Development of Unmanned Surface Vehicles System for Water Quality Inspection

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Abstract: In recent years, the problem of water pollution has attracted wide attention all over the world. To strengthen water quality monitoring, a water quality inspection system for Unmanned Surface Vehicles (USV) based on the Internet of Things (IoT) was designed. The system uses the Message Queuing Telemetry Transport (MQTT) protocol to construct the boat-cloud-shore communication link. Design the terminal system of the USV to realize state perception, motion control, and data sharing. The mobile client is developed based on the Android platform, which supports real-time monitoring and remote control of the USV. Automatic control of USV movement and real-time monitoring of water quality is realized. After the actual water surface trial, the communication of the system is stable, with manual remote control, fixed-point inspection, independent cruise, and other functions, which verify the feasibility of the system design.

1 INTRODUCTION

In recent years, people pay more and more attention to the exploration, development, and protection of water resources. The traditional water quality inspection is to organize personnel to the scene area, points for sampling, and then sent to the laboratory for data analysis and water quality inspection. It is time-consuming and laborious, easy to cause secondary pollution, and can't guarantee the timeliness of monitoring (Kondle R et al., 2020). Unmanned Surface Vehicles (USV) is a multi-purpose small surface carrying platform that can sail by remote control or autonomous way. It has broad prospects in the fields of marine transportation, marine environment investigation, and marine resources exploration. With the rapid development of the Internet of Things (IoT), Big Data and cloud computing, and other emerging technologies, the use of USV for water quality inspection has become a trend (Steimle E T and Hall M L, 2006). Therefore, it has certain research significance and engineering value to design and develop a set of USV water quality inspection systems based on IoT communication technology, which uses mobile terminals to monitor USV to perform water quality inspection tasks.

In actual projects, the water quality inspection system not only needs to receive remote sensing data in real-time, including water quality monitoring data and sampling positioning data, etc., for data processing and interactive display. In the USV water quality inspection system, the data acquisition unit is the core of the whole system. When designing the data acquisition unit, this paper focuses on the design of sensors for three indicators of water temperature, carbon dioxide concentration (CO_2), and Hydrogen ion concentration (pH). Use sensors and Internet of Things technology to collect and send data. At the same time, it is necessary to be flexible and compatible with various inspection modes, such as random inspection, fixed-point inspection, and roving inspection (Madeo D et al., 2020). To meet the needs of water quality inspection operations, this paper designed a water quality inspection system for USV based on IoT technology. In this system, the USV completes autonomous control, data acquisition and analysis. And the mobile client is responsible for state monitoring and command decision. In addition, a remote monitoring program and mobile phone application software was developed, and the IoT communication technology was adopted to realize remote information sharing and control instruction issuance. Through the system, a user can remotely control USV anytime and anywhere by using a

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mobile phone, water quality data collected at the USV terminal can be quickly obtained, and the performance of the traditional water quality inspection system is greatly improved.

2 DESIGN OF USV WATER QUALITY INSPECTION SYSTEM

As shown in Fig. 1, the overall architecture of the system is mainly divided into three parts, which are the USV subsystem, mobile client, and cloud server.

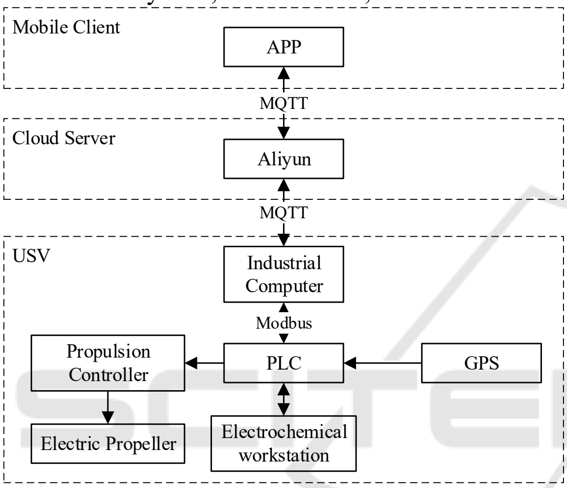

Figure 1: USV water quality inspection system structure.

The USV subsystem mainly consists of an onboard industrial computer, programmable logic controller (PLC), GPS receiver, propulsion controller, electric propeller, electrochemical workstation, and other equipment. The USV has a certain degree of autonomy, focusing on the functions of state perception, motion control, and data sharing, and can realize multi-source information fusion processing and drive control (T. H. Yang et al., 2018). Moreover, its modular design is easy to flexibly expand the subsequent functions.

The mobile client completes the remote monitoring function of the system. This paper specially designs the application software based on the Android system, which is based on the Android Studio program development environment and is developed using JAVA. Based on the cellular mobile network, users can obtain the status information of the USV in real-time at the mobile terminal and send various control commands.

Cloud server currently uses Alibaba Cloud server that supports free small-scale data transmission. Relying on the cloud platform of Aliyun Internet of Things, using Message Queuing Telemetry Transport (MQTT) for network communication, the USV terminal interacts with the mobile terminal through the cloud. To realize the remote monitoring of USV, a boat-cloud-shore communication link is constructed to complete the cloud flow of data in the cloud server.

According to the requirements of different projects, we can expand the related functional modules based on this architecture, such as video transmission unit, pollution source detection unit (G. Zhang and Y. Hao, 2020), etc. This paper, the design and application of the monitoring system are mainly focused on motion control in the water quality inspection task of USV.

2.1 Design of IoT Communication

MQTT is a lightweight IoT transport protocol based on message publish/subscribe mode, which has the advantages of low bandwidth and easy implementation. In this protocol, the publisher, server and subscriber are involved, i.e. each part in the corresponding boat-cloud-shore communication link. In this system, both the USV terminal and the shore mobile terminal serve as clients and simultaneously serve as a publisher and a subscriber of messages. The IoT cloud platform is used as a message cloud flow server. It completes the authentication of client devices by logging in and obtaining authentication information such as server address and port number and realizes the initialization and connection of MQTT communication.

When using the MQTT protocol to communicate with the cloud flow server, the transmitted message is divided into two parts, Topic and Payload. Where, the topic is the type of message, such as speed, mode, etc. If one terminal publishes a message about a topic, the other terminal will receive the content of the corresponding message after subscribing to the topic, that is, the payload (A. Eleyan and J. Fallon, 2020). In this monitoring system, the payload data adopts the ICA standard format Alink JSON data format and transmits the specific speed value and model number, etc. To distinguish messages under different topics, the topic communication identifier needs to be customized in the Internet of Things platform, and some customized topics are shown in Table 1.

Table 1: Custom Topic (Part).

Mobile Client Directive Title	Topic Identifier	USV State Title	Topic Identifier
Mode Switch	MODE	Latitude	Lat
Target Position	TGT	Longitude	Lon

Set Speed	RPM	Speed	Spd
Manual	WSAD	Heading	HDG
Testing	ANAL	Quality	WAQ

2.2 Design of USV Subsystem

2.2.1 Control Module

The control module is the core of the USV subsystem, and it consists of an Advantech ARK-3500 embedded industrial computer and a SIMATIC S7-1200PLC controller. Among them, the onboard industrial control computer is the control center of the USV subsystem. Equip and run the terminal monitor program, which can bidirectionally transmit real-time parameter information and control instructions. Responsible for the calculation of control logic and algorithms, with information interaction and processing functions.

S7-1200 controller has the advantages of compact structure, many interfaces, and modularization. Mainly through the accurate control of the thruster controller and the electrochemical workstation, the navigation control and water quality inspection functions of the USV are realized. At the same time, the internal logic program can also process double GPS signals and water quality inspection data, and carry out multi-source information fusion and processing to obtain USV sensing data. And the real-time data is packaged according to a specified interactive format and then sent to the onboard industrial personal computer.

2.2.2 Sensing Module

The sensing module is composed of GPS and an electrochemical workstation, which provides information such as the position, speed, heading, and water quality of the USV for inspection control. The USV is equipped with a TimeNav-H positioning and direction-finding receiver and two GPS antennas. Where the main antenna is located at the stern and the slave antenna is located at the bow, the current motion state can be calculated.

The electrochemical workstation realizes the water quality inspection function. The pump, solenoid valve, and analyzer work together to complete the integrated water sampling-water quality testing-visual analysis-water sample elimination, and other inspection processes (L. S. Bratchenko et al., 2022). Automatic collection, analysis, and treatment of water samples are realized.

There are three types of sensors used in monitoring purposes embarked on workstation. Water temperature, carbon dioxide concentration (CO_2) and Hydrogen ion concentration (pH), as follows:

a. Temperature transducer

Temperature is the basic information of water quality. When collecting temperature information, the sensor used by USV water quality inspection system is the temperature and humidity sensor of OMEGA Company. This sensor can realize the digital signal output function, and has the advantages of debugging-free and simple peripheral circuit. It still has high temperature detection accuracy under harsh water conditions.

b. Carbon dioxide concentration sensor

The concentration of carbon dioxide is the main measure of water quality. If the concentration of carbon dioxide is too high, the water area may be polluted. In the USV water quality inspection system, NDIR carbon dioxide concentration sensor is used. This sensor has the function of automatic calibration, and the accuracy of signal acquisition is high.

c. pH sensor

For the pH data of water area, the USV water quality inspection system adopts a composite pH electrode, which includes a glass electrode and a test electrode, and converts the pH value into an electrical signal.

2.2.3 Driver Module

The propulsion module of the USV subsystem adopts an electric propulsion mode with fast response and wide speed regulation range. It is equipped with two propeller propellers and two matched electric propulsion controllers (Rybin, V. G. et al., 2020). When the USV moves, the PLC inputs the corresponding digital signal and analog signal to the propulsion controller according to the received control command to realize the positive and negative rotation of the propeller as well as the speed regulation function. The steering motion of the USV can also be realized by using the rotation speed difference between the two propeller propellers.

3 SOFTWARE DEVELOPMENT AND REALIZATION

3.1 Mobile Client Application Software Design

In the mainstream mobile terminal operating system, Android is characterized by its Linux-based open-source operating system, which is highly applicable to portable intelligent terminal devices and has the advantages of low development cost, small difficulty, and large market share. Therefore, this paper will design the mobile client application software based on the Android operating system, as shown in Figure 2, which covers the functions of status display, target positioning, mode switching, speed regulation, and manual direction control.

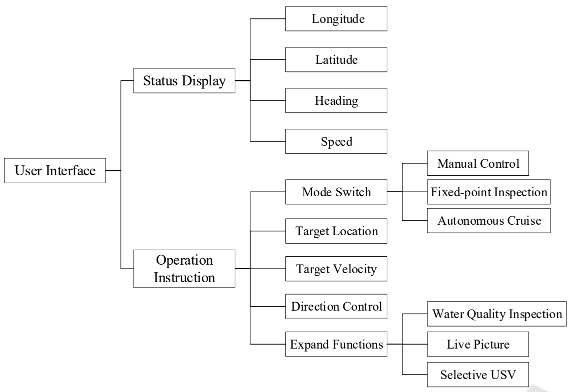

Figure 2: Mobile terminal application framework.

The key to developing mobile application software with Android Studio is to establish a communication connection with the IoT cloud platform (M. K. Madisa and M. K. Joseph, 2018). Considering the issue and subscription of topic content based on the MQTT communication protocol, the Handler message transfer mechanism is introduced in the design and development, which is used to send, receive and process messages, and realize the update of interface state data.

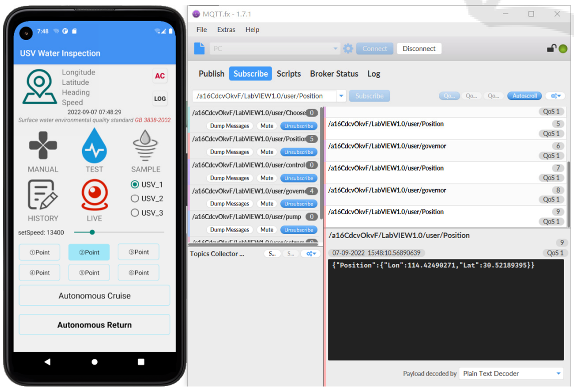

Figure 3: Mobile client application software interface.

As shown in Figure 3, on the mobile terminal interface, different control functions correspond to different topic information, triggering click events, and the instruction data will be uploaded to the IoT cloud platform in JSON format and sent to the USV terminal via the cloud server so that the remote USV can execute the control commands under the corresponding topic.

3.2 USV Terminal Program Design

3.2.1 Onboard Industrial Computer Program

The remote monitoring program for the USV terminal is designed and developed based on LabVIEW. The program block diagram replaces the traditional code language and adopts data flow programming. The program is intuitive and easy to understand and convenient to run. As shown in Figure 4, the software design of the onboard industrial computer mainly includes two parts: the cloud dialogue part and the communication cycle with PLC, so the parallel cycle design mode can be adopted.

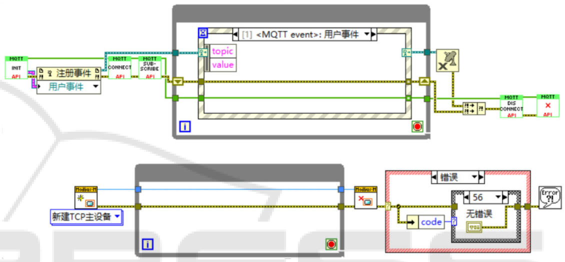

Figure 4: Parallel Loops.

The onboard industrial control computer can be regarded as a hub for data exchange at the USV terminal. Its data communication is divided into two parts, namely, communication with the cloud server of the IoT and communication with the underlying PLC controller, to collect, process, and transfer various data inputs and outputs.

In the circular structure of communication with the onboard PLC, the Modbus library encapsulated by LabVIEW is introduced to establish the Modbus communication connection. By reading the data in the PLC holding register, each state information of the USV is obtained and then used for cloud interaction after data processing. At the same time, various parameters of the USV terminal in operation will also be recorded by the monitoring program to the local file in real time for subsequent data analysis.

Based on the communication technology of the IoT, the USV terminal uses MQTT communication to publish and subscribe to topics with the cloud server. The monitoring program at the terminal of the USV obtains the data such as water quality information and USV posture collected and processed by PLC. Packaging the sensing information of the USV terminal into a plurality of topics to be released to the cloud. At the same time, subscribe to the remote instruction topic in the cloud server, and obtain the mode number, expected speed, target latitude, longitude, etc. according to the flag bit. In addition, as the control module of the USV subsystem, the terminal monitoring program, after obtaining the remote command information, converts each operation command into a data form through the built-in mode algorithm and sends the data form to the PLC controller (W. Wei et al., 2019), to finally realize the autonomous navigation of the USV and water quality inspection according to the command of the mobile client. It should be noted that the control algorithms in different modes can be independently designed and developed in the software, which facilitates the subsequent function expansion and greatly improves the flexibility of the system.

3.2.2 PLC Control Program

The main function is to collect, process and transmit GPS information and water quality information from the sensing module. At the same time, each control instruction transmitted by the onboard industrial control computer is received, and corresponding digital or analog signals are input to the propeller controller and the electrochemical workstation after logic processing. And finally, the navigation control and water quality inspection functions of the USV are completed.

In the main program of the PLC, the Modbus TCP communication connection with the USV terminal monitoring program is established first. Next, the perception information is extracted and analyzed to obtain the current longitude, latitude, speed, heading, and water quality. The data sent and received are formatted and stored into Data Blocks for program calls and data transmission. Finally, based on the received mode command, a function block for executing navigation control or water quality analysis is selected. In the motion control subprogram, the incremental PID controller is designed to calculate the rotation speed difference increment of the motor and correspondingly input the left and right motors to realize the navigation control of the USV.

3.3 Application of USV Water Quality Inspection System

As a platform for users to analyze and operate, the mobile terminal in the USV water quality inspection system plays the role of state monitoring and command decision-making, while the USV terminal has a certain degree of autonomy and can realize state perception, motion control, etc.

When the water quality inspection system works normally, the state parameters of the USV on the mobile user interface will be updated in real-time. Users can view the position, posture, and speed information of the real-time USV at the mobile client anytime and anywhere, and click the "position" icon to pop up the built-in Baidu map. As shown in Figure 5, calibrate the position and heading of the current USV on the electronic map.

Figure 5: Monitoring interface and electronic map.

Figure 6: Control interface and virtual joystick.

As shown in Figure 6, users can select different control modes according to the water quality inspection requirements and issue decision instructions at the mobile phone terminal, thus realizing the remote control of the USV. During manual control, the user operates the virtual rocker at the mobile phone terminal to remotely control the USV to advance, reverse, and right or left rudders. By dragging the rotating speed lever, the speed of USV can be controlled in real-time. To realize random sampling inspection in the water area. When the user presses the "TEST" button, the USV equipped with the electrochemical workstation will independently complete the integrated processes of water area sampling, water quality inspection, visual analysis, and water sample discharge, thereby helping the user to quickly obtain water environment information.

When fixed-point inspection, the user selects the navigation sampling point. The USV can get the latitude and longitude of the target point, sail from the current position to the target position automatically, and finally stop there. And start the electrochemical workstation for integrated water quality inspection and analysis.

Using the autonomous cruise function can realize the patrol inspection in the water area. The user needs to import the path planning file in advance and switch to autonomous cruise mode. The USV terminal reads the local planning file, sequentially traverses the longitude and latitude values of the path points, and conducts independent patrol inspections along the planned route.

4 COMMISSIONING AND ANALYSIS

4.1 Native Debugging

To verify the feasibility of the water quality inspection system proposed in this paper. Firstly, each module of the system is configured and debugged locally to test whether the communication, positioning, power, software, and hardware functions of the system are normal or not, to fully prepare for the water surface trial. Figure 7 shows the actual debugging situation.

Figure 7: Native debugging.

After testing, the IoT cloud platform has stable communication with the mobile terminal and the USV terminal and can carry out data flow in the cloud. The mobile client can display the status of the USV in real-time, and test the normal functions of the system such as manual control, speed adjustment, and mode switching by issuing instructions.

4.2 Trial Trip

Based on the motion control in the USV water quality inspection task, the water surface navigation test was carried out. After the trial voyage, the user can realize the remote monitoring of the USV through the mobile terminal, and the switching mode operation control can meet the expected demand. The actual flight test is shown in Figure 8.

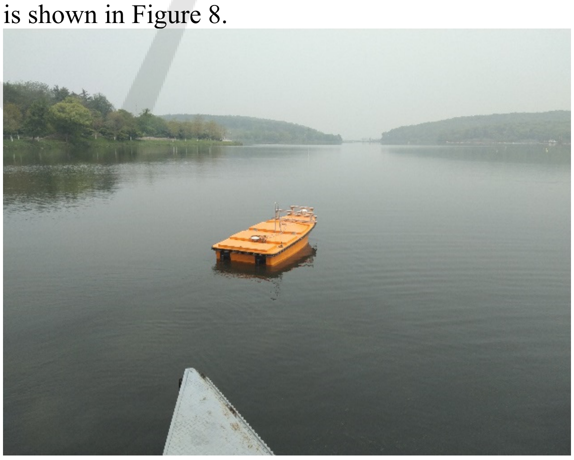

Figure 8: Trial Trip.

Collect the navigation data of the USV under the autonomous cruise mode (see Table 2) and analyze the status data.

Table 2: Status data collected by USV (Part).

Longitude (in deg.)	Latitude (in deg.)	Heading (in deg.)	Speed/ (in knot)
114.4245168	30.5225445	324.7	5.5
114.4245149	30.5225467	324.7	5.4
114.4245112	30.5225511	323.6	5.5
114.4245074	30.5225555	321.8	5.5
114.4245015	30.522562	316.7	5.4
114.4244971	30.522566	315.3	5.5
114.4244971	30.522566	313.1	5.4
114.4244902	30.5225715	314.0	5.4
114.4244807	30.5225786	314.8	5.3
114.4244807	30.5225786	315.8	5.3

First, the real-time longitude and latitude values are extracted, and the navigation trace is drawn as shown in Fig. 9. It can be seen that the USV can automatically adjust its attitude to approach the path node position after receiving the instruction, and it is approximate to a straight line trajectory within the allowable range of error.

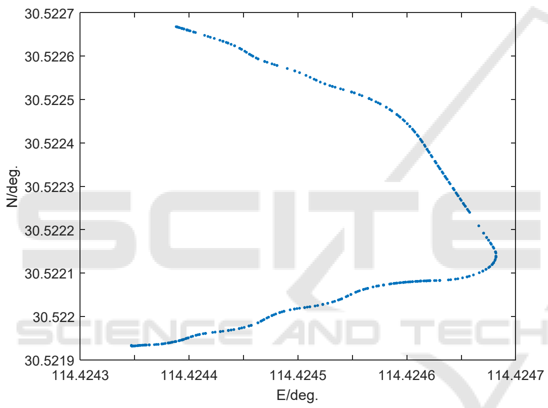

Figure 9: Trajectory of USV

Extract and analyze the heading angle and speed values of the USV during the trial voyage, and generate the heading angle scatter diagram and speed scatter diagram as shown in Figure 10 and Figure 11 according to the data acquisition frequency of 200ms. It can be seen from the image that the heading angle can be automatically adjusted during the trial voyage, and the change of speed meets the real-time control requirements.

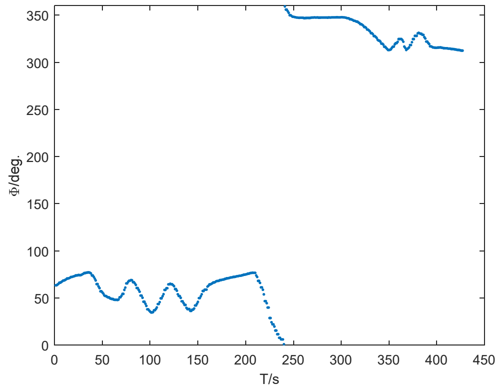

Figure 10: Heading scatter plot.

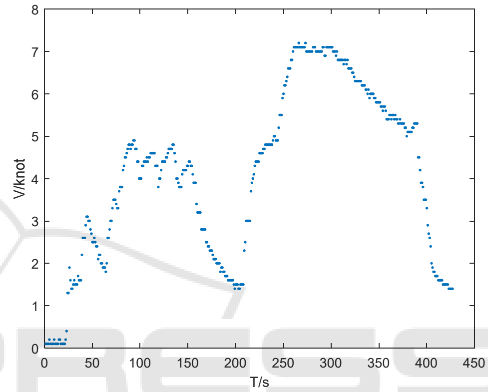

Figure 11: Speed scatter plot.

Judging from the overall test results, the remote monitoring system for USV based on the IoT technology designed in this paper performs well in water navigation. When the system is running, the information such as target, pose, speed, and distance displayed on the mobile terminal interactive interface can be updated in real-time, the USV terminal state information collection and storage function is normal, and the action is flexible and smooth, and the target instruction can be completed. From the above-mentioned tests, it can be seen that the positioning accuracy, communication quality, and operational performance of the system all meet the requirements of the water quality inspection system of the water USV and ensures the smooth completion of the follow-up water quality inspection, function expansion, and other applications.

5 CONCLUSIONS

This paper designs and develops a water quality inspection system for USV based on IoT technology, and introduces the design and application of a mobile client and USV terminal system. From the perspective of convenience, flexibility and compatibility, the mobile client of the system supports users to remotely monitor and issue tasks anytime and anywhere, making it more convenient to build a water quality inspection platform. The USV subsystem has a certain degree of autonomy, and its modular design is easy to flexibly expand the subsequent functions. The system has been proved to have stable remote monitoring capability for USV through water surface trials and can realize real-time synchronization of synchronous remote states. And can complete various operations such as manual control, fixed-point inspection, and autonomous cruise. It has reliable communication and good real-time performance. The next step will be to expand the functions of the mobile client and USV. And continue to improve the system on the existing hardware and software architecture based on the actual water quality inspection project requirements.

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NOMENCLATURE

Create the following nomenclature for easy reading.

USV	Unmanned Surface Vehicles
IoT	Internet of Things
APP	Mobile Application
PLC	Programmable Logic Controller
GPS	Global Positioning System
MQTT	Message Queuing Telemetry Transport