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Research Article

Design and Implementation of an Underwater Information Acquisition System Prototype Based on Optical Fiber Communication

Mengke Zhao, Yi Hao, Chunqiang Lu, and Suyi Li

College of Instrumentation and Electrical Engineering, Jilin University, Changchun 130026, China

Correspondence should be addressed to Suyi Li; lsy@jlu.edu.cn

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Ocean observation plays an important role in many areas, such as marine scientific research, environmental expedition, and resource exploitation. Traditional observation generally acquires periodical marine information and lacks real-time performances. To realize underwater observation of multi-information in real-time, an information acquisition system is designed in this study based on optical fiber communication. A multichannel interface between the diverse sensors and the slave computer is designed. It shields discrepancies of different sensor data and allows collecting information of various types, including conductivity, temperature, depth (CTD), attitudes, and images. At the same time, the full communication link is designed by constructing an optical fiber channel in collaboration with RS485 and USB. It provides a higher-rate link for real-time data transmission from underwater to overwater. Then, software procedures are, respectively, developed for the slave computer and the master computer based on the designed communication protocol. Additionally, a PC-based user interface is designed to realize data receipt, file saving, information display, and image restoration. Finally, an acquisition prototype is developed, and an underwater experiment is conducted to evaluate its performance. The results show that the underwater CTD, attitudes, and images can be collected and transmitted in real time. From its higher transmission rate and lower packet loss rate, the accuracy and the stability of the prototype are verified. The implementation of the acquisition prototype follows the trends of laying and networking submarine optical fiber cables. Therefore, its application can be expanded for ocean observation in information collecting, transmitting, and processing.

1. Introduction

Collecting, transmitting and processing of marine information play important roles in many areas, such as marine scientific research, environmental expedition, and resource exploitation. Ocean observation technology provides strong support for the development of marine science [1, 2]. Among various marine dynamic environmental elements, temperature, salinity, and depth of seawater are fundamental indicators to reflect oceanographic properties, making the observation of conductivity, temperature, and depth (CTD) indispensable [3]. Due to the complexity of the marine environment, underwater topography and hydrological characteristics are easily affected and changed by ocean currents. Hence, real-time attitude information is required to detect the direction and intensity of ocean currents. Besides, the acquisition of clear underwater images directly reflects additional information, including underwater physical properties and equipment working states, which is another important aspect of marine projects [3].

Real-time performance is one of the major goals to achieve in modern ocean observation technologies since it is conducive to a profound reflection of oceanographical properties. Traditional observation deploys acquisition systems underwater over long periods and acquires periodical information through regular salvage and recovery of observation equipment, lacking real-time performances [4, 5]. Therefore, the development of underwater real-time observation systems is significant, where electric cables, optical fiber cables, radio waves, visible lights, and acoustic waves serve as wired and wireless communication mediums. Radio wave propagation is highly attenuated, which limits its penetration depth [6]. Visible lights are severely disturbed by underwater environments and are confined to few applications [7, 8]. Acoustic waves are most widely used for underwater wireless communication but are typical of low frequency, limited bandwidth, and high delay. Electric cables allow valid signal transmission in a short distance, and their networking is difficult and costly in large underwater areas [9]. These methods have yet to be improved in data transmission rate and reliability. Depth affects the data transmission quality of the methods using electric cables or acoustic waves. This requires a decrease in transmission rate to guarantee quality. The systems developed in [10–12] all have packet loss rates over 10^{-2} order of magnitude, and the systems in [13, 14] have transmission rates lower than 0.2 Kbps. Optical fiber is to date the only communication medium that allows long-distance transmission, high data rate, and anti-interference in underwater data transmission. An optical fiber channel can provide a communication link for data transmission from the underwater collecting-end to the overwater receiving-end, which improves the real-time performance compared with the traditional method. Additionally, the depth has little influence on the data transmission quality and rate of the method using optical fiber due to its low attenuation and strong anti-interference. In recent years, laying and networking submarine optical fiber cables have become leading trends in marine data communication, where underwater optical fiber communication is increasingly stepping into ocean observation fields [15, 16]. In the ocean floor observation and bathymetry system (OFOBS) developed by Purser et al., real-time sensor data collected by the camera and bathymetry sonar were directly transmitted via optical fiber cables to a ship-mounted unit [17]. Kumar and Anjaneyulu designed and developed a redeployable real-time data communication link by laying special optical fiber cables from the ship to the underwater platform to provide higher bandwidth [18]. The towed controlled-source electromagnetic (CSEM) system developed by Qiu et al. utilized ethernet and optical fiber communication technology to communicate the user terminal with various nodes and acquired real-time information including attitude, depth, and altimetry [19]. The underwater gravimetry system developed by Xiong et al. utilized photoelectric composite cables to provide power and communication and acquired underwater dynamic gravity information [20]. With an optical fiber used as the data transmission channel, Lee et al. schematically proposed multiplexed passive optical fiber sensor networks for real-time water level monitoring [21]. Fan et al. investigated the interaction between autonomous underwater vehicles (AUV) and cable dynamic behaviors in dynamic marine environments, increasing the feasibility of optical fiber communication in underwater real-time surveillance applications [22].

This study is aimed at developing a prototype of an underwater information acquisition system based on optical fiber communication. Targeted at real-time performance, we focus on the advantages of optical fiber communication and follow the trends of laying and networking submarine optical fiber cables. The underwater data of CTD, attitudes, and images are first collected by corresponding sensors. Then, the multichannel sensor interface is designed to package different measurements in units of 32 bytes. Finally, real-time transmission of different data types is realized based on high-rate optical fiber communication. The remainder of this paper is organized as follows. The overall design of the system is proposed in Section 2. The hardware design and software design of the prototype are, respectively, explicated in Sections 3 and 4. The performance evaluation through the underwater experiment is presented in Section 5. Finally, the paper is briefly concluded in Section 6.

2. General System Description

According to the actual demands for underwater observation, the overall design of the acquisition prototype is conducted. As shown in Figure 1, the prototype implementation is divided into three parts: (1) the hardware design that applies the multichannel sensor interface technology and the full-link collaborative communication technology; (2) the software design that involves the single-chip control procedures and the PC-based user interface; and (3) the prototype package design and the underwater experiment. As shown in Figure 2, the use cases of the system satisfy end-users' interactive requirements in data acquisition, parameter configuration, information display, and file saving.

The workflow of the system shown in Figure 3 realizes data communication mainly by the control messages for receipt and transmission. Once the slave computer receives a system initiation message, it starts to collect and process sensor data. Under the three-side control for RS485 receipt and transmission from the optical fiber channel, the master computer, and the slave computer, the collected data pass the optical fiber channel along with its internal conversion and transfer, thus accomplishing a transfer from the slave computer to the master computer. After several processing operations, the collected data are transmitted to a PC serial port to realize corresponding functions on the user interface.

3. Hardware Design of the Acquisition Prototype

The hardware block diagram of the acquisition prototype is shown in Figure 4. In terms of the central controllers, STM32F103ZET6, which has abundant I/O ports and peripherals, is selected for both the master computer and the slave computer. The underwater collecting-end slave computer collects original data of various underwater information from the CTD sensors, the attitude sensor MPU6050, and the image sensor OV7725, respectively. The sensor signals are transferred to the single-chip computer through a multichannel interface. Then, an RS485 transmission control circuit is designed to transmit those signals to an optical transmitter where electro-optical conversion is conducted. The obtained optical signals are transferred by optical fibers and arrive at an optical receiver to conduct photoelectric conversion so that the obtained electrical signals can be transmitted to the receiving-end master

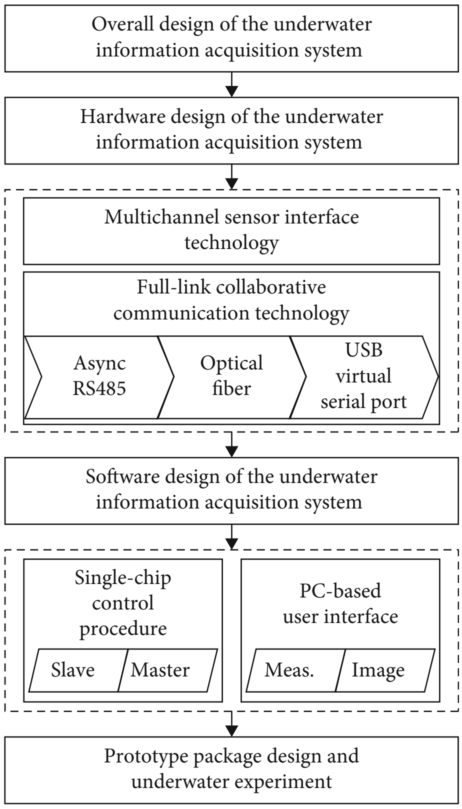

Figure 1: Prototype implementation.

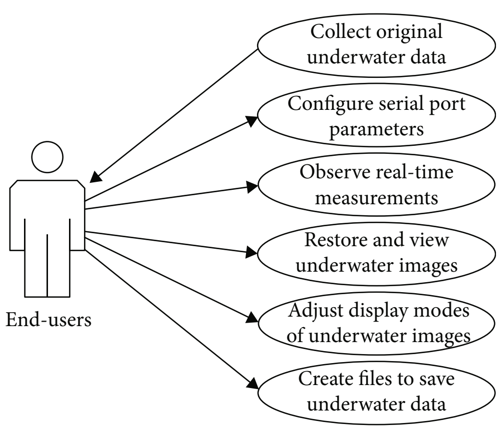

Figure 2: Use case diagram.

computer. Under the control of the single-chip computer, the data sequentially pass the RS485 receipt control circuit and the USB transmission control circuit. With the help of a USB virtual serial port, the data are transmitted to the PC for processing, saving, and displaying. By introducing the multichannel sensor interface technology and the full-link collaborative communication technology, the system hardware design concentrates on the multichannel interface, the optical fiber channel, the RS485 control circuit, and the USB control circuit.

3.1. Multichannel Sensor Interface Technology. In order to collect and transmit diverse data of underwater CTD, attitudes, and images, the collecting-end slave computer is connected to several sensors. Different sensors transmit signals to the single-chip computer in multiple formats, which can be classified into analog forms and digital forms. Under an appropriate interface design based on the communication mechanism between the slave computer and the sensors, the multichannel sensor interface technology shields the discrepancies among different signal formats provided by diverse sensors and generates double-byte data in a uniform format for the single-chip computer.

To acquire underwater CTD, a temperature sensor, a conductivity sensor, and a pressure sensor are selected to collect original analog data. Analog data of temperature, conductivity, and pressure are sent to the ADC channels of the slave computer for A/D conversion. To acquire attitudes of underwater equipment, a 6-axis motion tracking device MPU6050 is selected. It contains a digital motion processor (DMP) and utilizes a standard I^2C interface to output digital attitude data to the slave computer [23]. To acquire underwater images, a CMOS image sensor OV7725 is selected, which includes internal functional modules such as the analog signal processor, A/D converter, and digital signal processor. It utilizes a digital video port (DVP) of the FIFO chip to output digital image data to the slave computer [24]. The digital data of attitudes and images communicate directly with the I/O ports of the slave computer through bus interfaces. After the original sensor data are processed by software procedures, it is uniformed to a double-byte format which is convenient for transmission.

3.2. Full-Link Collaborative Communication Technology. Optical fiber communication, being the core, collaborates with asynchronous RS485 communication and USB virtual serial port communication to form the full collaborative communication technology. The data are sequentially transmitted through the underwater collecting-end slave computer, the optical fiber channel, the overwater receiving-end master computer, and the PC terminal and are finally displayed on the user interface. As for the hardware design of the full link, it is constituted of three parts, including an optical fiber channel, RS485 control circuits, and USB control circuits. The optical fiber channel, being the key component of the full link, is constructed by connecting waterproof optical fibers to an optical transmitter and an optical receiver. It provides a higher-rate communication link for real-time data from underwater to overwater. The underwater optical transmitter is used to convert the double-byte digital electrical signals into optical signals and send them to the optical fibers. At the other end of the optical fibers, the overwater optical receiver is used to convert the optical signals into digital electrical signals and send them to the master computer. To realize the aforementioned electro-optical conversion and photoelectric conversion, a pair of optical transceivers UT277 is used, one for the underwater transmitter and the other for the overwater receiver. Waterproof single-core single-mode optical fibers with SC-SC attachments are selected to fit the standard SC interfaces of the two optical transceivers.

RS485 communication has advantages like high transmission rate, great anti-interference, and long-distance

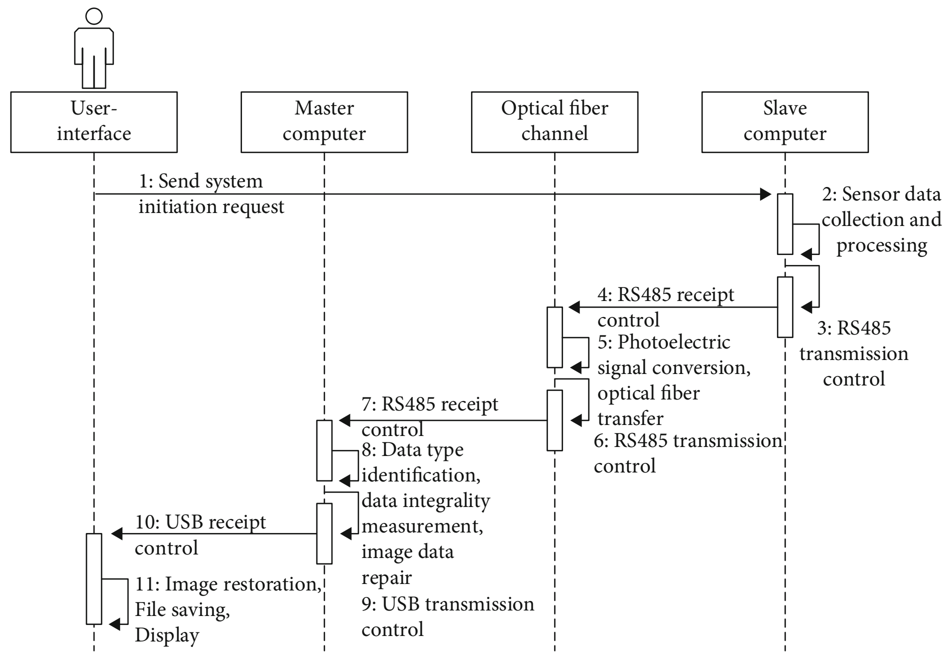

Figure 3: System workflow.

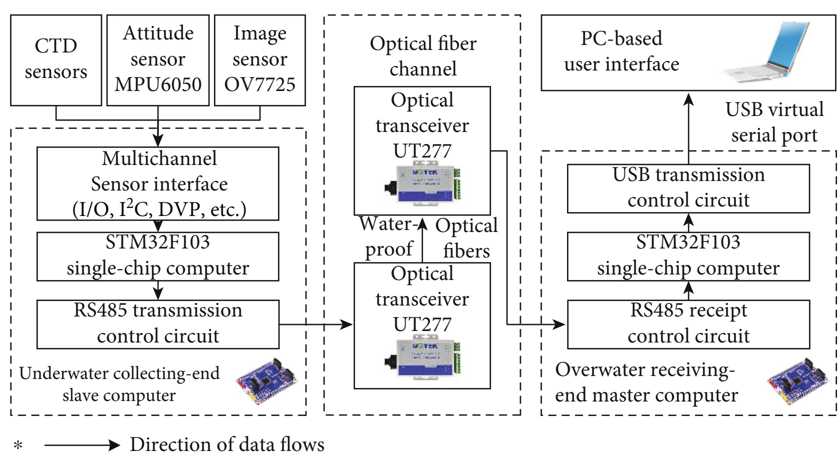

Figure 4: Hardware block diagram.

transmission. To simplify the data transmission between the single-chip computers and the optical transceivers, asynchronous communication via an RS485 connection is adopted. An SP3485 chip is selected as a transceiver for the RS485 control circuit design. Referring to the SP3485 datasheet, ports A and B of the chip are connected to the RS485 bus. Pins RO and DI are connected to one serial interface of the single-chip computer while pins RE and DE are connected together and controlled by an I/O port of the single-chip computer. Multiple signal margins are likely to emerge at high-rate transmission ports and lead to messy data, which necessitates impedance matching for transmission cables by the use of terminating resistors of $R = 120\,\Omega$ [25]. The differential voltage of idle buses tends to be unstable, causing a logical disorder. To ensure stable output remains as logical 1, two bias resistors are involved in the circuit to maintain the differential voltage above 200 mV.

Universal Serial Bus (USB) is a communication protocol broadly used to regulate the connection and communication between PCs and external devices. It is considered one of the best choices for data transmission in information acquisition systems because of its advantages including compatibility, ease of use, and plug-n-play. Hence, USB is utilized to communicate the master computer with the PC in this system. In the USB control circuit, pull-down resistors for the USB hub and pull-up resistors for the USB device are designed to identify the connection state between the master computer and the PC. USB is connected to the PC via a virtual serial port that has direct access to the data buffer shared by the PC and the single-chip computer. The standard USB

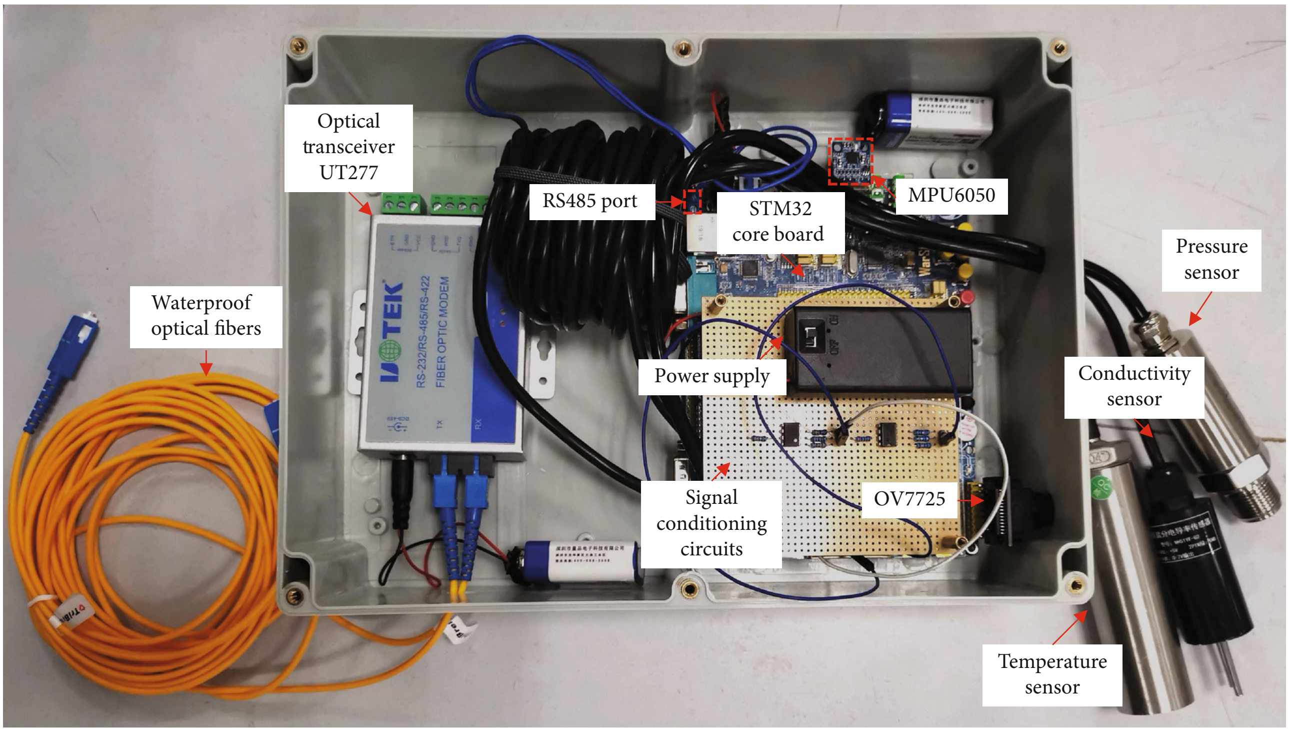

Figure 5: Packaged prototype.

connection uses four-wire cables, among which data buses D− and D+ are used for data transmission in the form of differential voltage [26].

3.3. Packaged System Prototype. The prototype package with both water resistance and reliability is appropriately designed, as shown in Figure 5.

4. Software Design of the Acquisition Prototype

The system software design is divided into two parts, including a single-chip control procedure design based on Keil C and a PC-based user interface design based on MATLAB.

The slave computer has original data collection, A/D conversion, and RS485 transmission control functions. After the initialization of all modules, quaternions are collected from the internal DMP of the MPU6050 sensor and transformed from q30 fixed-point numbers to floating-point numbers, which are used for pitch, roll, and yaw calculations. Analog data are collected from the CTD sensors, then being sampled and sent for A/D conversion. Afterward, data format conversion is conducted for the measurements above to generate double-byte data in a uniform format. The OV7725 sensor is configured in QVGA working mode and RGB565 output format. In this case, once the slave computer enters the data collection procedure of the current frame, double-byte RGB565 data of 320×240 pixels are obtained in the timing sequence. To prevent missing and disorders that may occur in the high-rate transmission of image data, complete pixel data of the current frame are temporarily stored into the SRAM of the single-chip computer. After data transmission of one frame is finished, the slave computer returns to the measurement collection procedure, devoted to another round of underwater data collection. In addition, start flags, end flags, and sampling periods are appropriately designed for the communication protocol due to diverse observation objects, including CTD, attitudes, and images. The flow chart of the slave computer control procedure is depicted in Figure 6.

The master computer has RS485 receipt control, image data repair, and USB transmission control functions. After the initialization of all modules, current data in the RS485 buffer are read by the single-chip computer, accomplishing one round of data receipt. Then, the data type is identified, and data integrality is measured. If it indicates that image data are received with byte missing, the data repair procedure is involved by supplementing bytes in time. Ultimately, the processed data are sent to the shared USB buffer so that the PC can realize USB virtual serial port communication by access to the buffer. The flow chart of the master computer control procedure is depicted in Figure 7.

GUI is a graphical user interface that realizes human-computer interactions. A PC-based user interface is designed by MATLAB, developing a program to receive, save, and display real-time underwater data, as well as restore images. The PC executes the serial port communication procedures to read the data received by the USB virtual serial port. Following the communication protocol, image data and measurements of CTD and attitudes are saved into designated text files. To realize the restoration and display of images, the software program loads original image data from the file and implements the image restoration procedure. With

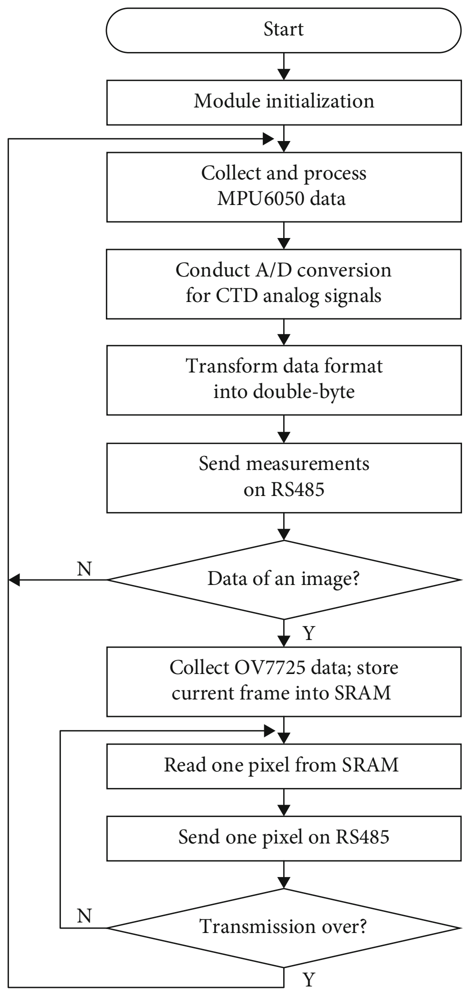

FIGURE 6: Flow chart of the slave computer.

physical measurements and restored images simultaneously displayed, GUI realizes underwater observation of multi-information for end-users.

5. Experimental Results

Conducting wires, waterproof optical fibers, and a USB cable are successively connected to corresponding ports to accomplish the full link establishment. The entirely packaged prototype is placed into the water container to conduct the underwater experiment with the temperature sensor, conductivity sensor, and pressure sensor soaked in water. The underwater prototype package is shown to be water-resistant and reliable. Once the MATLAB GUI is initialized and the button "Start Collection" is clicked, file "image.txt" and file "meas.txt" are created to save image data and measurements of CTD and attitudes, respectively. When the GUI displays those measurements, it indicates that the PC terminal succeeds in reading data from the USB virtual serial port. Additional required underwater information is available by clicking different functional buttons on GUI. Performance evaluation of the prototype concentrates on verifying its data collection accuracy and data transmission stability.

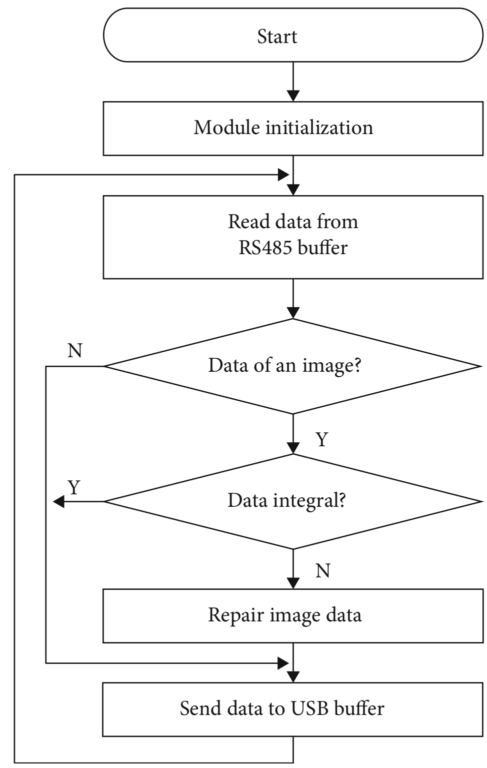

FIGURE 7: Flow chart of the master computer.

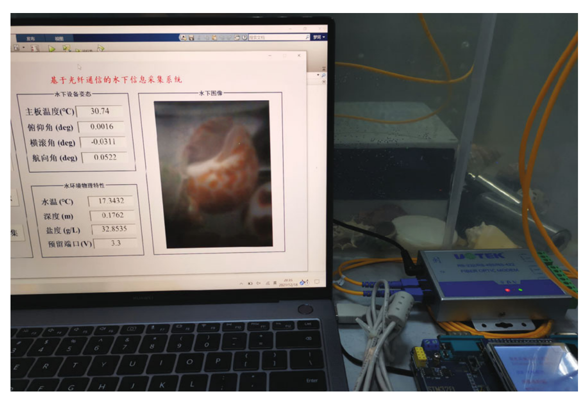

FIGURE 8: Underwater experiment of the prototype.

TABLE 1: Relative errors of temperature, salinity, and depth.

Physical parameter	Average relative error	Maximum relative error
Temperature	0.65%	1.28%
Salinity	2.24%	3.47%
Depth	2.09%	8.93%

The actual situation of the underwater experiment for the prototype is presented in Figure 8.

5.1. Verification of Data Collection Accuracy. Data collection accuracy is an indispensable index of the prototype. At first, physical parameters of temperature, salinity, and depth are,

Table 2: Packet loss rates of image data.

Test data	Test 1	Test 2	Test 3	Test 4	Test 5
Theoretical number of bytes			$320 \times 240 \times 2 = 153600$ (RGB565)		
Number of supplement bytes	1	3	2	7	5
Single packet loss rate	0.007‰	0.020‰	0.013‰	0.046‰	0.033‰
Average packet loss rate			0.029‰		

respectively, tested. Under initial conditions, those measurements displayed on GUI match the environmental parameters of the laboratory. Measuring instruments, including a thermometer, a conductivity meter, and a meter ruler in the laboratory, are used to conduct accuracy calibration. Under a series of predetermined physical conditions, measuring accuracy of three parameters is presented by average relative error and maximum relative error, as shown in Table 1.

When it comes to attitude information, underwater shock waves are artificially imposed. In this case, corresponding changes in angle data display of pitch, roll, and yaw are observed, showing performances in lower-delay. It indicates that the prototype can detect underwater anomalous dynamic interference to some extent. Finally, a test for underwater images is conducted. When the button "View Images" is clicked, images are successfully restored and displayed, with relatively few noise spots.

5.2. Verification of Data Transmission Stability. Data transmission stability is an essential guarantee for regular work and smooth operations. Artificial configurations with the temperature, salinity, and depth of the underwater environment are maintained for other experiments with a fixed prototype. The measurements displayed on GUI are regularly recorded at 1 min intervals in 30 minutes. Over the period, our system prototype guarantees continuous and stable transmission, which avoids uncertain occurrences of outages compared with the system in [7]. By loading the file "meas.txt," waveforms of all measurements are plotted and analyzed, which shows little fluctuation around the predetermined parameters.

Repeated tests show that the measured average transmission rate is 9.2 Kbps. Numbers of supplement bytes for image data are derived from the file "image.txt" and used for the calculation of packet loss rates. The calculation result for a single frame reaches up to 0.201‰. To improve the performance, parameters of software delay and the RS485 baud rate are adjusted for a better match. Recalculated packet loss rates for 5 random frames of image data during the experiment yield an average packet loss rate of 0.029‰ and a maximum packet loss rate of 0.046‰, demonstrating an improvement in the packet loss phenomenon, as shown in Table 2. The results above indicate that the full link works collaboratively, and the stability of data transmission is verified. The prototype's packet loss rate shows order-of-magnitude improvements compared with [10–12], and its transmission rate increases by over 40 times compared with [13, 14], which effectively overcomes the defects of previous studies.

6. Conclusion

Under the background of marine scientific research and resource exploitation, this study designs a real-time information acquisition system of underwater CTD, attitudes, and images and develops the acquisition prototype based on optical fiber communication. The multichannel sensor interface realizes the ordered transmission of various sensor data and avoids data conflicts and errors. The full-link collaborative communication technology, centering around optical fiber communication, realizes more stable and faster transmission of high-capacity data and overcomes the existing defects of outage occurrences and low transmission rates. By applying multichannel acquisition and data temporary storage solutions, the single-chip control procedures realize the real-time acquisition of various sensor data and effectively decrease the packet loss rate of data transmission. The PC-based user interface realizes data receipt, file saving, information display, and image restoration. Finally, the underwater experiment is conducted for prototype performance evaluation, verifying collection accuracy and transmission stability of CTD, attitudes, and images. Compared with previous studies, the prototype's packet loss rate shows order-of-magnitude improvements, and its transmission rate increases by over 40 times. The prototype implementation follows the trends of laying and networking submarine optical fiber cables. Therefore, its application can be expanded for ocean observation in information collecting, transmitting, and processing.

Data Availability

The data that supports the findings of this study are available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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