A Study of the Remote Control for the East China Sea Seafloor Observation System

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ABSTRACT

Seafloor observatories enable long-term, continuous, real-time, weather-independent, and multidisciplinary scientific observation and research that will promise major breakthroughs in ocean sciences. China has started to establish a seafloor observation system in the East China Sea (ECSSOS), and the purpose of this paper is to describe the remote control for ECSSOS. Technological development in system architecture and remote communication was first performed in this paper. Based on this work, an overall framework for the remote control solution for ECSSOS was developed, adopting a client-server architecture containing three components, that is, a control center, a shore station, and observatory facilities, as well as two strands of information flow, that is, flow of observation data and flow of control commands. To implement the present solution, operational data flow and the core module were further designed and the corresponding remote control subsystem for ECSSOS was developed against all design specifications. This backbone system has been put into operation in China’s first seafloor observatory in 2009, and in this paper the practical performance is evaluated addressing both the general descriptions and results from case studies. Given the successful trial in the Xiaoqushan seafloor observatory, the remote control solution proposed in this paper could be a useful reference implementation to the following construction phases of ECSSOS.

1. Introduction

Seafloor observatories emerge in response to the demands of earth system science (National Research Council 2000). Global change research starting from the late 1980s has strongly suggested the important role that oceans play in global climate and the necessity for long-term and continuous observation. With the global observatory network summits successively held in America and Japan (Wang 2005), ocean observation has risen to be a national priority. There is a particular need for observations with dedicated scientific instruments in the deep sea to record changes in a broad range of temporal and spatial scales and to monitor various extreme events, such as earthquakes and storms, which will be facilitated with an infrastructure that is able to provide continuous communication and power capabilities (Wang 2007). This is implemented with seafloor observation systems (Roy et al. 2006), the construction of which marks a new phase in marine research and will promise major breakthroughs for geosciences (Favali and Beranzoli 2009).

Scientific motivation for establishing seafloor observatories and the expected research and education outreach opportunities have been recognized for quite a few years. Many projects and programs on seafloor observatories have been implemented or are in a planning stage at different locations, as, for instance, in the United States, Canada, Europe, Australia, and Japan, just to mention a few of the initiatives (Favali and Beranzoli 2006). In Canada the main efforts in this field are North East Pacific Time Series Underwater Networked Experiments (NEPTUNE) and Victoria Experimental Network under the Sea (VENUS); NEPTUNE is by far the largest established seafloor observatory network used to study earthquakes and plate tectonics, marine processes and climate change, deep-sea ecosystems, and fluid flow in the seabed, and it employs state-of-the-art engineering and data management (Taylor 2009). In Japan the recent Dense Ocean Floor Network System for Earthquakes and Tsunamis (DONET) project is a unique development program of a submarine-cabled, real-time seafloor observatory network for monitoring seafloor earthquakes, tsunamis, and crustal movements related to the activity of plate boundaries (Kawaguchi...
et al. 2008). In Europe the focus on building a European-scale network of seafloor observatories (Ruhl et al. 2011) has been supported by the European Commission through the European Seas Observatory Network (ESONET) and European Multidisciplinary Seafloor Observatory (EMSO) projects. Presently, the Ocean Observatories Initiative (OOI) funded by the National Science Foundation of the United States is the largest ocean observation program in the world, striving to construct a networked infrastructure of science-driven sensor systems to measure the physical, chemical, geological, and biological variables in the world’s oceans and on the seafloor (Consortium for Ocean Leadership 2010).

China is now actively pursuing the design and construction of a seafloor observation system in the East China Sea (ECSSOS), which is an attempt to meet the increasingly prominent needs from scientific research, engineering construction, resource development, environment monitoring, and protection (Xu et al. 2010). The major scientific topic that will be addressed within ECSSOS is sea–land interactions, because the East China Sea is a marginal sea over a broad continental shelf located between the largest continent (Asia) and the largest ocean (Pacific) in the world. ECSSOS is initially planned to comprise three construction phases in chronological order, respectively, the Xiaqushan seafloor observatory, the seafloor observatories at the Yangtze estuary, and the seafloor observatory network on the continental shelf of the East China Sea. Construction contents of ECSSOS are expected to range from the fixed cabled seafloor observatory infrastructure to the dynamic observation subsystem based on autonomous underwater vehicles (AUVs), gliders, and moorings; the long-term stationary observation tower; the shore station; the management center; and other supporting infrastructure.

The established Xiaqushan seafloor observatory is located between 30°31′44″N, 122°15′12″E and 30°31′34″N, 122°14′40″E, in which area the average water depth is 15 m. A 1.1-km hybrid optical cable is laid to link the offshore platform with one specially designed junction box that has different waterproof plugs to separately connect to a conductivity–temperature–depth (CTD), an acoustic Doppler current profiler (ADCP), and an optical backscattering sensor. Since it has been put into service in April 2009, Xiaqushan seafloor observatory has been performing continuous measurement and satisfactory operation for more than 900 days. As the first seafloor observatory in China and an integral part of ECSSOS, Xiaqushan seafloor observatory will further strengthen its role as an experimental platform for establishing seafloor observatory networks both on the continental shelf and in the deep sea. The construction phase for the seafloor observatories at the Yangtze estuary will start next year, and research topics involve bottom-sediment boundary layer and transport processes, water quality change and environmental variability, time series of hydrodynamic parameters, and detection and early warning of earthquakes and tsunamis. Major infrastructure components include two science nodes (two low-voltage general junction boxes with various types of instruments), an engineering remotely operated vehicle (ROV) for service and maintenance, a dedicated shore station, and two data centers. The seafloor observatory network on the continental shelf of the East China Sea that is currently planned is part of the state seafloor observatory science and engineering strategy, and strives to become the unique seafloor observation system stretching from the largest estuary to the widest continental shelf in the world. Focusing on the multidisciplinary observation of the entire water column, the seafloor observatory network on the continental shelf of the East China Sea will be designed and constructed to provide scientists at home and abroad with an open, accessible platform to undertake in situ research in the shallow water and on the continental shelf.

In terms of carrying out the phased projects of ECSSOS, some critical technological components need some further development to guarantee the success of the entire construction efforts, namely, the monitoring of the proper function of the seafloor observatory components and the control of the measuring process in response to the changing environmental conditions. Thus, it is particularly important to put the design under scrutiny to develop a robust and reliable remote control solution for ECSSOS. In this paper, the system engineering aspect in particular, in regard to the remote communication system for ECSSOS, will be described. Second, the remote control solution for ECSSOS is defined, covering the overall framework, operational data flow, and core module design. Third, the practical performance of the developed remote control subsystem was evaluated. Finally, some objective conclusions are made on the whole research work.

2. Technological development

a. Technological challenges

In terms of constructing ECSSOS especially for designing the remote control solution for ECSSOS, a number of technological challenges should be taken into account to guarantee the normal operation of the entire seafloor observatory network. To be specific,
1) continuous observation data should be received, converted, stored, and processed in a real-time and efficient way; 2) the working condition of seafloor observatory instruments and the infrastructure should be monitored online to enable automatic fault detection; and 3) control commands should be remotely sent to seafloor observatory equipment in accordance with current observation strategy.

Challenges listed above are calling for a wide range of corresponding technological considerations for the planned remote control solution for ECSSOS. The two most important aspects, namely, system engineering and remote communication design, are discussed as follows.

b. Architecture development

The implementation of a remote control system is basically equivalent to the development of an application, which is generally divided into the client program and the server program. The architecture of applications differs in how the code is packaged and is most commonly achieved as a mode of either a client-server (C/S) or browser-server (B/S) system. A C/S architecture model is adopted in the remote control for ECSSOS based on the following two considerations: 1) a seafloor observation system demands strong interaction capabilities owing to huge data transmission and frequent remote interoperation, in which case C/S architecture is more appropriate than B/S architecture. 2) C/S architecture is characterized by its stronger ability to ensure information security than B/S architecture, which is a necessity for seafloor observatories (Chen 2003). ECSSOS mainly comprises the shore station, the backbone cable, and several science nodes (junction boxes with various instruments in local observatories), and every science node is functionally independent. These nodes share the common feature that in each node the junction box is connected to sensors of different types via standard waterproof plugs and each node is designed to support an extension when necessary.

In terms of the C/S architecture for ECSSOS, the client is the monitoring personal computer (PC) in the control center while the server is the in situ junction box (serial server) and sensors connected to it. Each junction box (serial server) is integrated with the socket program module that performs listening, connecting, as well as transmitting commands and data on established socket connections. To be specific, the client program running in the monitoring PC first sends a request to establish a remote connection to the observatory facilities at sea, and then the server program running in the serial server accepts the request. After a socket connection is built, the client could send commands to remotely control the working condition of various instruments, and the server responds to it by returning scientific data or infrastructure information. The messaging mechanism of C/S architecture for ECSSOS is shown in Fig. 1.

c. Remote communication development

Communication technology is crucial for a seafloor observation system, because remote communication forms the basis for the system implementing remote control. Current communication fitting for seafloor observatories fall into two categories, wired communication and wireless communication, and the chosen ones differ in the specific type of seafloor observation system (Chen et al. 2006). For instance, the Hawaii-2 Observatory (H2O) used serial communication and the RS422/232 protocol for a data path between junction box systems and underwater equipment in the local seafloor observatory (Petitt et al. 2002). In contrast, the Monterey Bay Aquarium Research Institute (MBARI) Ocean Observatory System (MOOS) strives to maintain compatibility with development projects of both portable and cabled observatories in the large oceanographic community (Chaffey et al. 2001; Akyidiz et al. 2005), and enable remote communication with, on the one hand, observation data that are transmitted sequentially via buoys and satellites until arriving at the shore station for further centralized processing and, on the other hand, junction box subsystems that connect to the backbone cable and transfer data to the shore station through the optic fiber.

Remote communication of ECSSOS mainly employs a wired communication system. An optic fiber Ethernet based on TCP/IP protocol constitutes both the backbone cable connecting the shore station with junction box nodes and the remote communication link between the shore station and the data center, while RS232/485/422 serial communication is in use for the subnet of the junction box and various attached instruments. In the case of ECSSOS, optic fiber communication is taken as the main approach because of its inherent characteristics, such as high transmission rate, large capacity, and strong robustness. Other communication technologies such as acoustic communication,
satellite communication, and serial communication are all less effective than optic fiber communication in terms of transmission capacity, transmission rate, real-time requirements, and most applicable seas (Chen et al. 2006). Currently, the transport layer using TCP/IP protocol could both provide a robust and reliable data connection and enable underwater sensors to send and receive messages to and from any platform with Internet connectivity, in which process the IP protocol enables data transmission and TCP guarantees the quality of the service for data transmission process. Additionally, the fact that TCP/IP protocol introduces the concept of IP and ports to uniquely identify the internetwork communication process (Winfield and Holland 2000) provides a concept for implementing the remote communication of ECSSOS, which is the basis for remote control. This concept could be briefly explained in the following way: the socket communication endpoint is first created in the communication process of both the server and the client of the remote control subsystem for ECSSOS, respectively; then addressing is conducted and socket remote connection is established based on IP and port number (Cena et al. 2007); finally, the two-way transmission of commands and data is performed using the established socket connection (shown in Fig. 2).

As shown in Fig. 2, the junction box is connected to a set of sensors of different types via standard waterproof plugs, whose built-in serial server runs applications, including socket listening, connecting, and sending and receiving data and commands. The junction box is also designed to convert and redirect the power transmitted from the shore station to keep various sensors under normal operation. Based on the fact that one combination of IP and port number uniquely corresponds to one seafloor observatory sensor, the remote monitoring PC conducts addressing and requests to establish a socket remote connection in accordance with TCP/IP agreement until the listening station running in the serial server detects and accepts this remote connection. Once the remote connection is established, the serial server could transmit various received commands from the monitoring PC to the specified sensor by RS232/485 serial communication protocol. In the meantime, the data collected from multiple sensors are transmitted to the shore station via optoelectronic composite cable under agreed communication protocols. The data buffered at the shore station will further be transmitted to the control center where the monitoring PC is located for subsequent processing, which also closes the cycle for the remote communication between the two ends of the remote control for ECSSOS.

3. Remote control solution

a. Overall framework

Taking into consideration the previous discussion on the software architecture and remote communication as well as the current construction requirements of ECSSOS, a C/S architecture based on the .NET Framework socket class has been adopted (Gómez and Estrela 2010) to primarily design the remote control solution for ECSSOS and develop its corresponding remote control subsystem.

As shown in Fig. 3, the overall framework of the remote control solution for ECSSOS is structured into three components (observatory facilities, a shore station, and a control center) and two types of information flow (observation data flow and control commands flow). The in situ ADCP sensor, CTD sensor, and junction box constitute an example for the science nodes of ECSSOS, of which ADCP and CTD are connected to the junction box via standard waterproof plugs. Observation data flow (green) contains the scientific data and infrastructure information gathered from various underwater instruments, while control command flow (red) stands for types of commands sent to underwater instruments of each observing node from the remote control center according to real-time monitoring conditions and observation demands. Furthermore, the raw data gathered by the remote control subsystem will be further processed by other subsystems for ECSSOS to fully support continuous measurement at a broad range of temporal and spatial scales, sustained operation under severe conditions, real-time data assimilation and modeling, rapid event capture and response, and adaptive observation and remote control.

b. Operational data flow

The sensors and the subsystem are remotely controlled in the following way, in which the way data flow is managed between them is simultaneously explained. Because the junction box’s built-in serial server is integrated with the program running socket listening, connecting, and sending and receiving data and
commands, scientific data and infrastructure information collected from various underwater instruments are first packed for TCP/IP relay by the serial server. They are then forwarded to the shore switch of the shore station for buffering via submarine electro-optic cable under agreed communication protocols, and finally are transmitted to the control center (illustrated as the green information flow in Fig. 3).

The remote control subsystem running at the control center is, on the one hand, responsible for receiving the real-time raw data (scientific data and infrastructure information), and converting and storing them in the ECSSOS database for further processing and dissemination. The data management subsystem for ECSSOS performs data ingestion and data transformation on the collected raw data for standardization as well as full and open access. The analysis and modeling subsystem for ECSSOS handles the standardized data with data analysis and visualization, modeling activities, and event detection for producing data products and model products, contributing to better scientific understanding as well as more reasonable observatory plan and control.

On the other hand, the remote control subsystem simultaneously sends various types of commands to remotely control all underwater instruments and observatory infrastructure relevant to the system’s adaptive control plan and dynamic monitoring demands. The sent commands are reversely transmitted in the same communication channel and under the same communication protocols as the way in which raw data are transmitted to the remote monitoring end. In this process the junction box plays a role in redirecting these
commands to the corresponding underwater sensors to control their functional status (illustrated as the red information flow in Fig. 3).

c. Core module design

The remote control solution for ECSSOS is implemented and integrated into a remote monitoring information system (remote control subsystem), of which the core module is the remote control module implemented as in Fig. 4. To meet the remote control demands of ECSSOS, the concept of the function node is first introduced in the specific design for the remote control module. The function node can be regarded as the agent for underwater observatory facilities in the main interface, containing the combined information of IP and port number that uniquely corresponds to one another in the in situ sensor and displayed as the tree node of TreeView control in a centrally managed manner in the main interface.

As illustrated in Fig. 4, the communication configuration submodule first takes the combined information of IP and port number of the underwater sensor to be remotely controlled from the database and loads it in the main interface by function node, referring to the system’s real-time remote control requirements. Then the function node operation submodule creates a socket communication endpoint, establishes remote connection with the in situ underwater sensor to enable Internet process communication, and sends commands to a specified sensor to control its working condition cooperating with command configuration submodule, all the while still based on the function node. At the same time, the interaction response submodule is charged with receiving, initially storing, and displaying all of the raw data transmitted back from underwater observatory facilities, and hands the backup infrastructure information to the real-time data monitoring submodule to perform data interpretation. The interpreted visualization information together with the in situ environment monitoring video provided by the in situ video monitoring submodule will, in return, give references for the system making real-time remote control demands, which completes the cycle of the whole remote control information flow of the remote control subsystem for ECSSOS.

To display the current condition of every underwater sensor in a real-time manner, three-color indicators are used for every corresponding function node that is added to the main interface representing offline (red), online/in use (green), and online/not in use (yellow). The blocking mode of the socket has also been adopted to regularly traverse and determine the real-time condition of all function nodes. If there is some node that is disconnected accidentally and still needs real-time remote control, the program will automatically reestablish the socket connection and regain control of the interoperation of both the commands and the responding scientific data and infrastructure information.

The remote control module and other related modules of the remote control subsystem for ECSSOS were developed, and the rendering for the remote control module is seen in Fig. 5 as follows.

The individual module test was first performed on the remote control module and other modules of the remote control subsystem for ECSSOS. This stage of the test guarantees that each module meets the requirements for functional integrity, reliability (result-running accuracy and error-handling capabilities), and adaptability (processing capacity for changes in demand). All of the modules were then integrated into a remote control subsystem for a tank test in the seafloor observatory laboratory of the State Key Laboratory of Marine Geology at Tongji University, in which the testing process of the developed subsystem and the special junction box with several types of connected instruments was simulated with the underwater seafloor observatory and was continuously debugged under both normal operation and boundary conditions. The tank test proved that the remote control subsystem is able to synchronously control multiple underwater sensors in a real-time way and perform data transmission and initial storage on the established remote connections, complying with all expected requirements and maintaining uninterrupted operation for as long as 2000 h. This remote control

![Fig. 4. Flowchart for the implementation of remote control module.](image-url)
subsystem for ECSSOS was finally tested during a shallow sea trial in China’s first seafloor observatory and proved to function well during the entire testing program. This subsystem has now been put into service in the Xiaoquashan seafloor observatory and has presented satisfactory practical performance, as described below.

4. Practical performance

a. General descriptions against specifications

From the major design specifications of the remote control subsystem for ECSSOS it follows that ECSSOS had to (i) receive raw scientific data and infrastructure information, convert, and initially store them to the appropriate database in a real-time way; (ii) monitor both the seafloor observatory facilities and the in situ environment online; (iii) send specified commands interactively to remotely control and reconfigure the working condition of underwater equipment; (iv) manage and maintain system permissions and operation records; and (v) allow for satisfactory response time for operation and extendibility for hardware expansions or software upgrades.

Because the Xiaoquashan seafloor observatory was put into service in 2009, the remote control subsystem for ECSSOS has presented satisfactory practical performance against all specifications listed above. Data (video data are not counted here) have been continuously collected, transmitted, and received by the remote control subsystem up to 30 Mb day$^{-1}$, including data of near-bottom temperatures, conductivity, pressure, turbidity, current profiles with a bin size of 25 cm starting at 80 cm above the sea bottom up to the entire water column, and status parameters of all underwater instruments and systems. Data integrity was rated no less than 95%. From October 2009 the sampling rate of both the ADCP and CTD sensor was shifted to one time every 15 s rather than one time per minute, as in the first 5 months, and the spatial resolution of ADCP sensor was set to 25 cm by the control commands sent by this remote control subsystem. As mentioned earlier, the Xiaoquashan seafloor observatory has been successfully functioning for more than 900 days, and it is just the remote control subsystem for ECSSOS that enables and guarantees the real-time collection of scientific observation data and infrastructure information, the online monitoring on the working condition of seafloor observatory facilities, the remote control and dynamic

![FIG. 5. Rendering for the real-time remote control.](image)
reconfiguration of underwater equipment, and the sustained operation of the seafloor observatory.

It is too early to judge the output from the Xiaoqushan seafloor observatory within the global or even regional ocean context. Given the hostility of the marine environment to underwater observation equipment, it is likely that without the remote control and dynamic reconfiguration of the remote control subsystem described in this paper the Xiaoqushan seafloor observatory will not provide datasets of long enough duration to contribute a continuous record for studying the sea–land interactions in the East China Sea. However, it is clear from the available operational period of the remote control subsystem on the seafloor observatory that there is considerable variability on a monthly or even daily time scale that is not captured by the routine boatsampling schedule. The practical performance of the remote control subsystem is specifically described and further supported by the following case study (Xu et al. 2011) on initial analysis of the in situ observations at the Xiaoqushan seafloor observatory.

b. Case study

Based on the present sediment models, the drag coefficient, shear stress, and sediment transportation rate of the bottom boundary layer for May 2009 in the coastal East China Sea were calculated from the corresponding ADCP and CTD measurements of high resolution. Periodic variations of these physical parameters during flood, ebb, spring, and neap tides were initially documented (Xu et al. 2011) in Fig. 6a–d, in which sea level obtained by CTD, drag coefficient (Cd), near-bottom boundary shear stress, and sediment transportation rate are respectively recorded. The black lines in Figs. 6b–d stand for hourly averaged data while the red lines represent daily averaged data.

To be specific, on the one hand, the notable daily cycle can be distinguished from the time series of the drag coefficient, near-bottom boundary stress, and sediment transportation rate. The drag coefficient maintained large values of $3.3 \times 10^{-3}$ to approximately $3.5 \times 10^{-3}$ during ebb tide, while during flood tide it decreased first and then increased. In contrast, transportation rate value rose from $2.0 \times 10^{2}$ up to $15.0 \times 10^{3}$ kg m$^{-2}$ s$^{-1}$ and then decreased during ebb tide and remained low during flood tide. On the other hand, the calculated drag coefficient values for the monthly cycle were in a range of $2.8 \times 10^{-3}$ to $3.6 \times 10^{-3}$, and the average value in neap tide was larger than that in spring tide. Because the drag coefficient is a determination of the near-bottom shear and stratification, stronger shear variance and weak stratification resulting from resuspension intermittently occurring in the weak current of the neap tide may account for the abnormal variations during neap tide 2, as shown in Fig. 6b. The shear stress near-bottom boundary layer varied little with the hourly averaged value ranging from 0.5 to 3.0 N m$^{-2}$ and daily averaged value ranging from 0.8 to 1.5 N m$^{-2}$. The transportation rate varied with the same trend as shear stress and also exhibited a spring–neap tide cycle with a mean value of
7.0 \times 10^{-3} \text{ kg m}^{-2} \text{s}^{-1} during spring tide, which was 40\% larger than the value of 5.0 \times 10^{-3} \text{ kg m}^{-2} \text{s}^{-1} during neap tide.

This calculation of near-bottom boundary layer parameters cannot only clearly describe the variation of sediment net flux during the floor–ebb tide cycle in the daily time scale, but also contribute to a better understanding of the sediment distribution during the spring–neap tide cycle in the monthly time scale. With observed data continuously gathered by the remote control subsystem, long-term datasets of the Xiaoqushan seafloor observatory and the practical performance of the remote control subsystem for ECSSOS from the perspective of data provision and usage.

5. Conclusions

The primary purpose of this paper is to address the remote control for the East China Sea Seafloor Observation System (ECSSOS). A remote control solution has been proposed based on state-of-the-art technologies, and its corresponding remote control subsystem has been developed to fulfill all design specifications. Although individual parts of the technology described in this paper are not necessarily new, it is the combination of the separate parts of the system architecture; remote communication; junction box and instrument interfacing, network configuration, and control; and object-oriented programming that form a base for a novel and robust system for remotely controlling the seafloor observatory facilities.

The remote control subsystem for ECSSOS can receive and initially store observed data in real time, monitor the seafloor observatory facilities and the in situ environment online, and send control commands to remotely configure underwater equipment interactively. This subsystem has already been put into use in the Xiaoqushan seafloor observatory, and this paper has shown that it has presented satisfactory practical performance against all design specifications determined at the very beginning. Given the successful trial in the Xiaoqushan seafloor observatory, the remote control solution proposed in this paper could be a useful reference both to the following construction phases of ECSSOS and to the implementation of seafloor observation system by other institutions. With some upgrading toward future design specifications of ECSSOS, the remote control subsystem developed in this paper will continue to contribute to the dynamic underwater network configuration and control, adaptive interfacing with instruments, and real-time data transmission and acquisition for both the separate construction phases of ECSSOS and the ultimate networked seafloor observation system in the East China Sea. All obtained scientific data shall, in return, resolve the fine temporal scale details and greatly promote the research progress in sediment source-to-sink transport and depositional dynamics, as well as biogeochemical processes and ecosystem health, considering major scientific topic of ECSSOS.

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