing Modbus RTU protocol, while LoRa network enables long-range data transmission between the perception layer (UAV) and the transmission layer (ground control station). The water quality data and location of the UAV are also sent to the web server for data storage and visualization. For the experiment, the UAV system has been deployed to measure pH, temperature, and TSS in an area of Thanh Nhan lake. The observed results are comparable with the ones obtained by analyzing the water samples taken from the UAV in laboratory. The comparison reveals that the developed UAV system is indeed beneficial for assessing water quality at both temporal and spatial variation. With advanced technologies on UAV (i.e., frame, battery, remote sensing, motor), the development and application of the UAV system will be efficient and certainly enhance the capacity for investigating water quality for large areas, based on that, it can early warn of pollution events before they spread. In future work, the UAV platform will be integrated with remote sensing technologies, such as multispectral cameras, to enhance water quality prediction and support more effective water management strategies.

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