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Research on an Extensible Monitoring System of a Seafloor Observatory Network in Laizhou Bay

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Abstract: An extensible remote monitoring system for a seafloor observatory network in Laizhou Bay was established to realize long-term, continuous and on-line monitoring for a marine ranching environment. This paper deals with data communication, device management and data quality control. A control model is introduced that is structured into four layers, enabling bidirectional information flow. Based on the control model, the standardized communication protocol and device object model-oriented dynamic management method are designed as plug-and-play, for data processing and control of a large number of devices . An improved data quality control method is proposed to reduce the data error rate. The monitoring system was developed based on socket network programming, MySQL database technologies and modular ideas. The seafloor observatory network was successfully deployed in Laizhou Bay marine ranching. The experimental results demonstrate that the monitoring system obtains better performance. The proposed algorithms can also be used in many other similar systems with adaptive requirements.

Keywords: marine ranching; seafloor observatory network; remote monitoring; data communication; device management; data quality control

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1. Introduction

Marine ranching is an important way to realize the harmonious development of ecosystems [1]. Building a system of automatic monitoring and early warning and forecasting of the key factors of the marine environment is the basis of studying marine ranching [2]. Smart ocean observation mainly includes sea-based observation based on survey ships, submarines and buoys, and space-based observation based on satellite remote sensing [3]. Cabled seafloor observatory networks play an important role in realizing long-term, continuous, on-line monitoring for marine ranching [4].

Many countries have carried out research on the key technologies of seafloor observatory networks. The United States started early in cabled seafloor observatory research and successfully established networks such as the Long Term Environment Observatory, which will be operated at 15 m (LEO-15) [5], Monterey Accelerated Research System (MARS) [6], Ocean Observatories Initiative (OOI) [7,8], Sound Surveillance Underwater System (SOSUS) [9] and Hawaii-2 Observatory (H2O) [10]. NEPTUNE, operated by Ocean Networks Canada (ONC) [11], is equipped with various instruments that can be used in different applications, such as a seismograph to monitor earthquake activity, bottom pressure recorders for real-time tsunami monitoring systems around the world, and specialized hydrophones to track marine mammal activity [12] and investigate how it is influenced by human activities. The European Multidisciplinary Seafloor and Water Column Observatory (EMSO) [13] consists of a system of regional observatories located at key sites around Europe. The EMSO infrastructure range runs at the European scale from the coastal area to the deep sea and open ocean, operating with both stand-alone observing systems and nodes connected to shore stations through fiber optic cables [14]. Japan focuses on deploying seafloor observatories for earthquake early forecast such as the Dense Ocean Floor Network System for Earthquakes and Tsunamis (DONET) [15], which began in 2006 and consists of several phases involving an increase in the number of observatories [16]. China has also been designing and building seafloor observatories in both the East China Sea and the South China Sea, the first trial of which is the Xiaoqushan Seafloor Observatory [17]. Furthermore, China has started the project of building a seafloor observatory network for marine ranching in the Yellow Sea and Bohai Sea in 2015 [2]. This paper designs a remote monitoring system for the construction of a seafloor observatory network in the Laizhou Bay stereo sensing network, which is a sub-task of the *smart ocean* project.

In terms of the seafloor observatory network, the monitoring system (SON-MS) is the key for data and control, and is also a link between users and seafloor devices [18]. Some research on monitoring systems of seafloor observatory networks has been conducted in recent years. One of the most important related advances is the Shore Side Data System (SSDS). The SSDS was established by the Monterey Biological Research Association (MBARI) of the United States in 2003 [19]. This system combines the collected data with metadata for analysis. The data is stored in a distributed database in various formats after preprocessing. The remote users can access it through relevant interfaces. Another mature system is the Data Management and Archiving System (DMAS). DMAS is established for the VENUS and NEPTUNE [11] Canada seafloor networks [20]. DMAS is divided into a data acquisition part and a user interaction part. The data acquisition part adopts the interaction mode with underwater devices. The user interaction part, which is called Ocean 2.0, includes data retrieval and information distribution. Web 2.0 technology is adopted to provide users with services such as data processing and visual communication [21]. DMAS mainly focuses on reducing data loss and maximizing time. It is a service-oriented architecture. DMAS adopts enterprise service bus and public subscription modes, and saves observation data in the form of files. The whole code is written in Java. The data of DMAS is scattered without considering the storage of observatory data over time [22]. It is difficult to query and analyze data to make data products. Besides the two related advances mentioned above, a data acquisition and management system that transmits IP packets through optical networks combined with event triggered and timing-driven devices is also of great relevance [23]. There is also a sensor web prototype for the seafloor observatory network in the East China Sea [24]. Most of the monitoring systems are only applicable to their corresponding local area networks with less functions. It is hard to meet the needs of dynamic device management and adaptive control for seafloor observatory networks. The major contributions of this paper are listed as follows:

- This paper focuses on the difficult problems and key technologies of the monitoring system in data communication, device management and data quality control;
- A standardized communication protocol and dynamic management algorithm are designed for plug-and-play of a large number of devices in the seafloor observatory network;
- An improved 53H algorithm is proposed to reduce the data error rate.

The rest of this paper is structured as follows. Section 2 is dedicated to modeling of the seafloor observatory network. The key technologies of SON-MS are explained and relevant implementation algorithms are designed in Section 3. Section 4 deals with the actual deployment test in Laizhou Bay marine ranching, and the results are also discussed. Section 5 summarizes the key conclusions of this work.

2. System Analysis

The control model of seafloor observatory network is divided into four layers. The sensing layer senses the dynamic marine environment information and it is also the information basis of the control model. The collecting layer collects on-site real-time marine observation data and forwards information between the service layer and the sensing layer. The service layer manages various types of information and provides a set of operations related to remote control. The application layer is a project oriented layer that utilizes different information to meet project requirements. The functions of every layer are independent and the interface between them is a standard form. Each layer uses the services of the adjacent lower layer and provides services to its adjacent upper layer.

As shown in Figure 1, the architecture includes three parts: the observatory node, the offshore platform, and the SON-MS, as well as two types of information flow (observatory data flow and instruction flow). The data flow (the green line) mainly includes the data obtained by the sensor at the observatory node, which needs to be uploaded to the SON-MS layer by layer. Similarly, the red lines represent the instruction flow; that is, SON-MS sends the instructions to the seafloor sensors layer by layer according to the requirements of remote monitoring. Compared with the control model and the architecture of SON-MS, the application layer and service layer are deployed in SON-MS, while the collecting layer and sensing layer are deployed in the observatory nodes. It can be seen from the architecture that SON-MS needs to establish a real-time communication link with seafloor devices, collect various sensor data and status data, and send corresponding instructions to seafloor devices at the same time. SON-MS manages hundreds of seafloor sensors and monitors the operation status and scientific data in real-time. Meanwhile, SON-MS needs to analyze, store, display and manage the collected data and provide the data service to users. The data communication of the two-way information flow is the premise for the normal operation of SON-MS. The dynamic device management of the observatory node is an important function for dynamic scalability. The data analysis and quality control are essential to designing SON-MS. More details are listed below:

(1) Data communication: In order to receive the data uploaded by the seafloor observatory network sensor through the submarine electro-optic composite cable, SON-MS must have the function of network communication;
(2) Device management: The whole seafloor observatory network has multiple junction boxes. Each junction box can connect to multiple data collectors and each data collector can connect to a variety of sensors. The IP address, communication protocol and communication data format of each device are different. SON-MS must manage the devices, the node information and subsystem information, and view the content of node information and subsystem information. SON-MS can add and modify the relevant information to ensure that the system can adapt to dynamic changes in the shortest time when the device is added or deleted;
(3) Data processing and products: The core of SON-MS is to obtain seafloor observatory data. SON-MS must distinguish different types of data, convert *source* data into *understandable* data, and store these data in the specified database table. At the same time, SON-MS needs to carry out effective quality control on the parsed data and make the data into products for users.

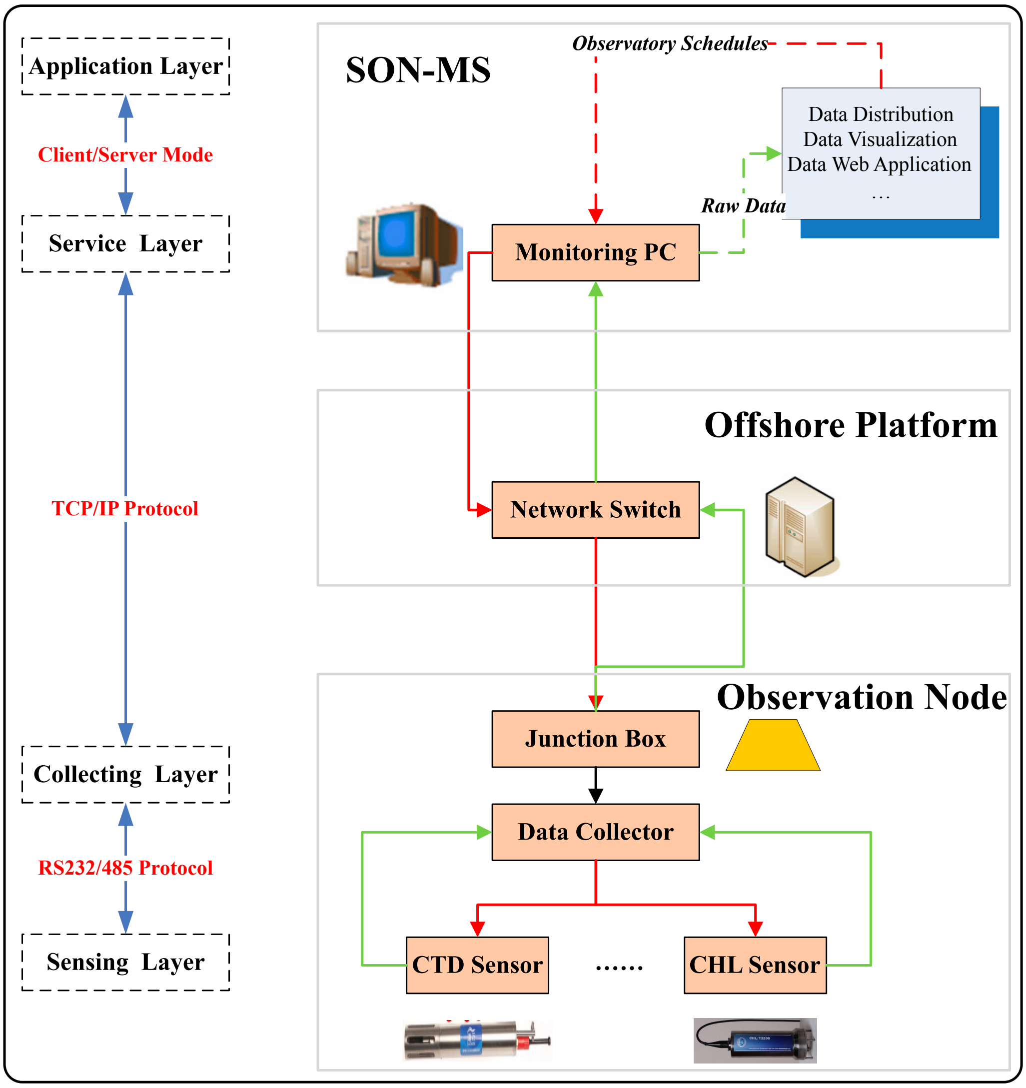

Figure 1. The information oriented architecture of SON-MS.

3. Key Technology and Implementation

3.1. Data Communication

3.1.1. C/S Architecture and Remote Communication Mode

The remote control system is basically equivalent to an application program, which consists of the client program and the server program. The architecture of an application is generally divided into client/server (C/S) mode or browser/server (B/S) mode. The remote monitoring system adopts C/S mode because the C/S mode has stronger interaction ability and information security capability than B/S mode.

In terms of C/S mode, the server is the monitoring computer running SON-MS in the monitoring center and the client is the on-site scientific node, including junction boxes, data collectors and sensors. TCP/IP network communication is used between SON-MS, the junction box and data collector, while serial communication such as RS232/485/422 is used between the data collector and sensor. The junction box and data collector are only electrically connected, without data interaction. SON-MS obtains the sensor data with the help of the data collector, which packages the data obtained through the serial port and sends it to SON-MS. The C/S architecture and remote communication form of the system are illustrated in Figure 2.

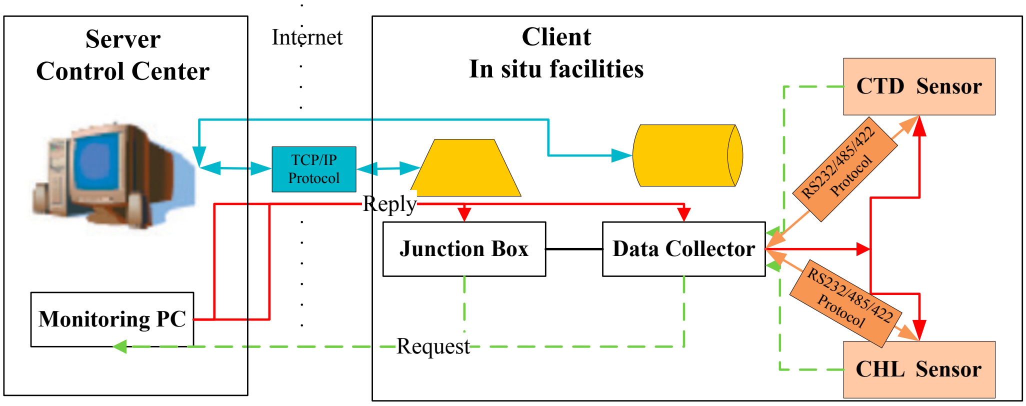

Figure 2. The C/S architecture and remote communication of SON-MS.

3.1.2. Bidirectional Socket Network Communication

There are two main information flows in remote communication. One is the data flow, in which the data obtained by the sensors needs to be uploaded to SON-MS layer by layer. The other is the instruction flow, in which SON-MS sends instructions to seafloor devices according to the remote monitoring needs. The bidirectional socket and long and short connection are adopted to avoid the data stream and the instruction stream interfering with each other. In the process of the receiving the data stream, SON-MS adopts the socket long connection and uses different ports to monitor the junction box and data collector. SON-MS also adopts the multithreading processing mechanism to realize parallel processing, and creates a thread for each connection to solve the concurrency problem of data processing. If the connection fails, the system is equipped with network state detection and a reconnection mechanism to ensure communication success. When the instructions are issued, SON-MS is the client, and the junction box and the data collector are the server. SON-MS establishes a short connection with the underwater server. After sending the instruction and receiving the feedback from the underwater, the connection is broken immediately to reduce the system overhead. The flow chart of the bidirectional socket network communication is illustrated in Figure 3, where nT ($n < N$, N, T can be defined according to the network load) is the time interval of each waiting period.

3.1.3. The Data Stream Communication Protocol

SON-MS establishes a bidirectional socket network communication mode for the data flow and instruction flow. However, the instruction flow is only executed when there is a demand for remote control. The seafloor observatory network works all day, and generates massive data. However, the data acquisition frequency and data format of seafloor devices differ, which greatly increases the difficulty of subsequent data transmission and processing. Therefore, in order to encapsulate the data of multiple sensors connected to the data collector and convert the scattered original data information into a user-defined protocol frame, a user-defined communication protocol is designed for the application layer of the transmission backbone network. This protocol is the basis of the dynamic device management. The protocol can be applied to marine environmental parameter sensors.

The communication protocol consists of the package header, package body, check bit and fixed terminator. The package header contains the synchronization header, collector number, protocol type and timestamp. Its length and format are fixed. The length of the data package body is not fixed due to the fact that the data sent by the different devices is different. The check bit is the CRC32 check of package header and package body. Its length and format are also fixed. The communication protocol ends with a fixed terminator, which represents the end of data. The communication protocol is summarized in Table 1.

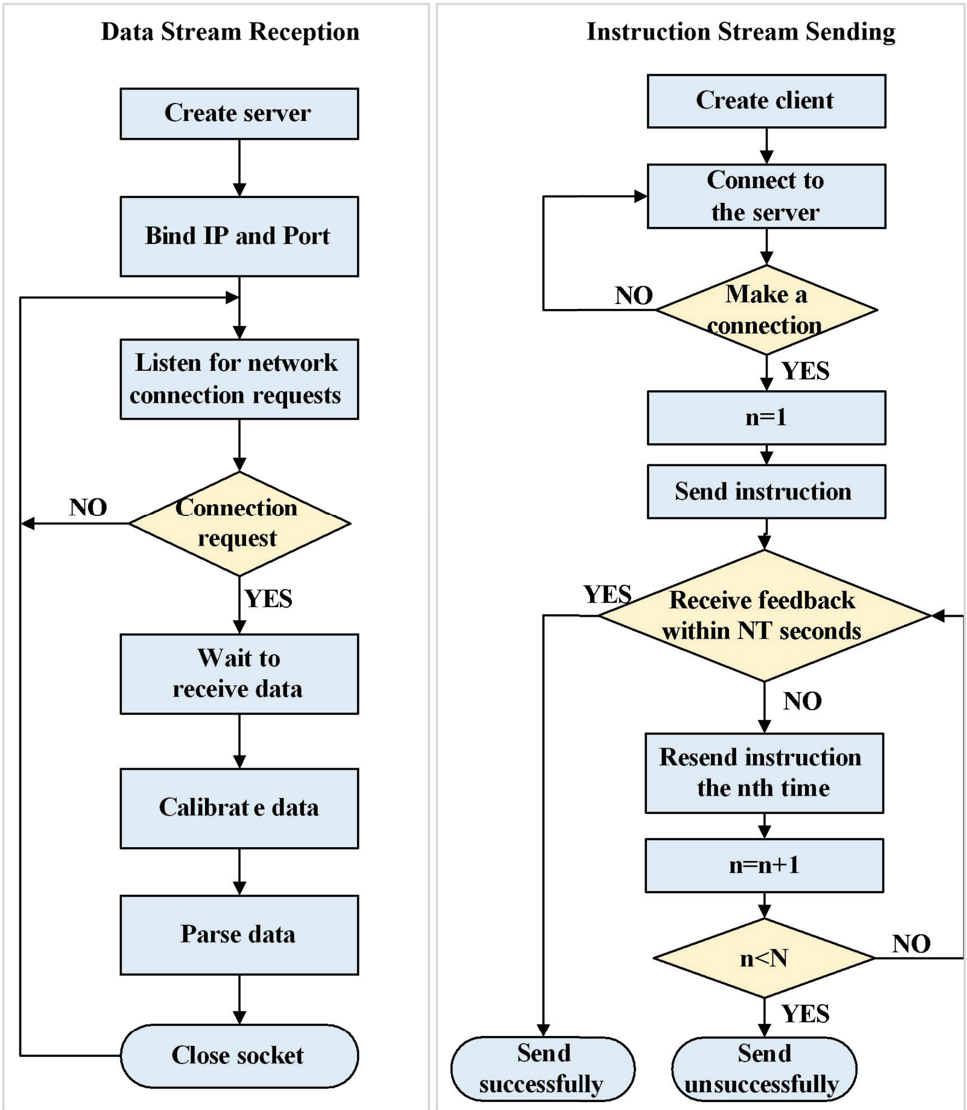

Figure 3. The flow chart of bidirectional socket network communication.

Table 1. The format of custom communication protocol.

Numb	Field Name	Type	Length	Remarks
1	Package header	16-bit unsigned integer	2 byte	The beginning of a fixed protocol
2	Collector numb	32-bit unsigned integer	2 byte	A data collector corresponds to a unique number
3	Port numb	32-bit unsigned integer	2 byte	Each data collector port has a unique number
4	Time stamp	ASCII	23 byte	The format is yyyy: mm: DD: HH: mm: ss: msms
5	Package Numb	32-bit unsigned integer	4 byte	Start counting at 0:00:00 every day, and add 1 automatically for each packet sent
6	Package Length	32-bit unsigned integer	4 byte	Length of the whole package
7	Package body	Composite format	Indefinite	The specific content is determined by the sensor

Table 1. *Cont.*

Numb	Field Name	Type	Length	Remarks
8	CRC check	32-bit unsigned integer	4 byte	Calculate CRC32 for the whole package
9	Terminator	8-bit unsigned integer	1 byte	Fixed terminator, representing the end of data

3.2. Device Dynamic Management

The seafloor observatory network is composed of multiple main junction boxes. A main junction box has a number of secondary junction boxes. A secondary junction box connects to a number of data collectors and a data collector connects to many sensors. The mapping relationship of the sensors, the data collectors, the secondary junction boxes and the main junction boxes is depicted in Figure 4. When the mapping relationship changes arbitrarily, SON-MS can perform scientific adaptation and analyze the final data without interfering with the current operation or rewriting the code.

The data obtained by the devices is the most important in SON-MS at the observatory nodes. The device dynamic management is used to solve the problem that the device needs to change the physical interface and the detection requirements in the long-term operation process.

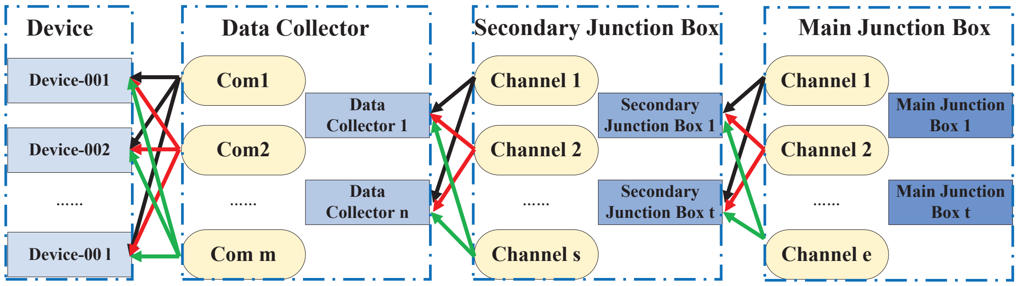

Figure 4. The mapping relationship of the nodes.

3.2.1. Device Object Model

The proposed device object model (DOM) considers every device as an independent object. DOM is conceptually a set of device resource objects (DRO) designed with object-oriented patterns. DRO represents a particular type of device and DOM can be expressed as in Equation (1).

$$DOM = \{DRO - 1, DRO - 2, \ldots DRO - n\} \quad (1)$$

DRO contains Device Code, device characteristics (DC) and device operations (DO). This can be expressed as in Equation (2).

$$DRO = \{DeviceCode, DC, DO\} \quad (2)$$

In the formula, device code identifies the uniqueness of DRO. DC is a set of characteristics that can be divided into five categories: device identification metadata (DM^I), device capability metadata (DM^{CP}), device access metadata (DM^A), device command metadata (DM^{CM}) and device processing metadata (DM^P). DC can be expressed as in Equation (3).

$$DC = \left\{DM^I, DM^{CP}, DM^A, DM^{CM}, DM^P\right\} \quad (3)$$

The detailed characteristics of DC are listed in Table 2.

Table 2. The detailed characteristics contained in *DC*.

Metadata Set	Metadata Elements
DM^I	Device name, device type, device platform, device node
DM^{CP}	Device geolocation, device quality, device observation parameter, device application range
DM^A	Device IP, device port, communication configuration, device interface
DM^{CM}	Command documentation, command configuration
DM^P	Observation valid time, data file, processing documentation, regular expression

DO of *DRO* describes how to use related characteristics to obtain the final result. The modes of data acquisition are divided into two categories: push mode and polling mode. A device working in push mode can autonomously return the observed data within a fixed time interval. Polling mode means that SON-MS sends a control command to measure and the device sends the data back. The device dynamic management only considers data push mode, which is realized with the help of a data collector. The data collector has the functions of communication control, power supply, distribution module and monitoring module. The multiple serial ports can be extended on the data collector to connect with underwater devices. Programs run on the data collector to package the sensor data from serial port communication according to the complete protocol introduced in Section 3.1.3 and then send it through the network. In brief, the data collector performs the functions of serial port reading, standard protocol packaging and network transmission. The mechanism between the underwater equipment, data collector and SON-MS is shown in Figure 5.

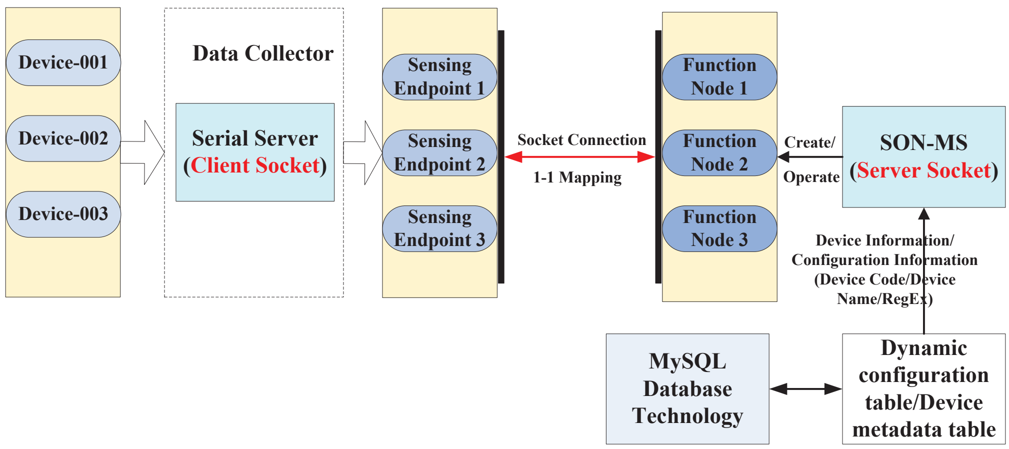

Figure 5. The mechanism diagram of an underwater device, data collector and SON-MS.

3.2.2. Dynamic Management Method

SON-MS establishes the metadata table of the underwater devices and the dynamic configuration table reflecting the mapping relationship between the underwater devices and other nodes. The device object model is stored in the metadata table. When the device information changes, it is mainly maintained by adding, deleting and modifying the device metadata table.

The dynamic configuration table stores the information about the topology relationship of the seafloor observatory network. Through the configuration form, we can obtain the ownership of the device. Figure 6 shows the mapping diagram of dynamic device management. It can be seen that the actual physical interface of the data collector with a one-to-one unique mapping relationship can be found in the dynamic configuration table. The number of the collector and the port can uniquely determine the actual physical interface. When the actual physical interface meets the electrical parameters and the interface conditions, any device from Device-001 to Device-00n can be connected, theoretically. That is, there is no unique mapping relationship between the physical interface and the connected device. The dynamic configuration table will change according to the many-to-many mapping relationships. The new mapping relationship will be established. As described in Figure 7, the program can find the mapping of the corresponding device from the device metadata table, so as to find the data format and other parameters stored in the metadata table. Then, the regular expression is used to parse the data.

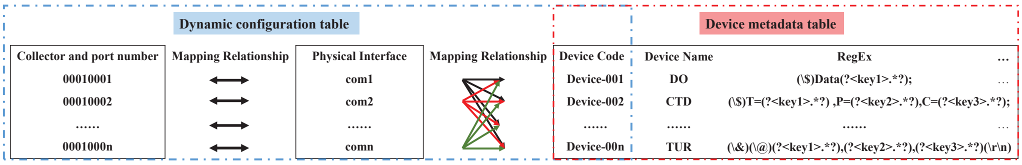

Figure 6. The mapping diagram of dynamic device management.

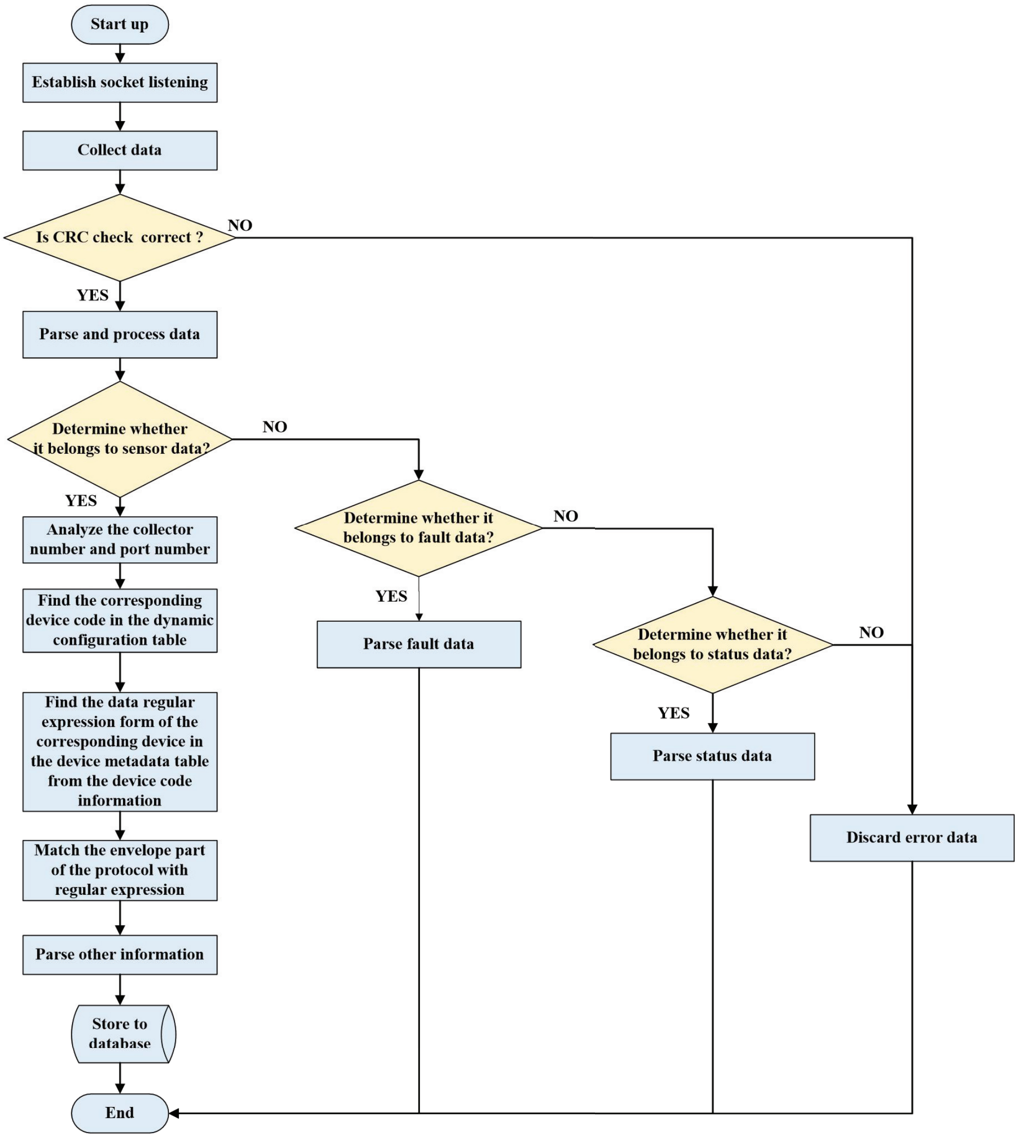

Figure 7. The flow chart of the dynamic management algorithm.

3.3. Data Quality Control

The sensors in the seafloor observatory network may be affected by the surrounding environment. The nonlinearity of the sensor itself and other factors may result in data loss or data distortion. SON-MS must effectively control the data quality of the parsed sensor data to make data products. The value of a sensor may be an invalid outlier caused by random interference or effective reference values due to continuous changes of ocean parameters. Therefore, it is essential to research data quality control to eliminate outliers and maintain the effectiveness of online data.

Traditional outlier elimination methods include the 3σ criterion [25], Nair criterion [26], Grubbs criterion [27], etc. The Grubbs criterion works well in small samples, while the Nair criterion requires knowing the standard deviation of the data in advance, and the 3σ criterion requires that the residual meet a Gaussian distribution. These methods can only deal with outliers while offline. Online outlier elimination methods include the Chi square test method [28], 5-point cubic smoothing [29], least square method [30], etc. The Chi square test method needs to be combined with a Kalman filter and is not suitable for preprocessing. The effect of the 5-point cubic smoothing algorithm is not ideal for large outliers. The smoothing filtering algorithm based on least square has a large amount of calculation.

An improved 53H algorithm is proposed in this paper. Turkey first put forward the 53H algorithm [31]. The 53H algorithm does not require that the data meet the Gaussian distribution, nor does it require knowing the standard deviation of the data in advance. Moreover, the implementation of the 53H algorithm is simple, which is suitable for online data smoothing of the data collected in the seafloor observatory network. Its basic idea is to generate a smooth estimation of the curve and then identify outliers by comparing the measured value with the estimated value [32]. The steps are as follows:

(1) Assume that $x(i)$ is the online data sequence of measurement. In order to construct a new sequence $x_1(i)$ from $x(i)$, we need to take the middle value of $x(1)$, $x(2)$, $x(3)$, $x(4)$, $x(5)$ as $x_1(3)$. Then, $x(1)$ is abandoned, $x(6)$ is added and $x_1(4)$ is obtained from the middle value. Follow the above steps until the last datum is added;

(2) In a similar way, the middle values of the three adjacent numbers of $x_1(i)$ are selected to form the sequence $x_2(i)$;

(3) Finally, $x_3(i)$ is composed of the sequence $x_2(i)$ as follows:

$$x_3(i) = 0.25x_2(i-1) + 0.5x_2(i) + 0.25x_2(i+1) \tag{4}$$

It is a Hanning smoothing filter, so the method is called the 53H algorithm;

(4) If the following formula is satisfied, $x_3(i)$ replaces $x(i)$:

$$|x(i) - x_3(i)| > k \tag{5}$$

where k is a predetermined value.

It can be seen from the operation steps that the first four points and the last four points of sequence $x(i)$ cannot be effectively smoothed. Therefore, this paper improves this algorithm as follows;

(5) The sequence $x^{'}(i)$ is generated by arranging the eight points at the beginning and the eight points at the end of the $x(i)$ sequence in reverse order. The new sequence is as follows: $x(8)$, $x(7)$, $x(6)$, $x(5)$, $x(4)$, $x(3)$, $x(2)$, $x(1)$, $x(9), \ldots, x(n-8)$, $x(n)$, $x(n-1)$, $x(n-2)$, $x(n-3)$, $x(n-4)$, $x(n-5)$, $x(n-6)$, $x(n-7)$;

(6) A new $x_3^{'}(i)$ sequence is formed by repeating the first four steps for the $x^{'}(i)$ sequence. Substitute $x_3^{'}(5)$, $x_3^{'}(6)$, $x_3^{'}(7)$, $x_3^{'}(8)$, $x_3^{'}(n-7)$, $x_3^{'}(n-6)$, $x_3^{'}(n-5)$, $x_3^{'}(n-4)$ for $x(4)$, $x(3)$, $x(2)$, $x(1)$, $x(n)$, $x(n-1)$, $x(n-2)$, $x(n-3)$, respectively.

Because the improved 53H algorithm smooths the eight points at the beginning and end of the sequence twice, as long as the appropriate k value is selected, the algorithm can effectively smooth all points without changing the characteristics of the sequence.

4. Experiment Result and Analysis

4.1. Experiment Scenario

Focusing on the requirements of marine ranching observatory in Shandong Province, the project carried out the construction of a marine stereo sensing network in the Yellow Sea and Bohai Sea in Shandong. As an important part of the stereo sensing network, the seafloor observatory network was arranged for Laizhou Bay marine ranching, Yantai, Shandong Province. The observatory network was successfully deployed on 11 August 2021. It has been running successfully for more than 7 months. The layout process of the sea trial is shown in Figure 8.

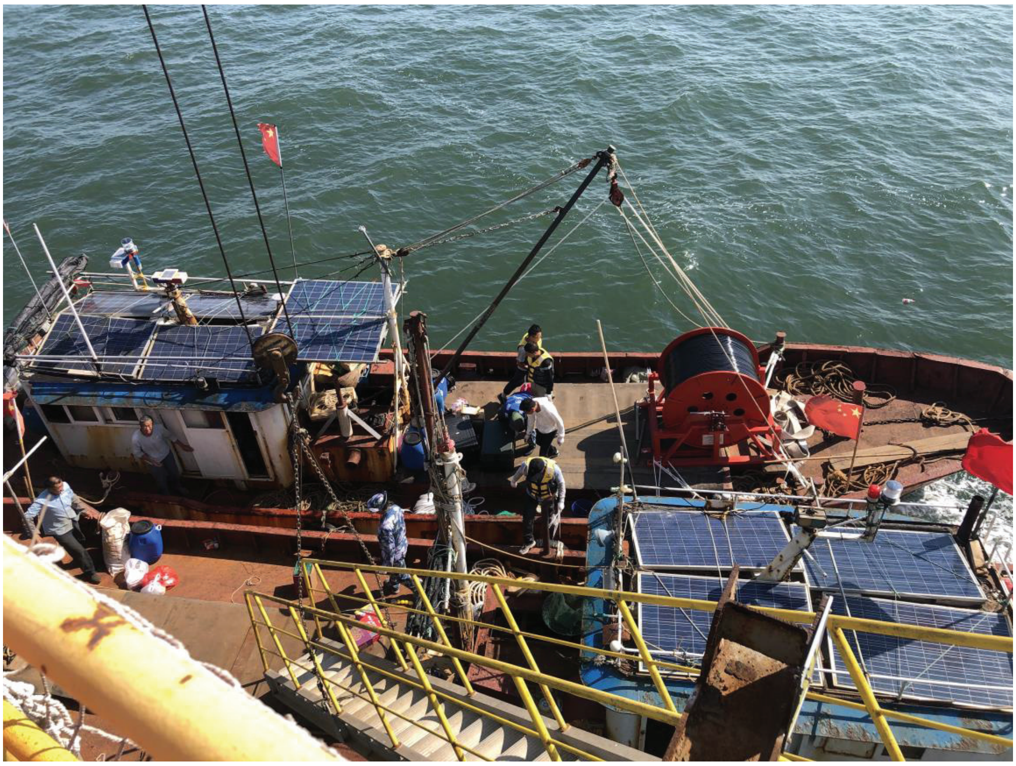

Figure 8. The layout process of sea trial.

The seafloor observatory network in Laizhou Bay marine ranching mainly includes four parts: the seafloor observatory node, a 2 km electro-optic composite cable, the shore station and the data control center (see Figure 9). The seafloor observatory node is composed of a junction box, a data collector and the sensors integrated on the data collector. The high voltage 2 KV onshore can be converted to 48 V by the junction box, whereas the 48 V can be converted to the suitable voltage for each sensor by the data collector. The data collector realizes the functions of data uploading and command issuing to the integrated sensor. The dissolved oxygen, conductivity-temperature-depth (CTD), chlorophyll, turbidity, underwater video and other sensors integrated on the data collector realize real-time, online and long-term observation of various oceanographic elements in the marine ranching. The shore station selects the monitoring platform at the wharf, which is composed of photoelectric separation protection, power supply, data transmission and cache system. The center of control and data is responsible for real-time sensor control, data acquisition and dynamic data processing, to ensure the stable operation of the whole observatory system. The shore station and the data center transmit data through FTP. The underwater devices connected to the seafloor observatory network are listed in Table 3.

Table 3. The underwater devices connected to the seafloor observatory network.

Observatory Node	Sensor	Observatory Parameter	Sampling Interval
Laizhou Bay Marine Ranching	Dissolved oxygen sensor (SDIOI)	Dissolved oxygen concentration	20 s
	CTD (Dao Wan)	Conductivity, temperature, depth, salinity	4 s
	Chlorophyll sensor (SDIOI)	Chlorophyll concentration	30 s
	Turbidity sensor (SDIOI)	Turbidity concentration	30 s
	Camera (Zhifan)	Real-time video	Continuous

Figure 9. The seafloor observatory network in Laizhou Bay marine ranch.

4.2. Experiment Results and Analysis

The seafloor observatory network in Laizhou Bay marine ranch has worked successfully for several months since August 2021. It has realized long-term, continuous and real-time monitoring of the marine ranching environments. As an important part of the whole observatory network, SON-MS plays an essential role in real-time observatory sensor control and data acquisition. SON-MS was created in Microsoft Visual Studio 2010. The functional modules are written in C# and the database type is MySQL. A socket communication technology based on the TCP-IP protocol is used for data communication, and serial communication technology is used for the instrument port. We tested four parts in the sea trial: the smoothness of the data transmission between the shore station and the seafloor observatory nodes, the effectiveness of shore station control sensors, the integrity of various data collected by the data collector, and the accuracy of data transmission and control instructions by communication mechanism. The test results indicate that SON-MS can accurately obtain oceanographic parameters such as dissolved oxygen, conductivity–temperature–depth (CTD), chlorophyll and turbidity during continuous operation for more than a few months, and can successfully send various instructions and execute them. SON-MS can accurately analyze, store, query and display various data. The typical interface is shown in Figure 10. In addition, SON-MS also solves the difficult problems involved in the key technologies of seafloor observatory networks.

SON-MS has received up to 2,404,326 valid data; the data packet loss rate is only 0.045% the command response time is less than 3 s, and the command execution success rate is as high as 98.2%. The results show that on the premise of ensuring system response capability, the communication protocol format can ensure the integrity of data communication, and the mechanism of bidirectional socket network communication and the combination of long and short connections can improve the reliability of data transmission. SON-MS has powerful capability in data communication.

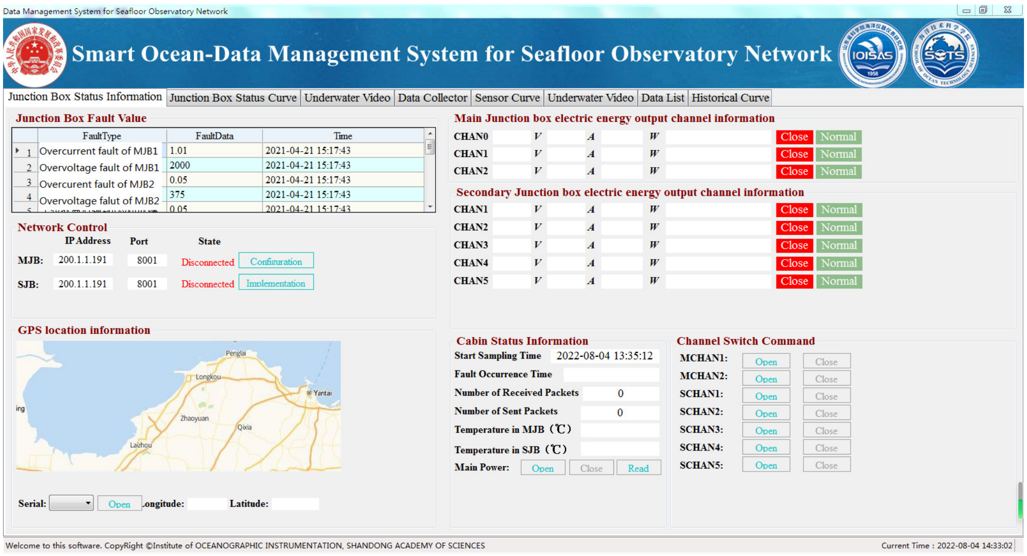

Figure 10. The typical main interface of SON-MS.

When the sensor needs to change the interface or add a sensor, the actual device connected to the physical interface only needs to be dynamically configured in the SON-MS configuration interface. Figure 11 describes the interface of the device dynamic management. The tree topology relationship of the seafloor observatory network is displayed on the left side of the interface. If we need to add, delete, modify and perform other dynamic management operations, we only need to right-click the mouse to list the corresponding menu options. In this way, the dynamic device management can be maintained in the software interface without changing the code. The conventional configuration can be completed within 2 min. The background of the SON-MS program (See the links provided in the Supplementary Materials for specific codes) can analyze the data according to the dynamic management algorithm after configuration. SON-MS has flexible device dynamic management ability.

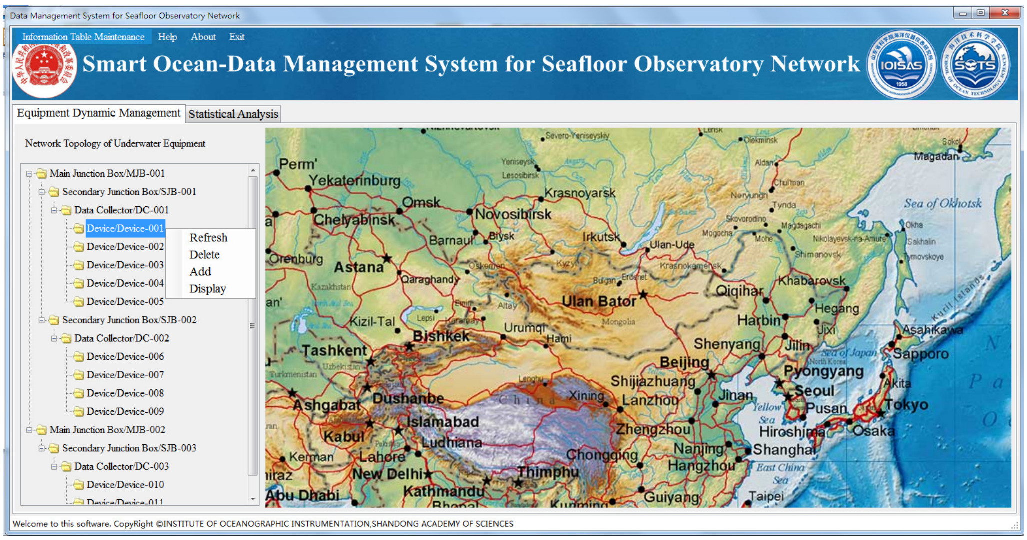

Figure 11. The interface of the device dynamic management for monitoring system.

Taking the level of dissolved oxygen in marine ranching from August to November in 2021 as an example, the original curve of the dissolved oxygen level and the data curve after using 53H algorithm, improved 53H algorithm and least square smoothing algorithm to improve data quality were drawn, as shown in Figure 12. It can be seen that the least square smoothing algorithm reduces the outliers of the original curve, but does not completely eliminate the outliers. Both the 53H algorithm and the improved 53H algorithm basically eliminate the outliers. In the middle part of the sequence, the 53H curve completely coincides with the improved 53H curve. However, the improved 53H algorithm can also smooth the outliers at the beginning of the sequence. From the local enlargement at the beginning of curves, it can be seen that if the first four points have outliers, the 53H algorithm cannot eliminate the outliers and the least square method can only reduce the outliers, while the improved 53H algorithm can smooth them effectively. The sampling interval of our self-made dissolved oxygen sensor is 20 s. Under normal circumstances, the level of dissolved oxygen changes slightly over a short time, and the burrs and spikes on the curve can be regarded as noise. The improved 53H algorithm can change the small noise signal, as illustrated in Figure 13. The changes due to sea environment factors such as temperature, tides, on-site operation status, and the status of the equipment itself in the long-term monitoring are real and valuable changes. The improved 53H algorithm can retain the useful information of the sequence, as illustrated in Figure 14. Specifically, taking the dissolved oxygen level on 19 August as an example, the dissolved oxygen level on this day has an obvious upward trend. It can be seen that, although the red curve filters out the peaks of the blue curve, it does not change this valuable changing trend. The turbidity data was also used for algorithm comparison and analysis, as illustrated in Figure 15. The turbidity value was increased significantly due to the agitation of seabed silt by shore vessels from 3:50 to 5:30 on 19 August 2021. The improved 53H algorithm smooths the whole sequence while preserving the effective changes of data.

Take a value between 3200 and 4000 as an effective value. If a data point exceeds this range, it is considered as an outlier. The results of the data error rate (the ratio of the number of outliers to the number of all data) between the original data and each smoothing algorithm are shown in Table 4. The improved 53H smoothing algorithm has the lowest data error rate. The improved 53H algorithm smooths the initial value of dissolved oxygen. The smoothed value is substituted into the formula to calculate the dissolved oxygen concentration. The filtering of the dissolved oxygen concentration value can be selected by the user's own noise filtering approaches or it can follow the quality assurance standards [33].

The data obtained by SON-MS can provide production decision guidance for marine ranching. SON-MS effectively obtains scientific data such as temperature, salinity, depth and chlorophyll of the marine ranching from the sensors carried on the seafloor observatory node. The analysis of several typical types of scientific data is given below.

The concentration of chlorophyll is not only the representation of phytoplankton standing stock, but also one of the important indicators of marine environmental monitoring. The observation of chlorophyll concentration in marine ranching is helpful to grasp the change characteristics of the marine ecological environment over time. Figure 16 shows the daily variation curve of chlorophyll concentration recorded by SON-MS on 19 August 2021. The sampling interval is 30 s. It can be seen from the figure that the chlorophyll concentration on that day was about 2 μg/L, which is basically consistent with the previous research on chlorophyll concentration in the Bohai Sea in summer. In addition, the chlorophyll concentration shows a significant daily variation law. It reaches a peak at noon every day, but the concentration is low in the morning and evening. It is estimated that this change law is mainly caused by solar radiation. The increase of phytoplankton biomass is caused by the rising temperature and light conditions at noon every day.

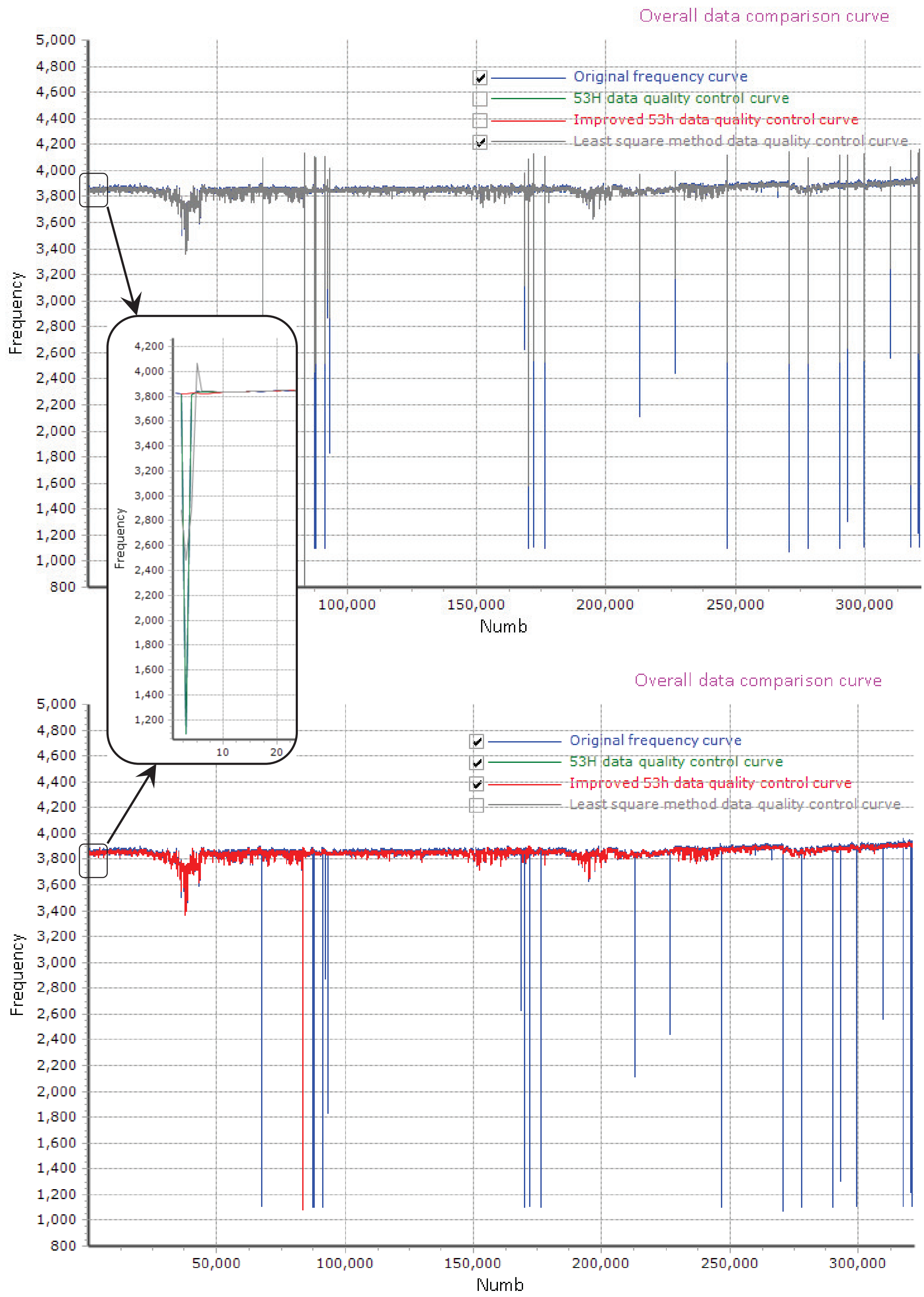

Figure 12. The comparison data curve of the dissolved oxygen level.

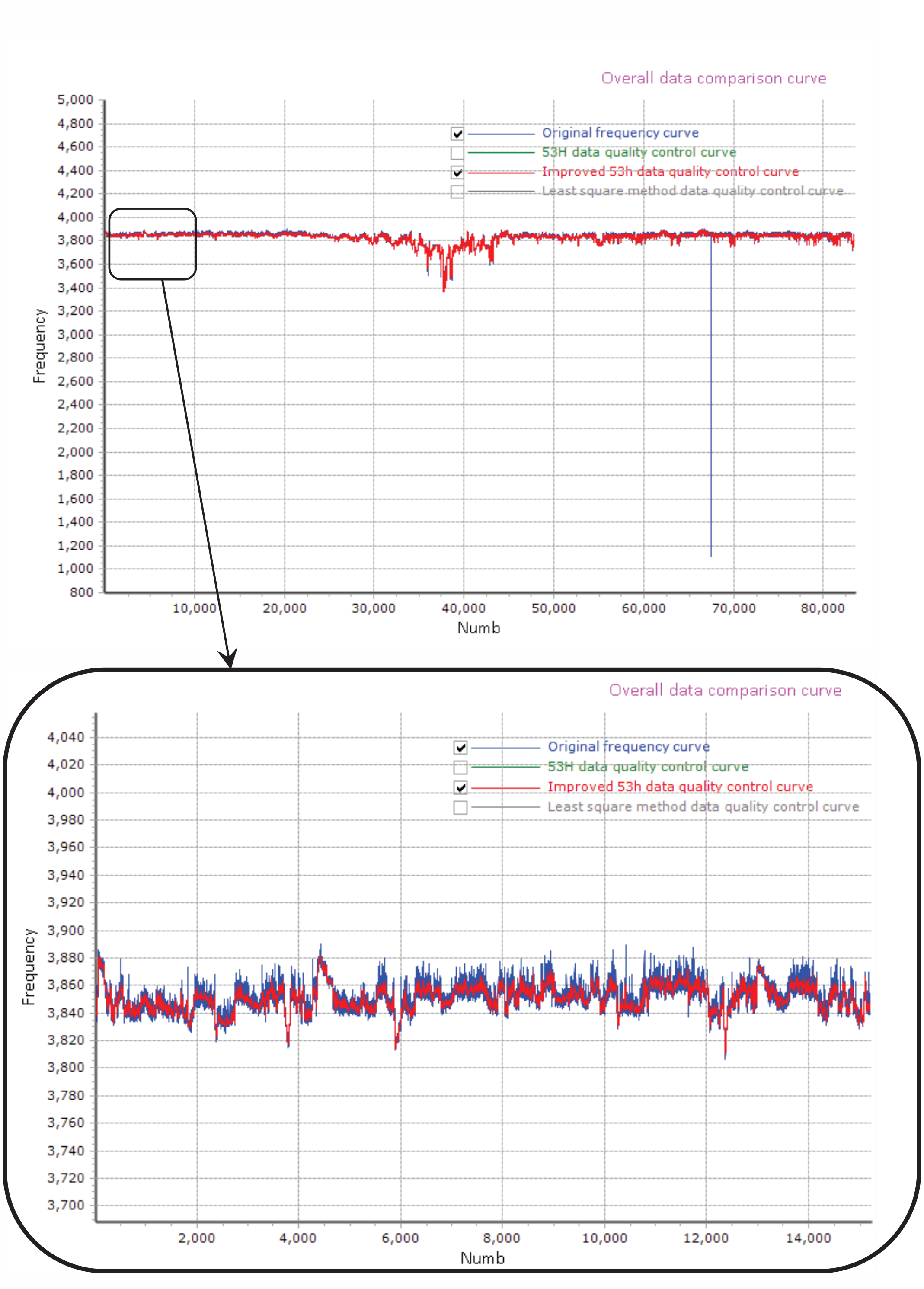

Figure 13. The filtering results of the improved 53H algorithm.

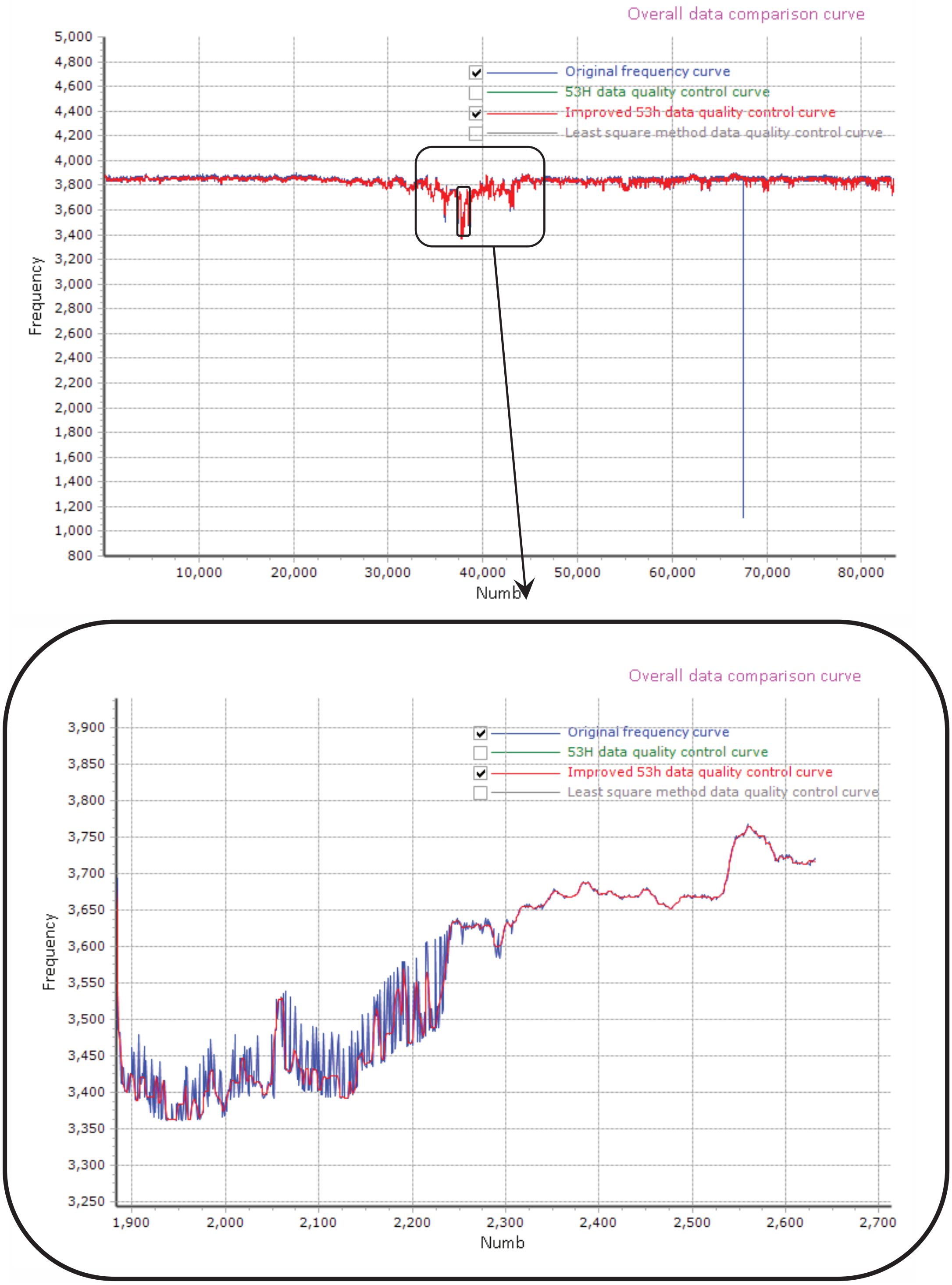

Figure 14. The improved 53H algorithm retains the effective information.

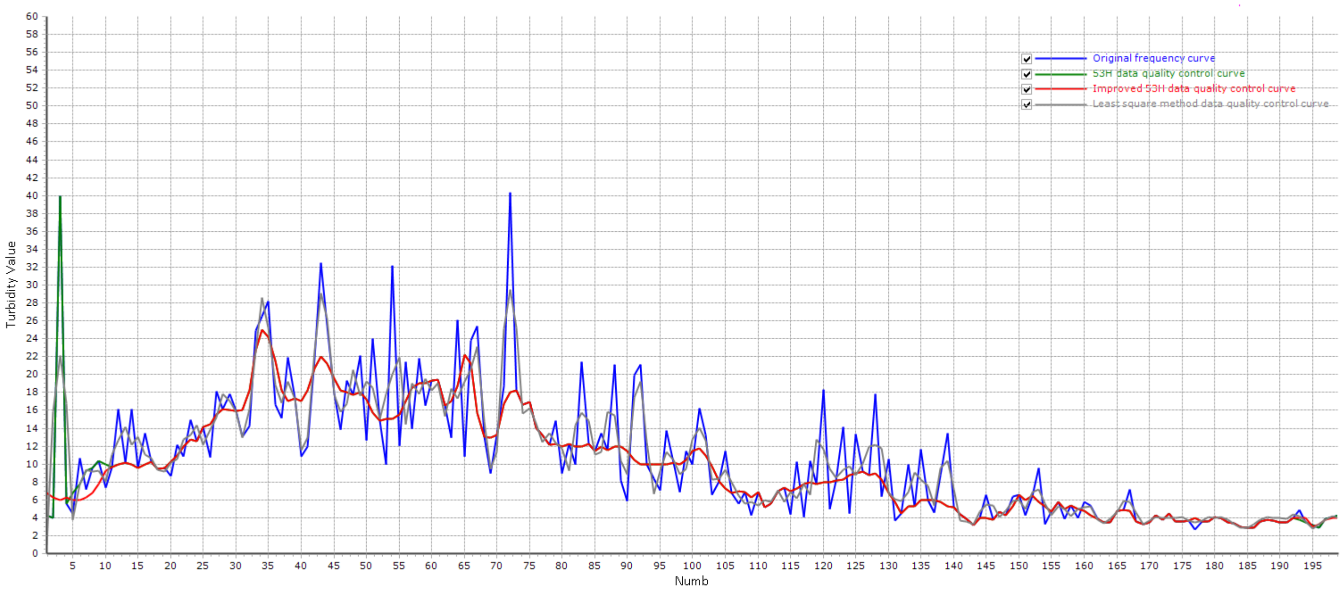

Figure 15. The comparison data curve of turbidity.

Table 4. The error rate analysis of sensor data.

Records	Abnormal Records				Accuracy			
	Raw Data	53H Algorithm	Improved 53H Algorithm	Least Square Method	Raw Data	53H Algorithm	Improved 53H Algorithm	Least Square Method
326,273	42	7	3	131	0.013%	0.0021%	0.00092%	0.04%

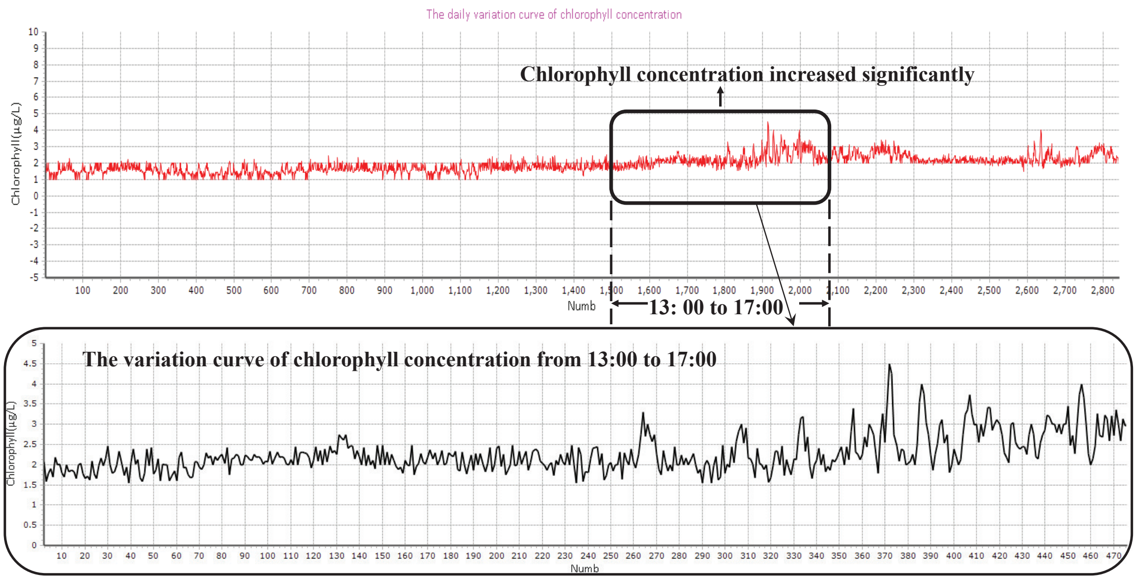

Figure 16. The daily variation curve of chlorophyll concentration on 19 August 2021.

The seafloor observatory network platform for marine ranching is also equipped with a conductivity–temperature–depth (CTD) sensor, which can realize the real-time monitoring of temperature, salinity and depth in marine ranching. Figure 17 shows the daily variation curves of temperature, salinity and depth on 19 August 2021. The sampling interval is 4 s. The green curve represents the variation of salinity with time, the red curve is the variation of water depth, and the blue curve is the variation of temperature. It was found that the salinity of the Laizhou Bay marine ranch is mainly affected by the tide. At high tide, the salinity decreases, while the salinity increases slightly at low tide. The black dotted line in Figure 17 is the time division between high and low tides. The temperature is different from the salinity. The main reason for this is that the change of temperature is not only affected by tide, but also affected by solar radiation. It can be seen from the depth measurement curve that the water depth is between 13.5 m and 16.5 m. With the change of high and low tide, the measured water depth also changes. At high tide, the depth gradually increases to 16.5 m, while the depth gradually decreases to 13.5 m at low tide. The water depth measured by the sensor is basically consistent with the data given by the previous sweeping sea, which indicates the data has high accuracy.

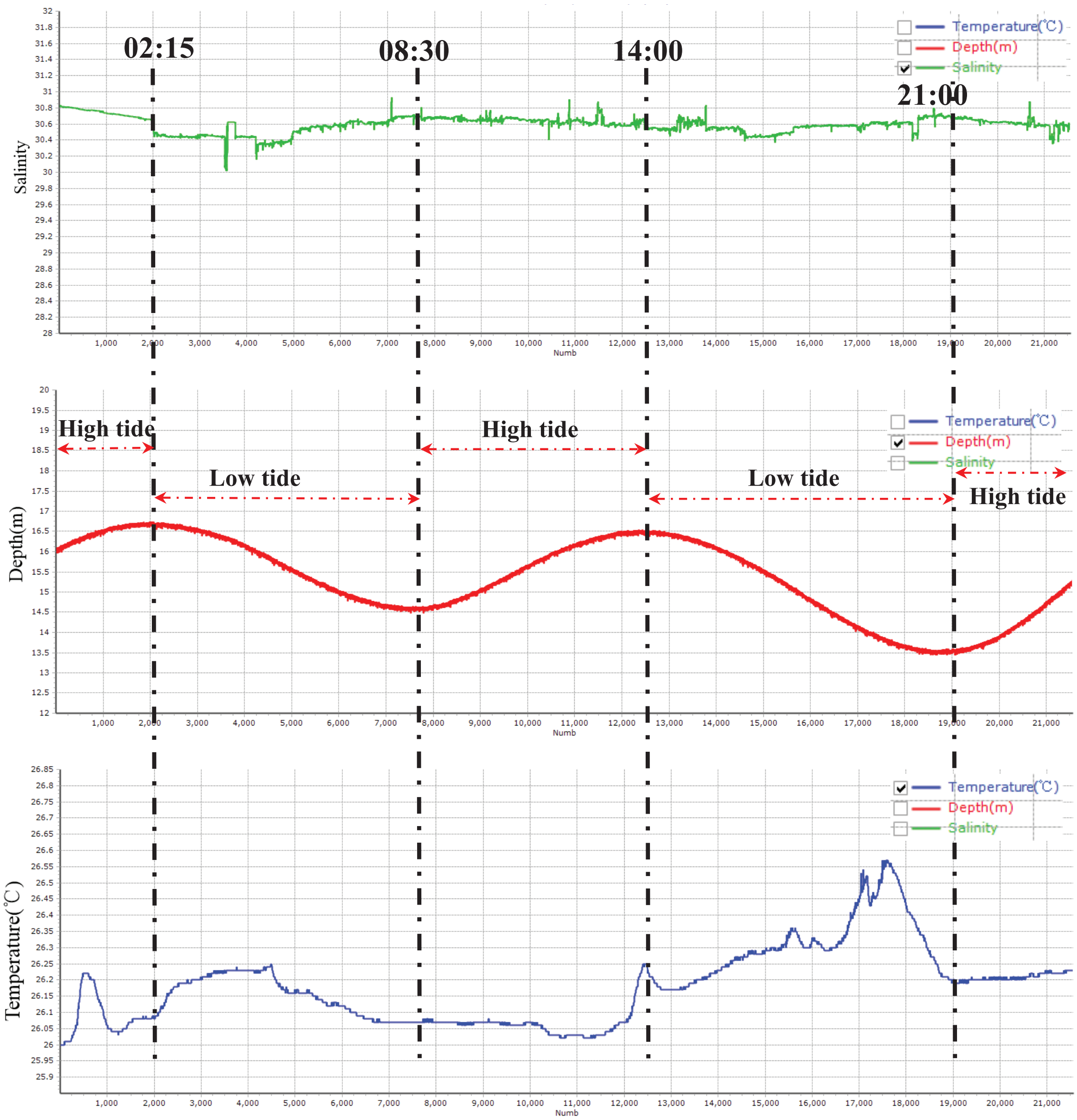

Figure 17. The daily variation curves of temperature, salinity and depth on 19 August 2021.

5. Conclusions

This paper developed an extensible remote monitoring system for the seafloor observatory network in Laizhou Bay marine ranching. The monitoring system focuses on solving the difficult problems involved in seafloor observatory networks, such as data communication, device dynamic management, data quality control and so on. Given the successful trial in Laizhou Bay marine ranching, we obtained oceanographic parameters such as dissolved oxygen, conductivity–temperature–depth (CTD), chlorophyll and turbidity. The data package loss rate was only 0.045%, which means that SON-MS has powerful capability in data communication. By analyzing the dissolved oxygen and turbidity data, the improved 53H algorithm can smooth the whole sequence while preserving the effective changes of data. It also has the lowest data error rate. The data obtained by SON-MS can provide production decision guidance for marine ranching. For example, the depth information obtained by the conductivity–temperature–depth (CTD) sensor can grasp the daily tide trend. The application in Laizhou Bay marine ranching demonstrates that the SON-MS has good stability and performance, and a convenient man-machine interface. It can realize long-term online observation of marine ranching. The proposed method can provide a useful reference for other seafloor observatory networks.

The dynamic management method of the seafloor device can also be extended to other in situ ocean observatory sensor systems. With the development trend of intelligence in marine ranching, there is still significant work to be done in the future. Future work will use artificial intelligence and big data technology to improve the application of monitoring data. Machine learning methods may be used to improve the prediction of environmental changes and the ecological effect assessment of marine ranching.

Supplementary Materials: The following are available online at https://gitee.com/chenjie91/system (accessed on 1 August 2021).

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Abbreviations

The following abbreviations are used in this manuscript:

SON-MS	The monitoring system of the seafloor observatory system
DMAS	The data management system of VENUS and NEPTUNE
DOM	Device object model
DRO	Device resource objects
DC	Device characteristics
DO	Device operations
DM^I	Device identification metadata
DM^{CP}	Device capability metadata
DM^A	Device access metadata
DM^{CM}	Device command metadata
DM^P	Device processing metadata

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