Sensors & Transducers

Water Quality Data Measurement and Analysis System Equipped in Underwater Navigation Robot

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Abstract: This paper introduces a water quality data measurement and analysis system equipped in underwater robot. The system consists of sonar navigation module, inertial navigation module equipped in underwater robot, data processing module and sensor detection module. Sonar navigation module and inertial navigation module equipped in underwater robot are separately used to detect current speed, azimuth and depth in different latitudes and longitudes. And then we strike differences of the measured data from two modules above, the difference will be feedback to the inertial navigation module after the filtering process to obtain a more precise location information. Sensor detection module uses the water quality sensors equipped in underwater robot to measure water quality parameters of the current location. Underwater robot data processing module matches the water quality data of the current position to its tracking latitude and longitude, forming water quality of the latitude and longitude distribution data. Underwater robot float to water surface, transmit water quality data to the shore-based facility micro-processor before moving on to the next testing spot. Shore-based facility has its own computer, our self-developed Density Map software is embedded in it. Water quality data from different testing point can be visually displayed. The feasibility of the system design and the rationality of the water quality parameter measurement results were verified by experiments and on-site tests.
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1. Introduction

In today's society, environmental issues have become one of the most important issues in the sustainable development of human society. The pollution of water resources is a part of the environmental pollution. Water is the basic element of human survival, water quality must be tested timely and effectively so that we human beings can take remedial measures in appropriate time.

The traditional method of detecting water quality data is: workers choose several testing spots in a river, recording water temperature, turbidity, and blue-green algae, chlorophyll, dissolved oxygen, PH, ORP data with sensors, and then make data sheets to analysis water quality of various spots [1-2]. The testing spots are quite limited using the traditional method, which also lacks the macro analysis of specific water environment. It is difficult to grasp the latitude and longitude distribution of various water quality parameters, let along predicting its future distribution trends.

Underwater navigation robot can work under complex water environment below a certain depth for

a long time, and conduct a wide range of water quality test, which are easily operated and labor-saving. They have been widely used today.

Underwater navigation is a key issue to be solved of the underwater robot water quality testing system. It includes how to get navigation trajectory and the latitude and longitude of each testing spots, how to match a variety of water quality parameters from all kinds of sensors with each specific latitude and longitude. The single navigation technology has low position accuracy, poor reliability and fault tolerance phenomenon. In addition, the unpredictable underwater environment, navigation error will be easily accumulate with time and traveling distance, eventually leading to the low positioning accuracy [3].

Aiming at the aforementioned drawbacks above, this paper introduces a measurement and analysis system for water quality data of different latitudes and longitudes. A serious of experiments have verified the feasibility and accuracy of the system design, and resolved the issue to a large extent at this stage.

2. System Design

In view of the disadvantages above, the system has adapted multiple navigation facilities to coordinate their work together and track its speed and position by using adaptive navigation algorithm to get the location (the current latitudes and longitudes) of the testing spots accurately. When Global Navigation Satellite System （GNSS） signal exists, it can help to optimize robot position. Then water quality parameters are obtained and match to the latitudes and longitudes. Density Map shows the testing results intuitively, from which we can conduct comprehensive analysis in any areas we have tested. The schematic diagram of the overall system design is shown in Fig. 1, it includes sonar navigation module, inertial navigation module equipped in underwater robot, data processing module and sensor module. Sonar navigation module and inertial navigation module combine with the filter information fusion system to get underwater robot's position accurately. Data processing module consists of underwater robot built-in microprocessor and shore-based facility computer, the former deprives water quality parameters and matched them to corresponding latitudes and longitudes. While the latter helps to display data on the screen, so that workers can analyze conveniently. Sensor module includes all kinds of sensors and analog-to-digital conversion module.
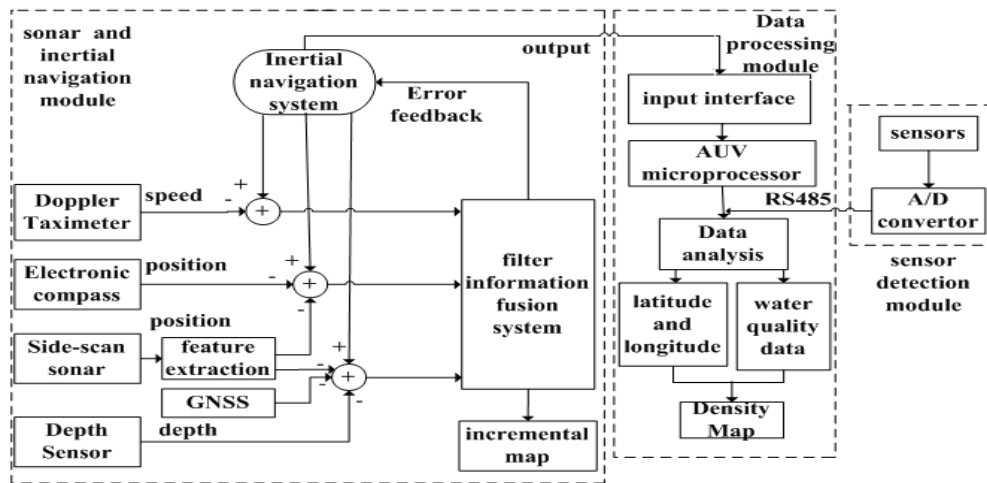

Fig. 1. Schematic diagram of the overall system design.

3. Underwater Robot Navigation System

Sonar navigation module and inertial navigation module detect current speed, position and depth respectively, and then the system compute speed, position and depth differences respectively from two modules. These differences will be processed by filter information fusion system [4]. Filter information fusion system output its processing results back to inertial navigation module. The patched and superimposed speed orientation, depth information is sent to the underwater robot built in microprocessor. Considering the obstacles will appear when the robot navigates autonomously, the obstacle diagnostic method is added to SLAM algorithm in order to ensure safer navigation of the robot.

3.1. Underwater Robot Simultaneous Localization Algorithm

The positioning of underwater robot refers to determine the location of the moving robot relative to the global coordinates in the two-dimensional (three-dimensional) working environment, and its own posture. It is the basic steps when the robot is moving.

Underwater robot works in an unknown underwater environment, without any human intervention. We need to get the real-time speed, orientation, depth information, and incrementally create environment maps, which at the same time can help to position itself more accurately. In order to obtain a more optimized estimate, we adapt fusion algorithm (Kalman filter) [5-6] to fuse the same parameter deprived from different modules. The algorithm use simultaneous localization and mapping (SLAM) algorithm Kalman filtering theory and as the core basis to get a more accurate position.

SLAM algorithm includes prediction and updating two stages. Control signal from underwater robot input to the system state equation to predict position and map features [7]. Updating stage includes adding new features, deleting disappeared features and updating repeated observed features.

Coordinates of underwater robot position and environment features are expressed in a state vector [8]. During underwater robot's motion, system state vector is represented as:

$$\hat{X}^B = \begin{bmatrix} \hat{X}^B_R \\ \hat{X}^B_{F_1} \\ \dots \\ \hat{X}^B_{F_n} \end{bmatrix}, \tag{1}$$

where $\hat{X}^B_R$ is the pose vector of underwater robot, $\hat{X}^B_{F_i}$ is the vector of all environmental characteristics [8] of $F_1 \sim F_n$, covariance matrix of the system is:

$$P^B = \begin{bmatrix} P^B_R & \dots & P^B_{RF_n} \\ \dots & \dots & \dots \\ P^B_{F_n R} & \dots & P^B_{F_n} \end{bmatrix}, \tag{2}$$

where P^B_R, $P^B_{RF_n}$, $P^B_{F_n}$ subarrays denote underwater robot, environment features, difference matrix between environment features. They all use ground absolute coordinate system B as reference coordinate system, an extended Kalman filter to estimate the state variables and covariance matrix P [9-10]. Between prediction and updating, we need to finish feature matching or data relating. Only matching features can be used to update the position and feature map [11]. Underwater robot will be interfered during its motion, so the motion model is:

$$X^{R_{k-1}}_{R_k} = \hat{X}^{R_{k-1}}_{R_k} + V_k, \tag{3}$$

where $X^{R_{k-1}}_{R_k}$ is the displacement value from time k-1 to time k, DVL provided the UNDERWATER

ROBOT speed to estimated displacement value of the underwater robot in time k:

$$\hat{X}^{R_{k-1}}_{R_k} = [V_x \Delta T \quad V_y \Delta T \quad 0], \tag{4}$$

where ΔT is the time interval [12] from time k-1 to time k, V_x, V_y is the underwater robot speed value measured from the DVL sensor with noise. Speed value integrated in time interval ΔT can get underwater robot displacement value, assuming that the gain of the angle is very small and appears in the form of system noise. Covariance matrix of displacement estimation σ_{V_x}, σ_{V_y} is the standard deviation of the noise-containing speed. σ_{Φ_r} is angle noise variance to simulate the change amount of the underwater robot azimuth. Q_k is zero mean additive white Gaussian noise.

$$Q_k = \begin{bmatrix} (\sigma_{V_x} \Delta T)^2 & 0 & 0 \\ 0 & (\sigma_{V_y} \Delta T)^2 & 0 \\ 0 & 0 & (\sigma_{\Phi_r} \Delta T)^2 \end{bmatrix} \tag{5}$$

In order to obtain the ultimate underwater robot position vector in the absolute coordinate system B, we need a synthetic transformation of the coordinate space, signed with the signal $\oplus$, convert formula is defined as:

$$\hat{X}^B_{R_{k|k-1}} = \hat{X}^B_{R_{k-1}} \oplus \hat{X}^{R_{k-1}}_{R_k} =$$

$$\begin{bmatrix} \hat{X}^B_{R_{k-1}} + V_x \Delta T \cos \hat{\phi}_{R_{k-1}} - V_y \Delta T \sin \hat{\phi}_{R_{k-1}} \\ \hat{Y}^B_{R_{k-1}} + V_x \Delta T \sin \hat{\phi}_{R_{k-1}} - V_y \Delta T \cos \hat{\phi}_{R_{k-1}} \\ \hat{\phi}_{R_{k-1}} \end{bmatrix} \tag{6}$$

$$P^B_{R_{k|k-1}} = J_{1\oplus} P^B_{R_{k-1}} J^T_{1\oplus} + J_{2\oplus} Q_k J^T_{2\oplus}, \tag{7}$$

where $J_{1\oplus}$, $J_{2\oplus}$ are the Jacobian determinants of spatial coordinates composite transformation.

$$J_{1\oplus} \{ \hat{X}^B_{R_{k-1}}, \hat{X}^{R_{k-1}}_{R_k} \} = \begin{bmatrix} 1 & 0 & V_x \Delta T \sin \hat{\phi}_{R_{k-1}} & -V_y \Delta T \cos \hat{\phi}_{R_{k-1}} \\ 0 & 1 & V_x \Delta T \cos \hat{\phi}_{R_{k-1}} & -V_y \Delta T \sin \hat{\phi}_{R_{k-1}} & 1 \\ 0 & 0 & & 1 & \end{bmatrix}$$

$$\tag{8}$$

$$J_{2\oplus}\left\{\hat{X}_{R_{k-1}}^{B}, \hat{X}_{R_k}^{R_{k-1}}\right\} = \begin{bmatrix} \cos\hat{\phi}_{R_{k-1}} & -\sin\hat{\phi}_{R_{k-1}} & 0 \\ \sin\hat{\phi}_{R_{k-1}} & \cos\hat{\phi}_{R_{k-1}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (9)$$

The complete system state vector expression is:

$$\hat{X}_{R_{k|k-1}}^{B} = \begin{bmatrix} \hat{X}_{R_{k-1}}^{B} \oplus \hat{X}_{R_k}^{R_{k-1}} \\ \hat{X}_{F_1}^{B} \\ ... \\ \hat{X}_{F_n}^{B} \end{bmatrix} \quad (10)$$

In order to constantly update and create map, the new environment features need to be added to the state vector, feature points corresponding to the underwater robot's position is represented by vector $\hat{X}_{F_i}^{B}$, covariance matrix is $P_{F_i}^{B}$, the augmented matrix vector is:

$$\hat{X}_{aug}^{B} = \begin{bmatrix} \hat{X}_R^B & \hat{X}_{F_1}^B & ... & \hat{X}_{F_n}^B & \hat{X}_{new}^B \end{bmatrix}^T \quad (11)$$

where

$$\hat{X}_{new}^{B} = \hat{X}_R^B \oplus \hat{X}_{new}^R \quad (12)$$

the updating covariance matrix is:

$$P_{aug}^{B} = F_{aug} P^B F_{aug}^T + G_{aug}^B P_{new}^R G_{aug}^T, \quad (13)$$

where

$$F_{aug} = \begin{bmatrix} I & 0 & ... & 0 \\ ... & ... & ... & ... \\ 0 & 0 & ... & I \\ J_{1\oplus} & 0 & ... & 0 \end{bmatrix}; G_{aug} = \begin{bmatrix} 0 & ... & 0 & J_{2\oplus} \end{bmatrix}$$

P_{new}^{R} is the new covariance matrix of the feature vector.

In Fig. 2, it shows that the robot in the two-dimensional space is simulation effect picture of SLAM algorithm. The movement location of the robot is updated by the measured value in every state, then according to the location of the robot the coordinates of feature point are measured. In the figure, the blue point is the route sign testing point for robot, and the red point is the obstacle testing point. The red curve is a work route set for robot in advance and the orange thick line is a navigation route obtained based on SLAM algorithm. Through MATLAB simulation, it shows that the route is better consistent with the one set beforehand. But when there are too many environmental characteristics, the calculation spends a lot of time, and it is easy to cause offset. The algorithm is worth optimizing.

3.2. Underwater Obstacles Identification

It is necessary for underwater robot to have the ability of obstacles-identification during a travel underwater. The obstacle data obtained from the sensors must match the obstacle in the pre-processing map, if the successful matching number reaches a certain threshold, it proves that the obstacles do exist. And then do SLAM calibration process, in order to improve the diagnostic accuracy of obstacle information. When the same obstacle within the detection range of the sensor, it should be collected many times continuously in theory, however the obstacle added to the pre-processing map has not been collected many times continuously, then the match fails, which can diagnose that the obstacle information is not accurate, we should remove it from the pre-processing map. Now we need to set two thresholds of obstacle judgment m & n, if the matching number is less than m, we remove the obstacle from the pre-processing map, if the matching number is greater than n, it judges that the obstacle does exist.
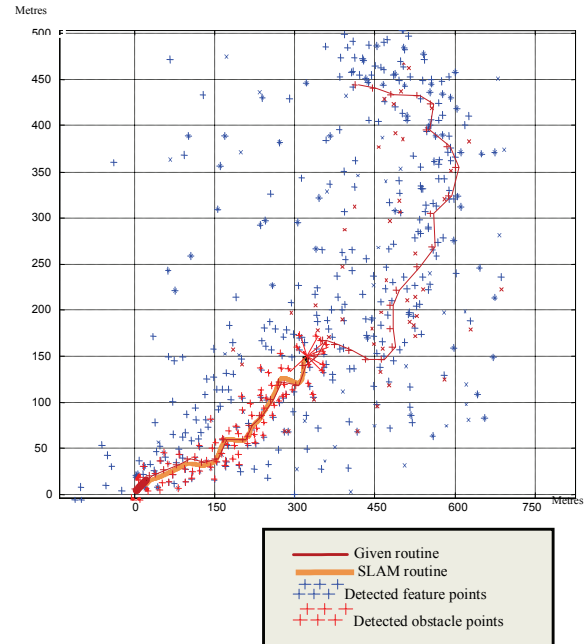

Fig. 2. Underwater Robot SLAM Incremental map simulation diagram.

4. Water Quality Measurement and Latitude and Longitude Match

4.1. Water Quality Measurement

The sensor probe integrates 7 kinds of sensors, they are: temperature, turbidity, blue-green algae, chlorophyll a, dissolved oxygen, PH, ORP. The test data from sensors is converted by A/Dmodule [13], and then the data transfer through RS485 communication interface to the underwater robot built-in microprocessor. RS485 level conversion chip choose MAX485. It has the advantages of low power consumption, automatic hibernation. In order to avoid mutual interference of the signals [14], and also to avoid failure of one signal affect other road signals, and the brightest chips are mutually independent in power supply, and the junction of the signal is opto-isolated [15,16]. This method can improve the reliability and stability of the system.

4.2. Water Quality Match Latitude and Longitude

Underwater robot built-in microprocessor contains a sensor database, the database mainly receives the test point data of each latitude and longitude, and at the same time open up enough memory to store the water quality parameters, the memory space is named with the current latitude and longitude. At the end of the test, the database now has stored all water quality parameters in different latitudes and longitudes. The research and development of Density Map software is based on this database created above. Firstly, the software automatically draws a contour map of the testing area, the then calls database data. The software shows different shades of color in the corresponding region according to the concentration of various water quality parameters, which can visually analyze the current water quality conditions .It also provide a research basis to the relevant departments. The data processing flow is shown in Fig. 3.
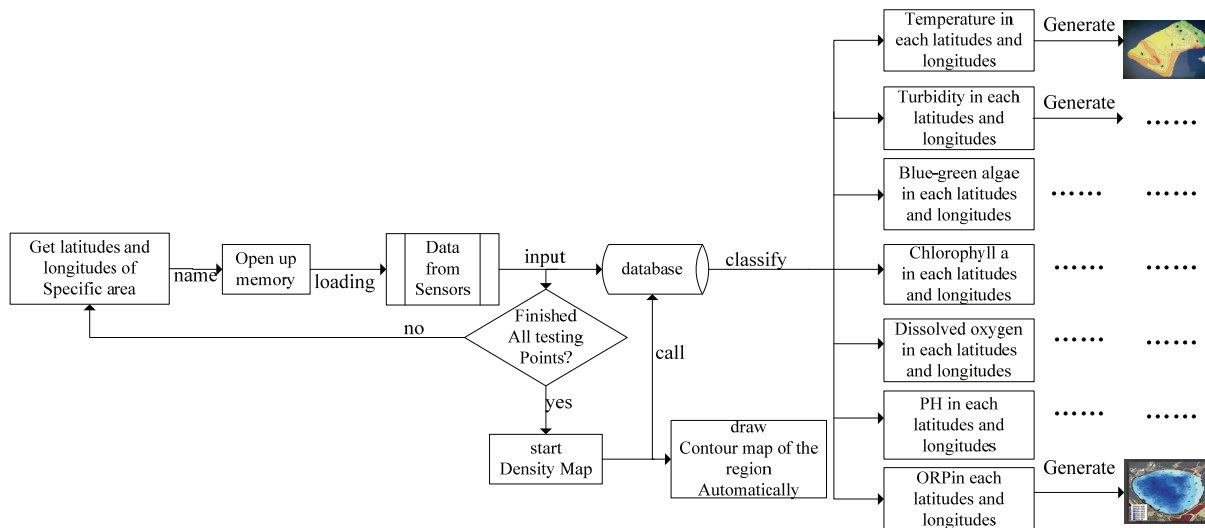

Fig. 3. The data processing flow of the system.

5. Experiments and Analysis

In November 2012, our groups have conducted several experiments in Nanjing External Qinhuai River of China. And at the same time we carry two kinds of the market water quality detector for simultaneous detection, which has initially verify the reasonableness of the design and the feasibility of the testing results.

5.1. Implementation Methods

The experiment was divided into two parts. The first part: the research group uses our own underwater robot to conduct water testing. The robot's hardware configuration mainly includes: 10 ADCP Doppler velocity taximeter instruments; 4 speed beam and a vertical (down) beam sounding and altimetry; electronic compass, model: Honeywell, HMR3000 electronic compass; side-scan imaging sonar, model: Delta T multibeam sonar; the depth sensor, model: Canada NetMind. The overall hardware device is shown in Fig. 4 The second part: we choose two kinds of water quality testing instrument sold in markets to do a comparative analysis. The two water quality testers (Fig. 5) are: XZ-0111 type 11 parameter water quality analyzer; 5B-3B (V8) multi-parameter water quality analyzer. They can not navigate autonomously, so we use fixed-point detection method.

Fig. 4. Prepare debugging.

5.2. Analysis

At the end of the underwater robot navigation, water quality parameters have been stored in the shore-based facility computer. Fig. 6 shows the Density Map software operation interface, the software is developed into to match the test parameters with the latitude and longitude match. As can be seen from Fig. 6, according to the needs of the environment of the area we test, we can selectively obtain the required measurement parameters. In the experiments, we choose temperature, dissolved oxygen, and turbidity three kinds of water quality parameters. Fig. 6 displays the concentration of each area, color difference represents different concentration, the darker the area, indicates that the concentration of the substance of the region is the deeper. Density Map not only show the latitude and longitude of each parameter diagram, we can also choose the drop-down box inside the data sheet directly to obtain the other parameters in different latitude and longitude.

In the experiment, we select the XZ-0111 type 11 parameter water quality analyzer and-5B-3B (V8) multi-parameter water quality analyzer for reference. Test results are as follows.

Tables 1-4. We treat the average of XZ-0111 and $5 B - 3 B$ measuring data as a standard reference value, then the error calculated as: Error=|underwater robot testing data - standard| /standard.

From the Tables 1 - 4, we can see, robot water quality parameters measurement error is always maintained within ± 5 %, to some extent shows the feasibility of our design. However, the biggest advantages of this system are that it can be combined with shore-based facility, and get the latitude and longitude matching diagram of water quality parameters.
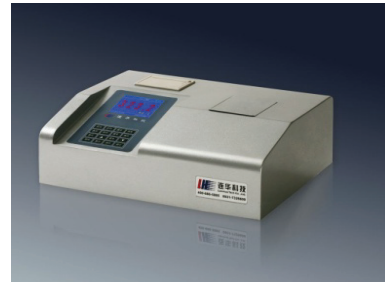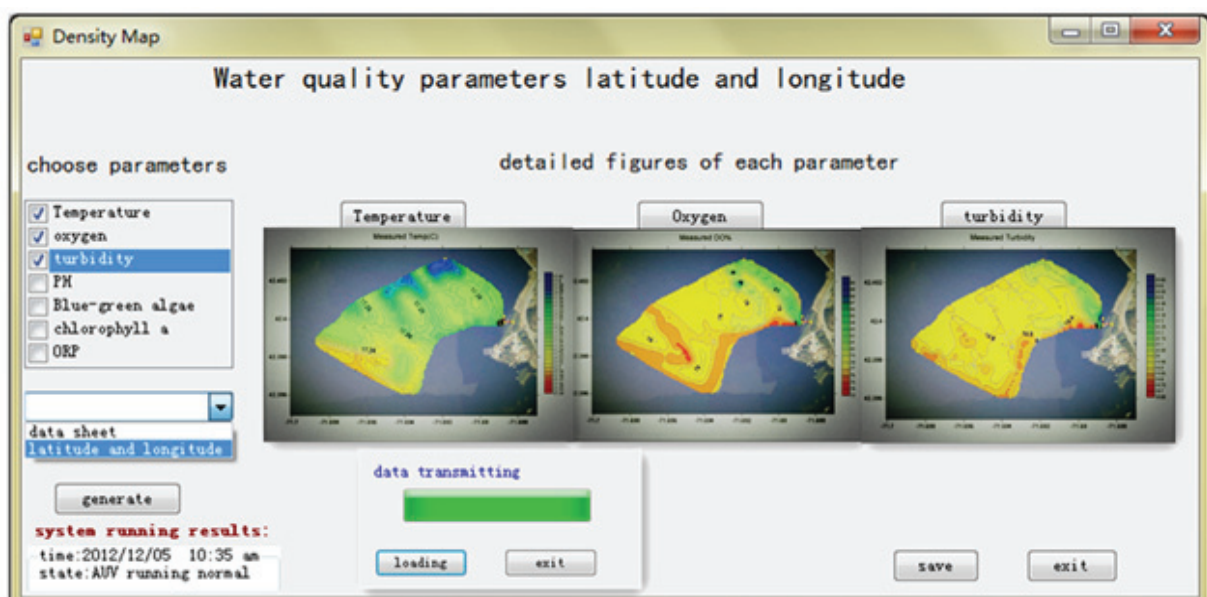

Fig. 5 (a). XZ-0111.

Fig. 5 (b). 5B-3B.

Fig. 6. Measuring results displayed on Density Map.

Table 1. 118.31°E, 32.04°N, 10 am.

Instrument	Tempera-ture, °C	Dissolved oxygen, mg/L	Turbidity NTU
XZ-011	13.7	9.2	20.5
5B-3B	13.9	9.5	21
Robot	13.6	9.8	20.2
Error	1.44 %	4.81 %	2.65 %

Table 2. 118.28°E, 32.27°N, 11 am.

Instrument	Tempera-ture, °C	Dissolved oxygen, mg/L	Turbidity NTU
XZ-011	14.1	8.8	22.5
5B-3B	14.5	8.9	21
Robot	14.4	8.8	21.2
Error	0.7 %	0.56 %	2.6 %

Table 3. 119.05°E, 31.52°N, 1 pm.

Instrument	Tempera-ture, °C	Dissolved oxygen, mg/L	Turbidity NTU
XZ-011	12.7	9.5	18.6
5B-3B	12.4	9.9	18.8
Robot	12.4	9.4	18.9
Error	1.2 %	3.1 %	1.1 %

Table 4. 119.14°E , 32.15°N, 2 pm.

Instrument	Tempera-ture,°C	Dissolved oxygen, mg/L	Turbidity NTU
XZ-011	12.9	9.2	21.5
5B-3B	12.6	8.9	21.8
Robot	13.0	9.3	21.3
Error	2.0 %	0.56 %	2.8 %

6. Conclusion

This paper innovatively put forward a water testing system equipped in underwater robot, getting rid of the traditional fixed-point measuring mode. The measuring method and accuracy have been greatly improved. However, there are still large room for improvement in data acquisition and processing.

In future research work, the following can be drawn with respect to the reach examined:

- The accurate and high efficient wireless communication between underwater robot and shore-based facility is very important to improve system performance, which can reduce memory spending.
- The present system now can choose to measure specific parameters, if the measurement conditions change, the other parameter measurements maybe required to measure, sensor needs to increase, the

more kinds of data fusing together is a major difficulty.
- When there are too many environmental characteristics, the calculation spends a lot of time, and it is easy to cause offset. The algorithm is still worth optimizing.
- Underwater robot positioning is still a problem, and how to further precise positioning, coordinate the various navigation facilities working together is an important task for future research.

Acknowledgements

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