

# System Design of Water Quality Monitoring Robot with Automatic Navigation and Self-test Capability

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## Abstract

*This paper proposes a water quality monitoring system of underwater robot with self-test and diagnosis capability. The system consists of underwater robot, water quality data collection module, self-test and diagnosis module, wireless communication module, and shore-based facility. The measurement results from each sensor of water quality data collection module are transmitted to the built-in micro-processor of the underwater robot. And the self-test and diagnosis module based on DSP connects with the built-in microprocessor through RS232. The self-test and diagnosis module conducts wavelet transform for the sensor information, generating extreme points of the wavelet transform, which are used to detect the abnormal state of the current system. The threshold method is introduced to reduce the influence of the noise. The disturbance of the noise can be alleviated by setting threshold for high frequency parameters of the wavelet transform. The exceptional information was detected by the self-test module and the water quality data information was transmitted to the shore-based facility through the wireless communication module. The shore-based facility can process, analyze and determine the collected information, and then give feedback to the underwater robot. The feasibility of the system design and the rationality of the water quality parameter measurement results were verified by experiments and on-site tests.*

**Keywords:** Underwater robot, Water quality monitoring, Self-test and diagnosis, Wavelet transform, Data communication, Micro-processor

## 1. Introduction

Underwater robot is a new facility for water quality monitoring, self-test and diagnosis. In the existing water quality monitoring and data processing robots, there still exist some drawbacks. Firstly, as the underwater robot needs to work underwater for a long time, it is impossible for GPS to precisely locate its position through water [1, 2, 3]. Secondly, the underwater robot normally works in the mild environment. Therefore, the accuracy of water quality monitoring in complicated water environment cannot be guaranteed [4, 5, 6]. Particularly, once the robot is broken, it will be out of control from the shore-based facility. Thirdly, there exist many problems in the network system, such as the instability and high failure rate, which are unable to meet high-performance and stability requirements [7]. Finally, the existing communication system between underwater testing and shore-based

station only allows data transmission. Therefore, data analysis and decision making functions need to be added.

Aiming at the aforementioned drawbacks (especially the third point), this system combines the self-test module based on DSP and the 802.11 Ethernet wireless communication, enabling the data acquisition of robot operation condition and water quality. Experimental results verified the feasibility and effectiveness of our design scheme.

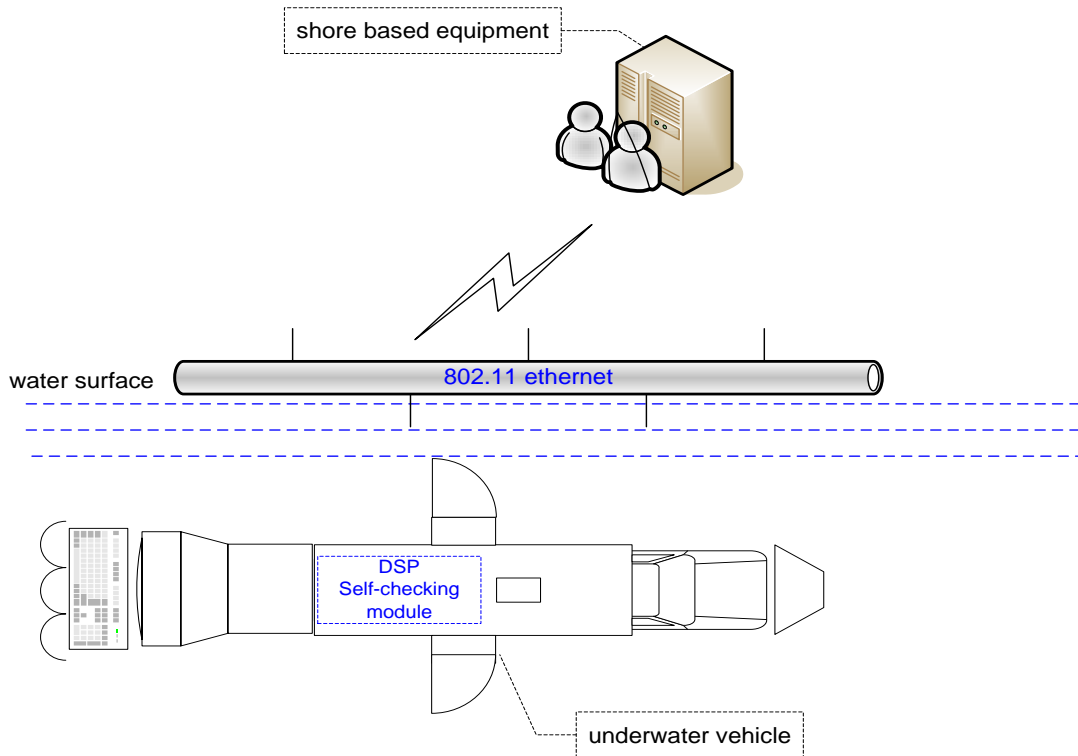
## 2. The Overall Design Scheme

The scheme of underwater water quality monitoring robot with self-test ability is shown in Figure 1. It consists of underwater robot (with water quality data collection module and self-test module embedded), wireless communication module and shore-based facility. The self-test module independently researched and developed based on DSP is embedded in the robot and connected to the built-in microprocessor by RS232 [8]. The module can acquire and analyze the water quality real time data at each point and then send the analysis result and the water quality data to the shore-based facility through the 802.11 Ethernet wireless communications [9, 10]. Independently researched and developed communication system software has been installed on the shore-based computer, which will analyze the real-time operation of the underwater robot on-line [11].

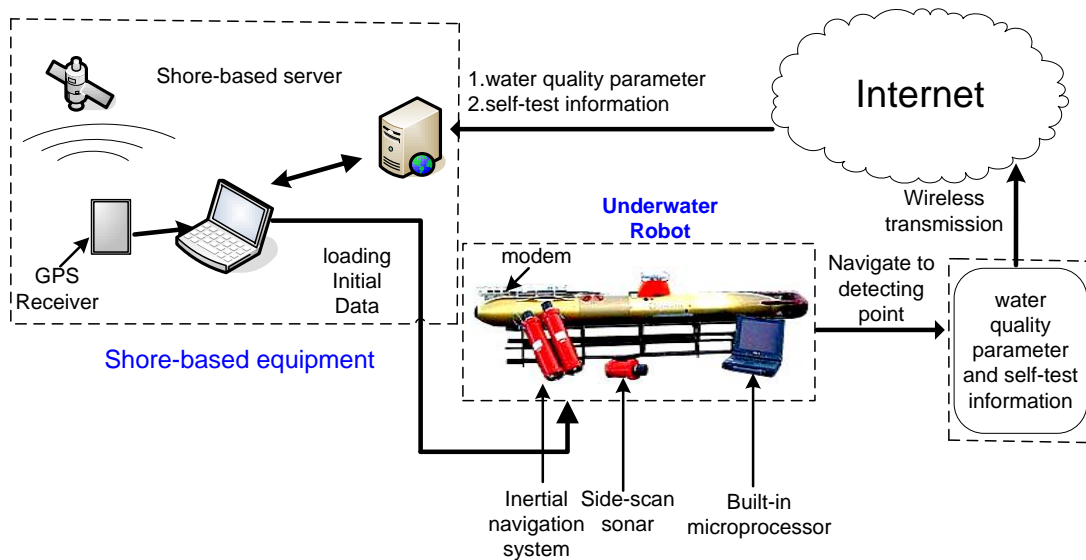
The underwater robot self-test and diagnosis module mainly include non-visual sensors, including electronic compass, speedometer, side-scan sonar, depth sensor and a variety of water quality sensors. Reasons causing system failure are as follows: damage to the sensor element, aging of components, and strong pulse interference upon electric circuit [12]. Underwater robot usually presents system errors in two ways: mutations failure (sudden transition in sensor output data) and oscillation failure (the sensor output data oscillates in the time domain and eventually stabilizes at a specific value) [13, 14].

In this paper, the input and output signal of the system is processed using wavelet transformation, which will obtain singular points of the input and output signal, and then remove the extreme points caused by the input mutations [15]. The rest of the extreme points are caused by the mutation failure of the system. With the use of this method, there is no need to establish a mathematic model of the monitoring object and a lower level of the input signal is required. Besides, this method is also advantageous in low computational complexity and high sensitivity, which has strong noise resistance and can realize real-time online fault detection [16].

The software was developed using VS2008 software and programmed using C language, with in C# Graphic User Interface. Independently researched and developed software has been installed on the shore-based facility which will show the operation condition of the system and water quality data directly, facilitating in-time decision making [17, 18].



**Figure 1. Schematic diagram of the overall system design**



**Figure 2. System operation flow chart**

Figure 2 shows the flow chart of the system. Shore-based computer initializes the lane, speed and fixed testing time of underwater robot in the test area and transmit the initialized

data via the wireless serial port to the built-in computer of the underwater robot. The head of the underwater robot is equipped with antenna and modem. The built-in computer will transmit the data received to the modem and then back to the shore-based computer via the antenna. Multi-sensor acquisition system has been installed in the underwater robot for water quality data collection, such as water temperature, turbidity, blue/green algae, Chlorophyll A, DO, PH, ORP and *etc.* Data will then be allocated to the relevant latitude and longitude which will be sent to the built-in computer of the underwater robot [19]. Meanwhile, the computer begins to self-test to determine whether the robot is in normal operation. Before moving on to the monitoring of the next test point, underwater robot will send the result to the shore-based computer via wireless communication. The above process is repeated before the data of all the points are obtained. Afterwards, the robot will return to the initial location and the monitoring task ends. Water quality data are obtained via wireless communication network and displayed on the shore-based facility.

Comparing with the existing schemes from the other researchers, we have designed the newest robot system not only with water quality monitoring system, but also has self-test and diagnosis module. In hardware design, the self-test and diagnosis module based on DSP interconnects with the built-in microprocessor through RS232. It can help relevant researchers get water quality timely and quickly without any danger as long as self-test module transmit system running state quickly. In software design, self-test and diagnosis module conduct wavelet transform for the sensor information. The two aspects above are the great innovation parts in the whole design.

### **3. Hardware System Design**

#### **3.1. Brief Introduction**

The system is based on underwater robot, which includes: 10 ADCP Doppler velocity taximeters, Honeywell (model: HMR3000) electronic compass, Delta T multi-beam side-scan imaging sonar, and the NetMind (Canada) depth sensor. Water quality data communication module is installed into the underwater robot, which is connected to the underwater robot micro-processor through asynchronous serial data transmission interfaces for water quality data acquisition. This module is equipped with temperature, turbidity, blue/green algae, chlorophyll A, dissolved oxygen, PH and ORP sensors.

Self-test module is the most important part of the hardware system as a whole, which is connected to the underwater robot micro-processor using RS232. When the self-test information is received by the micro-processor, it will be sent to the shore-based facility via wireless network. The system errors are often displayed as: (1) shore-based facility cannot receive water quality data in the pre-set time and (2) software user interface of the shore-based facility presents unstable data and sudden change appears frequently in the same region. Once error is detected by the shore-based equipment, it will call back the underwater robot and suspend the ongoing task.

Wireless communication model relies on 802.11 Ethernet for water quality data and self-test information transmission. After data collection and self-test information have been finished at a certain longitude and latitude, the underwater robot will immediately go to the water surface and send the data to shore-based facility then continue navigate to the next point until all data are collected or system error occurs [20].

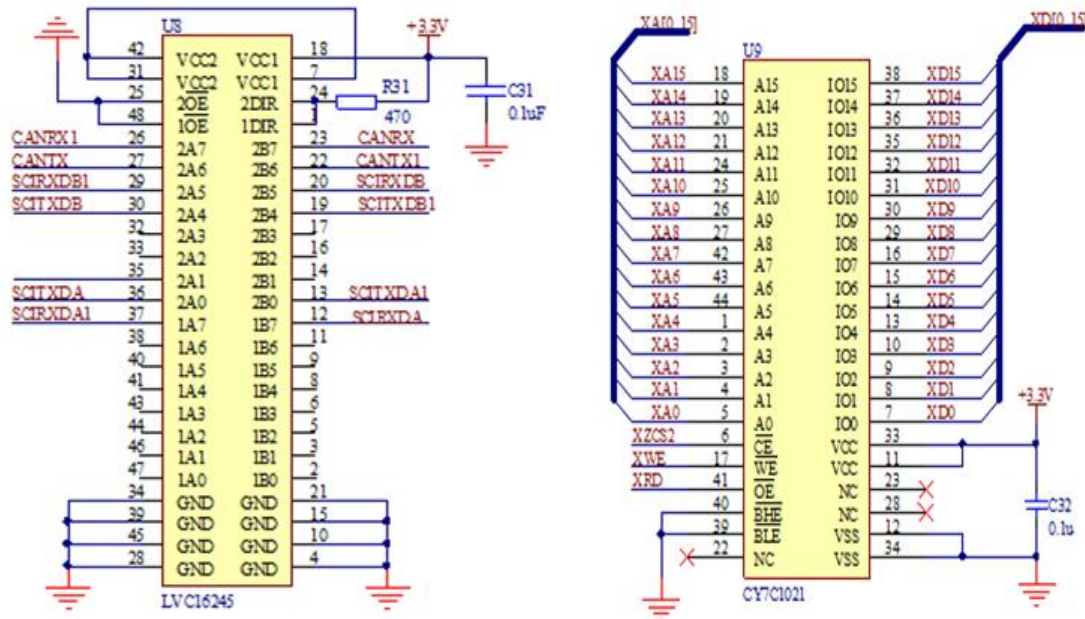
### 3.2. Self-test and Diagnosis Module Based on DSP

The Self-test and diagnosis module is based on DSP, which uses digit signal processor (model TMS320F28335). As for CPU, we used TMS320F28335 produced by Texas Instrument Company in USA. It is a chip with highly integrated peripherals, which will simplify the design, save wafer space and enhance the stability of DSP system. Figure 3 shows the design of the circuit wafer including power module, DSP data processing template, RS232 serial communication template and keypad control module [21].

Figure 3 shows the core part of hardware module of DSP and Figure 4 shows the hardware model of power filter and corresponding interface, which is based on TMS320F28335 DSP chip self-test system [22]. Underwater robot communicates with DSP self-test and control model through RS232 serial communication interface. The logic control circuit of the sensor in water data communication template will display the data received on the screen of shore-based facility, where the Vector Map has been installed [23]. Vector Map will control the movement of underwater robot and send data collection command. RS232 asynchronous serial communication is used to transmit information to the DSP self-test module and the controlling shifter in DSP control module [24]. In the circuits design, RS232 communication module consists of MAX232 chip and 74CBTD3384 chip. IS61LV25616 chip can be used on external memory with a read-write cycle of 10 ns and 0.5 M storage space. Program source code and communication data between the underwater robot and DSP self-test as well as the controlling module can also be stored in the chip.



**Figure 3. The core part of hardware template of DSP**

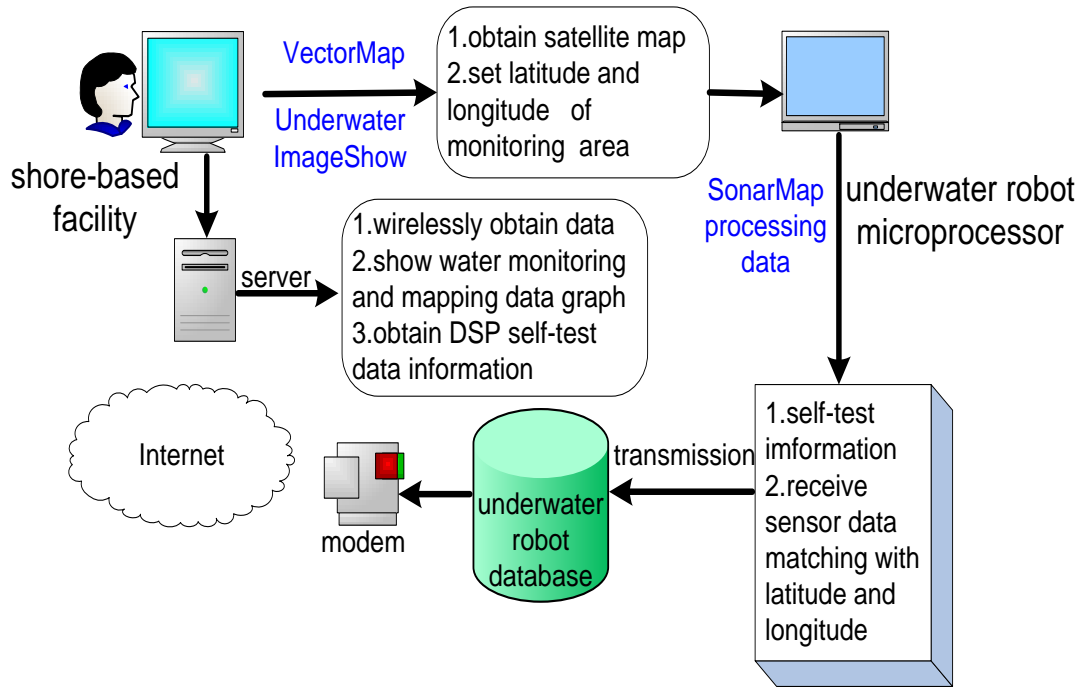


**Figure 4. Hardware template-power filter and relevant interface**

U8 in Figure 4 represents buffering and level switch. Pin 2OE and 1OE are connected to the ground, pin 26, 27, 29, 30, 36 and 37 connects to 22, 23, 19, 20, 12 and 13, respectively and to CANRX1, CANTX, SCIRXDB1, SCITXDB, SCITXDA and SCIRXDA1, respectively, at the same time. U11 is the EEPROM interface unit, and A0, A1 and A2 are connected to the ground, WP, SCL and SDA are connected to IOB13, IOB12 and IOB11 of the TMS320F28335 chip respectively. U14 is the main interface of the CAN unit. The sending terminal CANTX1 and the receiving terminal CANRX1 are both connected to +5 V 470  $\Omega$  power supply. CANH and CANL are connected to CANL and CANH output terminal, respectively. T1OUT of MAX202E chip is connected to PCTXDA, R1IN is connected to PCRXDA then output to COM1. T2OUT of MAX202E is connected to PCTXDB and R2IN is connected to PCRXDB then output to COM2.

#### 4. Software System Design

We have independently developed a software system which includes three components: Vector Map, Underwater Image Show and Sonar Map. The first two are embedded in the shore-based facility computer, and Sonar Map is embedded in the robot. 802.11 Ethernet provides remote information transmission among the three components and Figure 6 shows the schematic diagram of the software architecture [25].

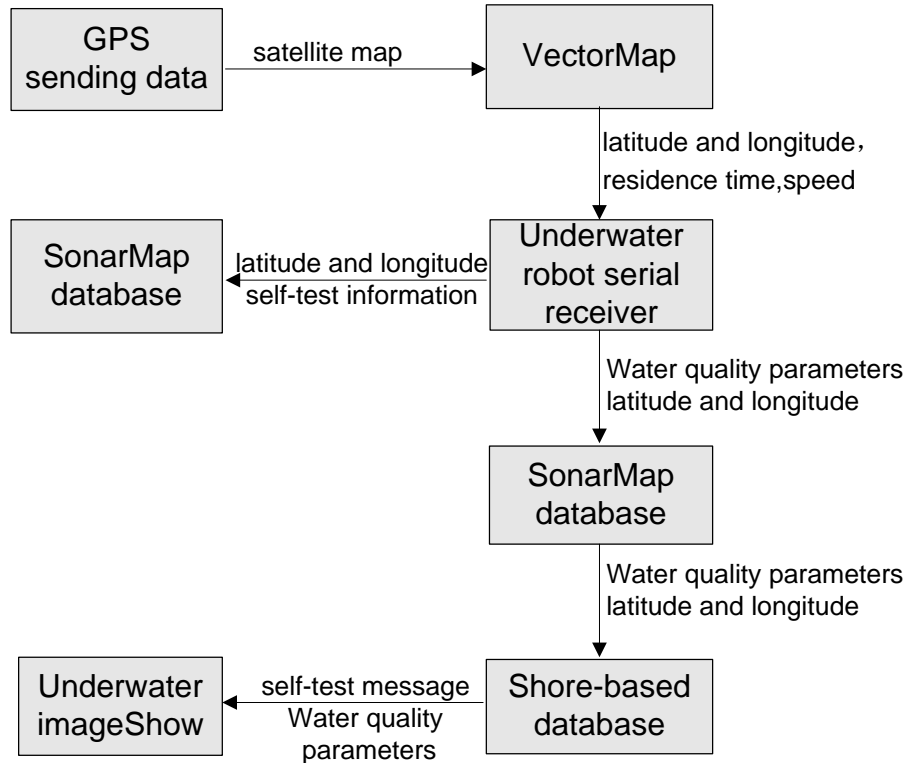


**Figure 6. Schematic diagram of software architecture**

#### 4.1. Software Data Flow

Figure 7 shows the system top level data flow diagram between internal software, the entire data flow diagram shows coordinate working process of the software system, self-test and control module based on DSP, wireless communication network communication module and water quality data module [26, 27].

The data flow module is controlled by the software system. It has a working process of (1) According to the satellite map of its own, Vector Map can get the following information including latitude and longitude of testing spot, test duration for each spot, speed, which will be used to initialize the underwater robot through RS232. And when the initialization information is received by the underwater robot via serial port, it will be passed the built-in micro-processor database. (2) The initialization information will also initialize the SonarMap software. SonarMap will also receive data including water quality data of each testing spot DSP self-test and module self-test information.



**Figure 7. Top level data flow diagram in software systems**

If the data acquired by the robot is normal (no sudden interruption nor data skipping), underwater robot will float to water surface and transmit water quality data to the shore-based facility micro-processor before moving on to the next testing spot with the help of 802.11g Ethernet wireless network. If an exception occurs, the robot will transmit abnormal information to the shore-based facility micro-processor and the computer will send back commands immediately to terminate the execution of task through the wireless net, and the underwater robot will return to the shore.

#### 4.2. Wireless Communication Protocol

Data link layer in wireless communication network uses CSMA/CA (Carrier Sense Multiple Access with Collision Detection, Carrier Detect Multiple Access with Collision Detection) protocol in the Ethernet MAC layer. When underwater robot needs to send data after finishing monitoring a certain testing spot (referred as the detection node), it goes up to the water surface, and then Ethernet will check whether the channel is occupied. If the channel is busy, Ethernet will wait until the channel is free. Then Ethernet begins to send data to the shore-based facility immediately. If two or more detection nodes monitor channels are idle and they send data at the same time, conflicts will be caused. Once a conflict is detected, the node will stop data transmission, and wait for a random length of channel free time [28]. Length of waiting time depends on BEB (Binary Exponential Back off, binary regression algorithm) fallback algorithms. After the 10<sup>th</sup> fallback, waiting time will return to a fixed value [29]. After the 16<sup>th</sup> fallback, the detection node will stop working and send out error



signal to shore-based facility. Each detection node must obey the algorithm mentioned above to guarantee the accurate data communication through the free channel.

### 4.3. Self-test and Diagnosis Algorithm Based on Wavelet Transform

Wavelet transform is able to detect abrupt changes in the signal, which helps to determine whether the system is in an abnormal operation condition. As the powerful DSP processor has high-speed input and output interfaces and high-speed data transmission it would be more beneficial to make full use of the combination of wavelet transform and DSP processor.

The basic idea of the self-test and diagnosis method based on wavelet transform can be described as: the input signal is processed using wavelet transform, and the abrupt change points are detected. The abrupt change points caused by input mutation are then removed, leaving the rest corresponding to the abnormal operation condition of the system [30]. The method does not require the establishment of a mathematic model for the diagnostic object, and requires a lower level of the input signal, which will lead to low computational complexity.

If signal  $f(t) \in L^2(R)$ , continuous wavelet transform can be defined as:

$$W_f(a,b) = |a|^{-1/2} \int_{-\infty}^{+\infty} f(t) \bar{\psi}(a_0^m - nb_0) dt \quad (1)$$

where  $a$  is a scale factor,  $b$  is a translation factor,  $\psi(t)$  is the generation function. Because the continuous wavelet transform has a large redundancy, we can sample the scale factor and translation factor, namely:

$$a = a_0^{-m} (a_0 > 1) \quad (2)$$

$$b = nb_0 a_0^{-m} (b_0 > 1) \quad (3)$$

Then the discrete wavelet transform is:

$$D_f(a,b) = \int_{-\infty}^{+\infty} f(t) a_0^{m/2} \bar{\psi}(a_0^m - nb_0) dt \quad (4)$$

when  $a_0 = 2, b_0 = 1$ . Then the binary wavelet transform can be obtained. Mallat algorithm is used in wavelet decomposition and detailed procedures are as follows:

$$c_{j,k} = \sum h_{n-2k} c_{j-1,n} \quad (5)$$

$$d_{j,k} = \sum g_{n-2k} c_{j-1,n} \quad (j=1,2,\dots,J) \quad (6)$$

The signal reconstruction algorithm can be derived as:

$$c_{j-1,n} = \sum h_{n-2k} c_{j,n} + \sum g_{n-2k} d_{j,n} \quad (j = J, J-1, \dots, 1) \quad (7)$$

If  $f(t)$  or its derivative is not continuous at a certain point, then the function is singular at that point, which can be represented as Lipschitz exponent. If  $0 \leq a \leq 1$ , for any number around  $t_0$ , there exists a number  $K$  satisfies the equation:

$$|f(t) - f(t_0)| \leq K |t - t_0|^a \quad (8)$$

Then we can say the function has a Lipschitz exponent  $a$  at point  $t_0$ .  $a$  represents the degree of singularity at  $t_0$ . The larger  $a$  is, the weaker the singularity is. The relationship between singularity and maximum of modulus can be described as that if  $t_0$  is a singularity point, wavelet transform in the point has modulus maximum. By determining the wavelet transform modulus maximum, the position of abrupt change point and the time it occurs can be found.

#### 4.4. Denoising Algorithm for Abrupt Change Signal

In order to increase the accuracy of self-test and diagnosis and make the diagnosis result more effective, we need to find out ways to optimize the wavelet analysis method. In low-scale detail, the wavelet transform coefficients of noise is very big, while in high-scale coefficient, its amplitude decreases drastically. Therefore, we can set a threshold for the high frequency coefficients, which would guarantee the elimination of the influence of noise in the abrupt change points and the vicinity where wavelet transform modulus reaches the maximum. The threshold is usually defined as:

$$\lambda = \sigma \sqrt{2 \log(Num)} \quad (9)$$

where  $\sigma$  is the noise variation,  $Num$  is the number of the wavelet coefficients at different scales.

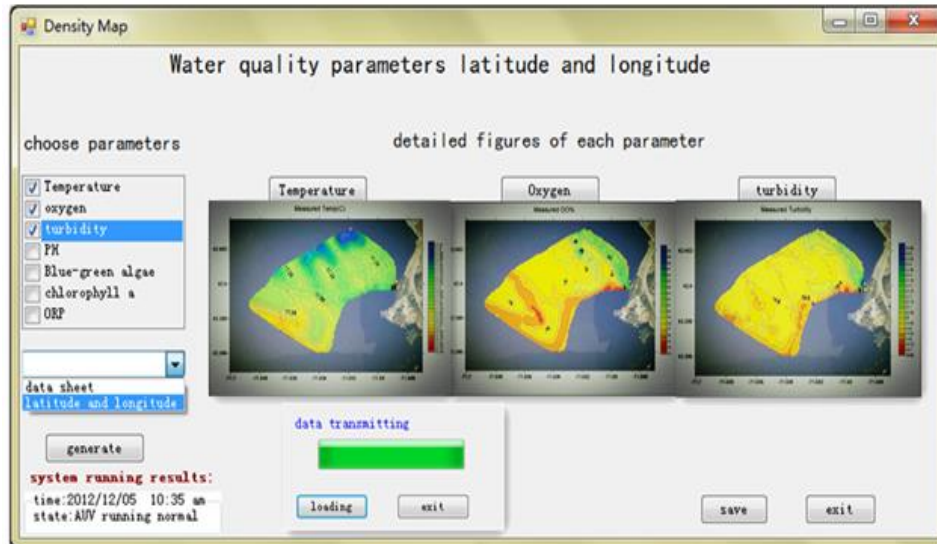
Mallat algorithm is used to process the signal. The high frequency part of signal passing through the first layer of wavelet transform is difficult to be identified. At this time, in order to determine the existence and location of the abrupt change signal, we can only use high-level wavelet transform and select the appropriate frequency for analysis. With the threshold analysis method, the experiment showed that the abrupt change in signals disappeared in the second and third layer of wavelet transform, which drastically improved the measurement accuracy.

### 5. Experimental Results and Analysis

This experiment was carried out in Nanjing Qinhuai river in China. The the research group members carried out experiments with the independently researched and developed experimental apparatus. The experiment is divided into two parts. One is experiment in normal condition so that we can compare the test results with normal water quality data to determine the accuracy of the system. The other is experiment in abnormal condition so that we can check the system function of independent error detection.

#### 5.1. Water Quality Parameters Measured in Normal Condition

In order to further confirm the accuracy of this system, the experiment also selected the XZ-0111 type and 5B-3B type multi-parameter water quality analyzer for reference and comparison. Figure 8 shows the Density Map with normal robot, from which we can see the loads of data and obtain the latitude and longitude of the map of three water quality data.



**Figure 8. Density Map display of robot running in normal condition**

The test results with three measurement tools are listed in Table 1 to 3 (Only the temperature, dissolved oxygen and water turbidity are measured in this experiment). We take the mean value measured by XZ-0111 and 5B-3B as the standard reference, and the error formula is given by:

$$\text{error} = |(\text{robot measured value} - \text{standard reference value})| / \text{standard reference value}$$

**Table 1. 118.31°E, 32.04°N, 10 am**

Instrument	Temperature °C	Concentration mg/L	Turbidity NTU
XZ-0111	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**

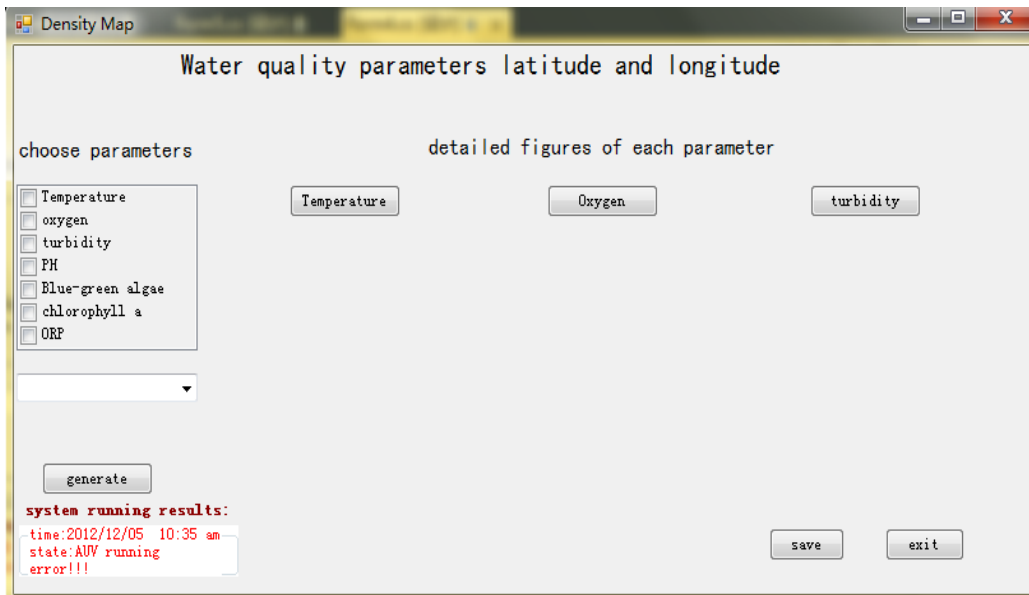
Instrument	Temperature °C	Concentration mg/L	Turbidity NTU
XZ-0111	14.1	8.8	22.5
5B-3B	14.5	8.9	21
robot	14.4	8.8	21.2
error	0.7%	0.56%	2.6%

**Table 3. 119.05°E, 31.52°N, 1 pm**

Instrument	Temperature °C	Concentration mg/L	Turbidity NTU
XZ-0111	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%

**5.2. Water Quality Parameters Measured in Abnormal Condition**

In order to get the operation condition of the robot underwater in abnormal condition, we deliberately disconnected the interface between the water quality parameter sensor and the computer in the robot which would simulate abnormal condition for robot in order to determine whether the DSP self-test module can give abnormal feedback. We determine the operation condition of the robot using the two references: one is to observe whether shore-based computer could give show real-time message in Figure 9.



**Figure 9. Density Map display of robot running in abnormal condition**

Water quality data are compared with data obtained from XZ-0111 and 5B-3B. Therefore, if there is a big difference, it means abnormal condition appears. The results are shown in Tables 4 to 6.

From the data in Table 4 to 6, we can see that when the mean values measured by XZ-0111 and 5B-3B are taken as the standard reference value, the error of the water quality data of the robot is nearly above 50%. Shore-based facility regularly prompt as in Figure 9, which means that the abnormal self-checking module can work normally.

**Table 4. 118.31°E, 32.04°N, 10 am**

Instrument	Temperature °C	Concentration mg/L	Turbidity NTU
XZ-0111	13.7	9.2	20.5
5B-3B	13.9	9.5	21
robot	1.6	0.8	0.2
error	88.40%	91.44%	99.04%

**Table 5. 118.28°E, 32.27°N, 11 am**

Instrument	Temperature °C	Concentration mg/L	Turbidity NTU
XZ-0111	14.1	8.8	22.5
5B-3B	14.5	8.9	21
robot	0.7	12.8	0.2
error	95.10%	44.63%	99.08%

**Table 6. 119.05°E, 31.52°N, 1 pm**

Instrument	Temperature °C	Concentration mg/L	Turbidity NTU
XZ-0111	12.7	9.5	18.6
5B-3B	12.4	9.9	18.8
robot	22.3	0.4	27.9
error	77.69%	95.88%	49.20%

## 6. Conclusion

This paper proposes a self-test and data transmission system which can be applied onto underwater robot. It can get the real-time information of the current working condition of the underwater robot accurately to guarantee even more accurate access to the water quality data and also support decision making.

In future research, there is still large room for improvement in terms of hardware and software of the system. Further research will be built upon the following aspects. Firstly, the distance between the underwater robot and the wireless communication of shore-based facility is the bottle neck. Hence, it requires further study on how to maximize the free test range of the underwater robot. Secondly, the communication delay between the underwater robot and the shore-based facility is long and the position and the data fit errors occur occasionally, which puts forward new requirements for the real-time performance of the system. Thirdly, underwater robot for a long time underwater navigation gets easily polluted by impurities, causing sensitivity decrease of the sensor. Therefore, how to incorporate mechanical automation technology and come up with a kind of probe automatic cleaning technology remains to be solved in future.

## Acknowledgement

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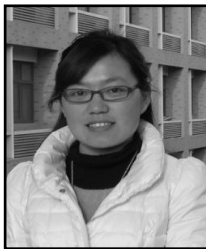
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