An approach for designing supervisory control and data acquisition system on submarines

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ABSTRACT

In this paper, the authors proposed a design of a SCADA system for controlling, monitoring, and collecting information and operating parameters on manned submarines. The proposed system improves and speed-ups the supervising and monitoring tasks as well as enhances the operation reliability. The control and supervision model of submarines (CSM-SM) is implemented by dividing the supervisory control system into sub-modules, each sub-module has its computer, installed the dedicated software running on the QNX operating system, responsible for independent supervisory control on the assigned location, and at the same time, can control the actuators in other compartments. All components in the system are connected through a data network using the military transmission standard MIL-STD-1553B, they hence form a unified surveillance control system. The model has been fully tested in laboratory condition and on-site with working submarines and received positive comments from the operational unit.

Keywords: CSM-SM; SCADA; SUB-SCADA; QNX.

1. SCADA MODEL

Modern SCADA (Supervisory Control and Data Acquisition - SCADA) [1] provides an appropriate monitoring method to maintain optimal operations by identifying and correcting problems before they turn into serious system failures. The hardware module of the SCADA system measures signals and collects data under the control of a software program installed in a dedicated computer in the system. The process of measuring and monitoring is conducted continuously and ensures a high level of reliability. In addition, the system also gives safety warnings during operation so that the operators can make accurate and timely decisions, ensuring the safety of both people and equipment on board [1].

A SCADA system consists of several remote terminal units (RTU). RTU is an independent electronic device that collects data at monitored and controlled locations, and exchanges the collected data with a central control system through a communication network [2]. RTUs communicate with sensor devices through either analog or digital interfaces. Meanwhile, the central control station displays the received data and allows the operator to perform remote control tasks through the RTUs.

Currently, people have many methods to approach and build a SCADA system. For common civil systems, SCADA systems are built on the Internet of Things (IoT) platform [3]. However, for systems with strict requirements for safety and reliability, these models still have some limitations. Specifically, those commercial platforms are not satisfied with strict timing requirements for data and control signals; a high level of stability of the control software; reliability of the data collection process, and the ability to timely detect errors and issue warnings to the users. Therefore, with the safety requirements related to people and equipment, the commercial platforms are not suited for SCADA systems on underground vehicles with people operating inside. In this paper, we propose a SCADA model for the CSM-SM system. The system is built on high-profile industrial computers and specialized peripheral cards are installed with control software on the QNX real-time operating system.

2. DATA ACQUISITION SYSTEM ON MANNED SUBMARINES

The structure of the data acquisition and control system includes:

- The central control device in the underground vehicle, which issues control commands and displays information about the technical status of the equipment of the CSM-SM system; conducts machine status and behavior monitoring, actuators' connections, and data sources checking. This equipment is designed with two computers having an identical function, serving as the central computer and backup computer. Two computers can operate independently or in parallel. In parallel operation, one machine works as the main controller, while the other supervises the whole process.

- Peripheral devices collect all technical status information from the system's equipment and the testing parameters of the sub-systems in the compartments and transmit them through dedicated channels to the central computer.

- Environmental parameters (temperature, pressure, concentration of oxygen, nitrogen, hydrogen) are measured by a measurement system (namely MSK system) from sensors and transmitted to the peripheral computer and central computer. The MSK measurement system transmits data to the peripheral computer via RS485 serial line, then the data is aggregated and transmitted to the central computer via MIL-STD-1553B.

- The control system receives information from peripheral devices (i.e., sensor data from the compartments), information on valves' status, mechanical structures, etc., and generates control commands to the actuators.

3. PROPOSE THE SCADA SYSTEM ON SUBMARINES

3.1. System specification

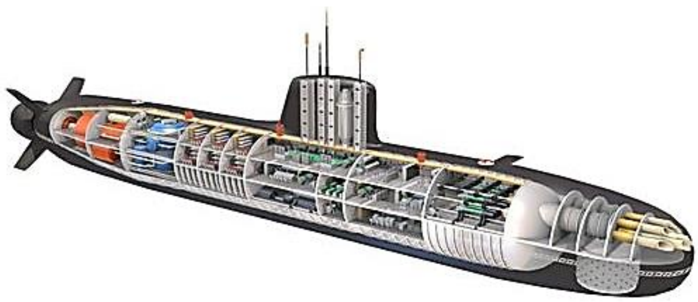

Figure 1. *Spatial distribution of underground vehicles.*

The underground vehicles are designed to be divided into different compartments with special splitters that ensure independent and strictly isolated space for each compartment (see figure 1). With such a design, the control and monitoring problem of the ship's technical equipment needs to meet the following criteria:

a) The systems in the compartments are designed to fit limited space on the ship and to be able to monitor and control independently between the compartments.

b) The system has flexibility in monitoring and controlling at many different locations on the vehicles.

c) The control and monitoring system has to operate in real time.

d) The system performs supervisory control with absolute stability, reliability, and accuracy.

e) The software running on the system ensures stability and continuous operation for a long time.

f) High reliability of control monitoring process.

With limited space in the compartments, especially in the case of underground vehicles, the system requirements need to be designed to ensure compactness and a high degree of integration. Also, the system design permits all equipment states can be managed in each location through the sensors. In the case of conventional systems that use computers and PLC devices or embedded boards to form conductive monitoring and control, the system will need large space for installing equipment and wires. Those clustered designs also degrade the system reliability, which tightly relates to factors such as the working reliability of the computer, the reliability of the PLC equipment, and the reliability of the data communication between them. Therefore, it is necessary to have a simple, suitable solution to replace the computer cluster and PLC (embedded board) while still ensuring full functioning and having an appropriate form factor. As an alternative solution, we suggest using an industry-standard computer using the VME bus in this case, which has been proven and certified for reliable stability.

3.2. Design of the proposed SCADA model

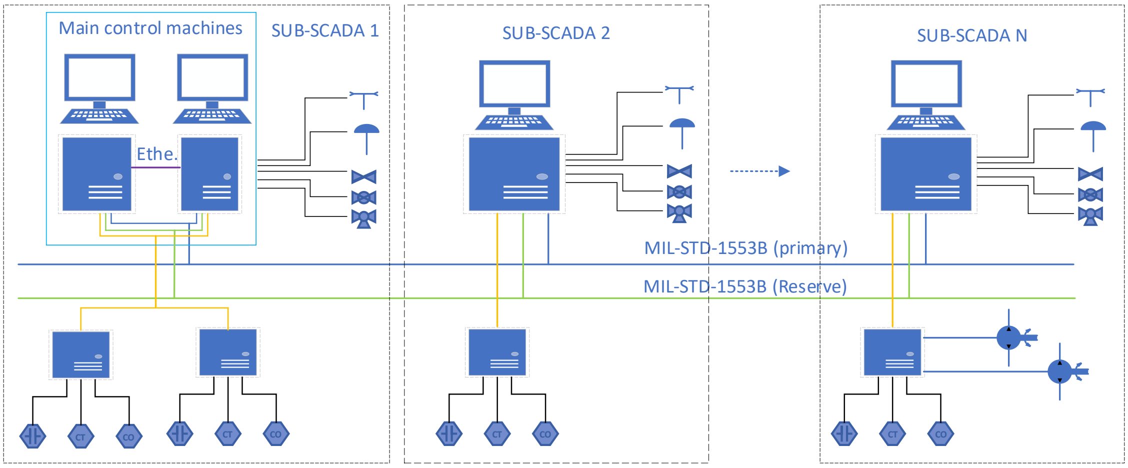

Figure 2. *The proposed CSM-SM system for distributed control monitoring on submarines.*

To ensure the above requirements, we propose to build each compartment using a SUB-SCADA system. In such a way, a complete SCADA system on underground vehicles consists of multiple SUB-SCADA networks joined together to form a local network. The SUB-SCADA systems on the vehicle exchange information with each other via two MIL-STD-1553B data exchange channels, a main channel, and a backup one so that the system can still work normally when one channel has any problems [4]. Communication in traditional SCADA systems often uses Ethernet where additional hubs or switches are required. Thus, according to reliability theory, these hubs and switches may introduce additional reliability degradation factors. Also, compared to the Ethernet standard, the MIL-STD-1553B standard works in harsh environments affected by electromagnetic interferences with more reliability and stable operation [5]. With the MIL-STD-1553B network, the communication network is wired directly from the network card to the network card of the computer devices [4]. Besides, the MIL-STD-1553B data transmission standard technically better tolerates harsh environmental operating conditions, such as high electromagnetic interference. MIL-STD-1553B network permits the connection of additional devices without the need for switches or hubs. This greatly enhances the flexibility in design, saving space while guaranteeing reliable communication between the system.

Figure 2 depicts an inter-network model for managing technical equipment in underground vehicle compartments. The system is organized into SUB-SCADA networks corresponding to clusters of controlled devices in one or several compartments. Each SUB-SCADA network uses a control station whose main component is the industry-standard VME-bus-supported computer as mentioned above. Distributed control stations in the compartments perform monitoring and data collection tasks, real-time manage system status, and deliver the collected data to the central control station via the MIL-STD-1553B interface. The central control station also adopts the same peripherals and processing unit as the distributed control stations in the compartment, however, the central control station is located in a more spacious central compartment equipped with a working desk and display for the operator. The central control station apart from monitoring and control functions is also capable of self-checking the system status, managing and granting access rights, and requesting information from the distributed stations in other compartments. To ensure the reliability of its mission-critical operations, the central control station is designed into two control desks of equivalent structure, capable of operating independently and/or supporting each other. The industrial computer modules of the control stations all use the QNX 4.25 real-time operating system platform with control software designed according to the desired functions, control objects, and data acquisition tasks.

3.3. Implementation of the proposed SCADA system

3.3.1. Design of control model

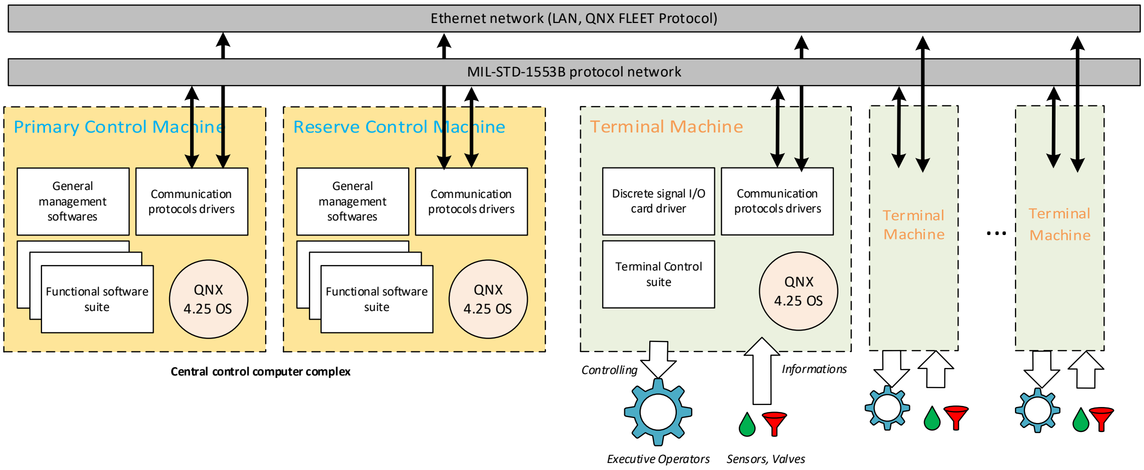

Figure 3. *Distributed control model CSM-SM using QNX 4.25.*

From technical specification, QNX 4.25 operating system is an appropriate choice for applying in control systems on underground vehicles. We hence built entirely SCADA control software on QNX 4.25. The control system model shown in Figure 3 includes control computers and scheduled software with different algorithms and priorities. The hardware system that acquires and exchanges sensor information and control commands to the actuators is built with discrete input/output signal processing sub-modules; the communication modules support both MIL-STD-1553B and Ethernet.

3.3.2. Main control software modules

a) Control the discrete signal communication module at the peripheral machine

The process of receiving, processing, and sending discrete signals plays an important, regular, and continuous role in data collection and control of technical equipment. Figure 4 depicts a flowchart of the software for digital control signal transmission. After starting, the software analyzes input parameters to enter a stable operating mode. Initial settings are carried out including setting up the scheduling algorithm and priority and setting up shared memory for interprocess communication (IPC). The software then identifies the hardware module and initializes the converters for each module accordingly. From this stage, the software starts an infinite loop to ensure the timely processing of discrete input/output signals. The program continuously waits to receive I/O instructions and buffers data for processing. If it is a read command from the SDI (Switching Data Input) channel, SDI read command is issued, and if the error report is sent if the command returns the zero read value before getting back to the loop. Otherwise, the read command is executed until the SDI port number is exhausted. If there is a read instruction for data from the input channel (DI), then read data from DI is performed. In the case of a command to write to the data output channel (DO), a write data loop sub-routine is launched for writing data until the number of DO ports is exhausted.

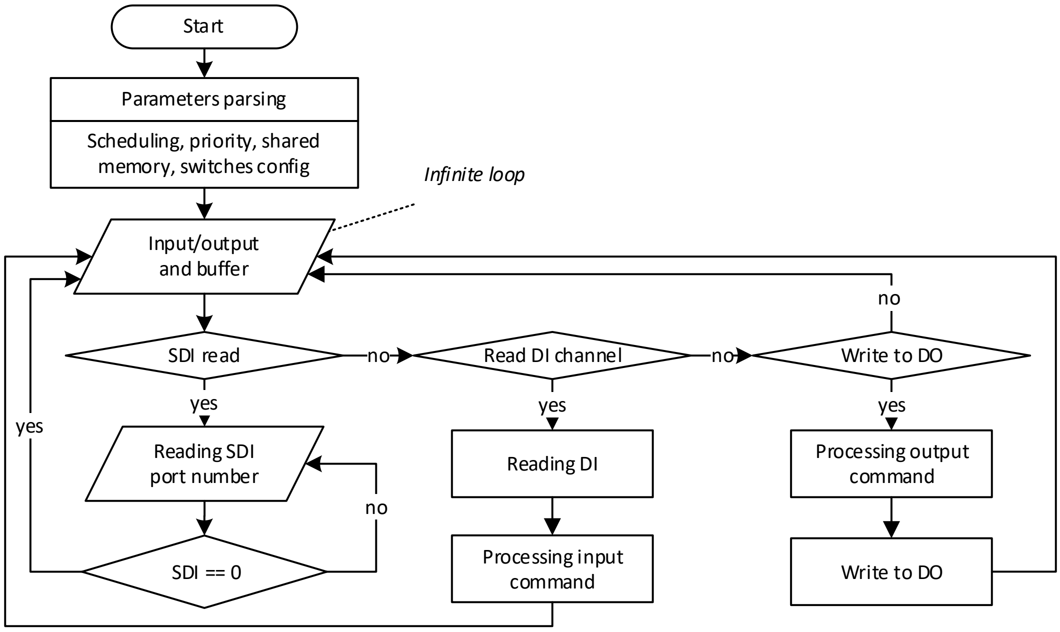

Figure 4. *Flowchart of the control algorithm of the discrete signal transmission module.*

b) Communication protocols management

This software module is responsible for managing all communication protocols of the computer, including the central processing unit and the peripheral ones. These protocols include LAN, RS485, and MIL-STD-1553B protocols. Using a unified and centralized software module for managing communication protocols guarantees the timely response of the system and permits effective real-time data transmission and processing.

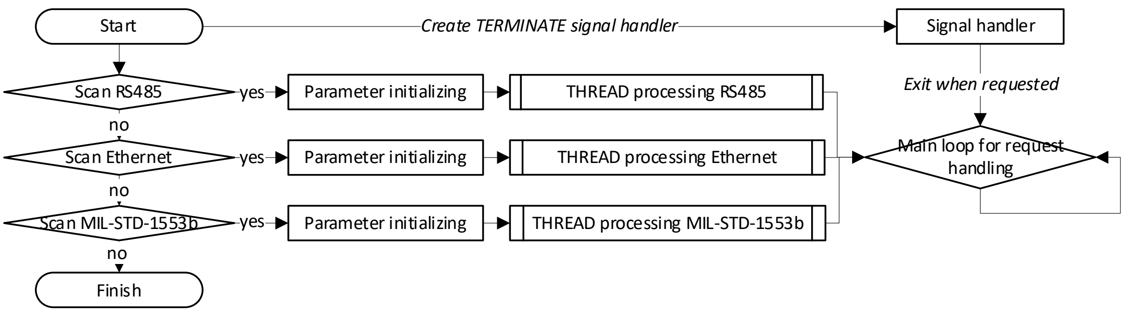

Figure 5. *Flowchart of a software module for communication protocols management.*

Fig. 5 shows the functional diagram of the software module, including the main process and the child processes that perform the assigned function accordingly. The process is launched at the start-up and stays permanently in memory, this continuously scans for hardware modules and their supporting protocols; if a hardware module is found, the main control process will initialize parameters (such as hard interrupts, baud rate, port address, cache setting) and generate a child process (or thread) to manage the transmission and reception of the corresponding protocol. Finally, the process executes an infinite loop to classify and manage the launched threads that process the requested messages from the user software.

c) Peripheral computer working algorithm

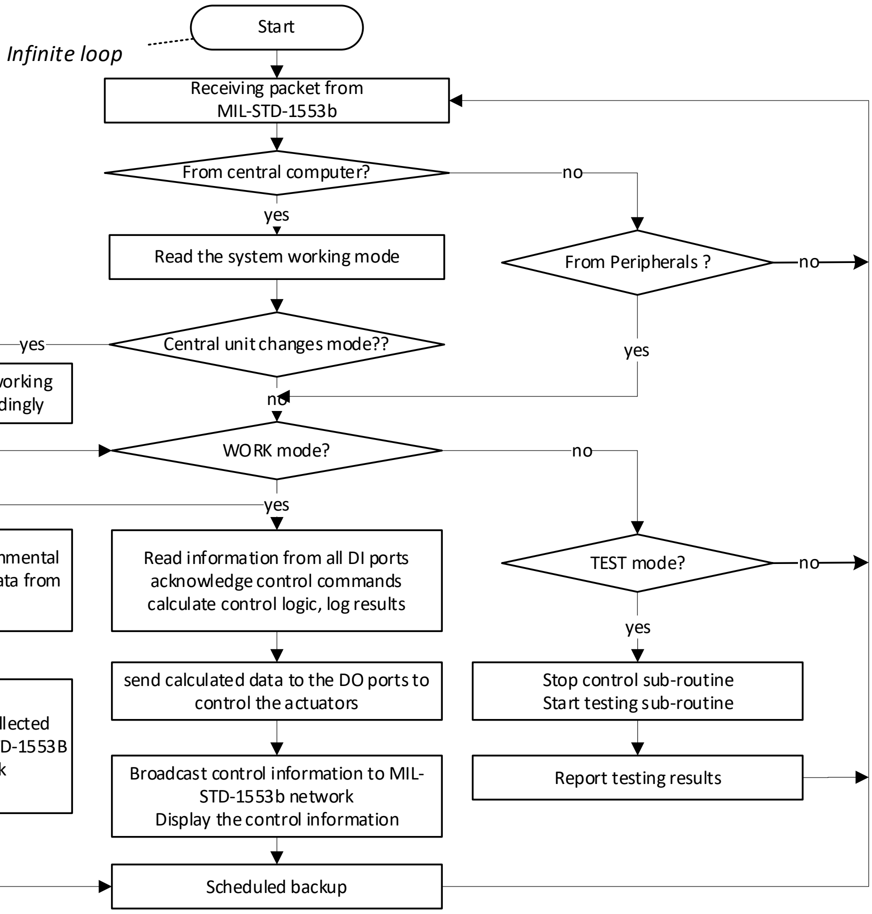

Figure 6. *Main working algorithm of the peripheral computer.*

Figure 6 shows the main working algorithm of the peripheral computer, which is responsible for collecting environmental parameters via the RS485 interface, receiving sensor signals and issuing control commands via discrete input/output channels, and aggregating status and control information before sending it to the central computer via the MIL-STD-1553B interface. As soon as the central computer changes its state (i.e., WORK mode and TEST mode), the peripheral computers must also perform the corresponding state transition.

In working mode, the peripheral computer needs to read sensor data, the valve status, and control mechanisms; issue control commands, and send aggregated data to the central computer over the MIL-STD-1553b interface. In test mode, the computer stops the control instructions and launches, the test cycles, collects data and sends the result report to the central computer. In addition, the computer must also periodically log all system information. The packaging and storage algorithms are presented in the next section.

d) Data packing and backup

It is important for the system to be monitored and backed up regularly. The packing and backup software suite consists of two independent software modules: the data collection module periodically (hourly) collects the information and encapsulates it and sends the packed data to the backup module. Meanwhile, the backup module is put in an infinite wait loop for writing data using the CRC16 checksum and the LZW compression algorithm. The backup software module also needs to perform some other service tasks, such as checking the free space of the HDD and creating a directory tree by date/time for post-checking if required.

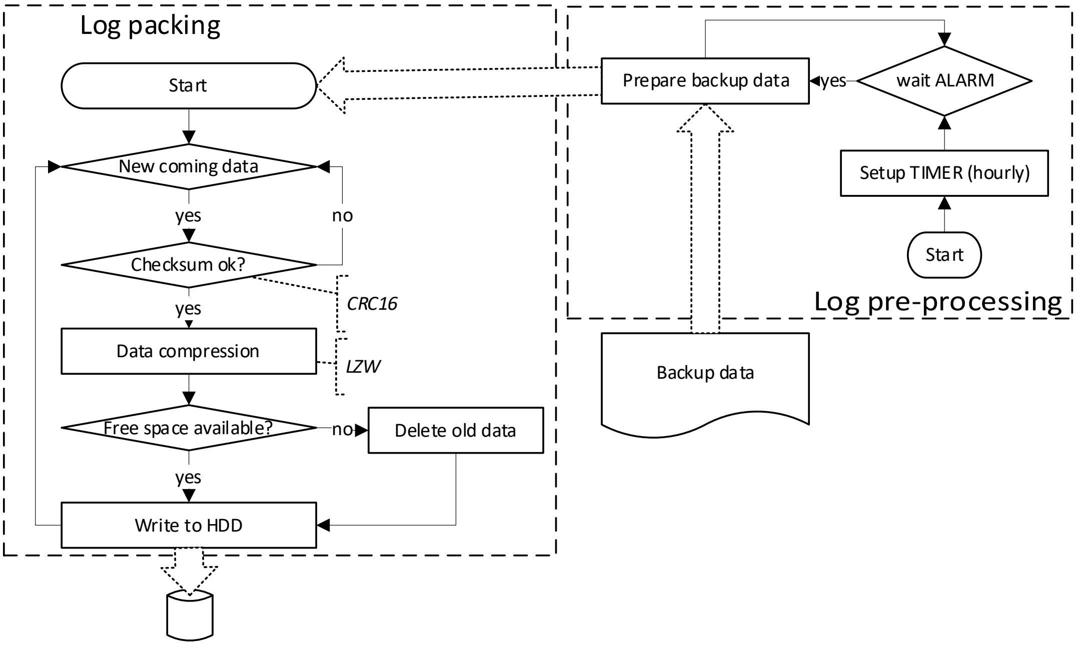

Figure 7. *Flowchart of data packing and backup module.*

3.4. System performance evaluation

The software module for the CSM-SM is installed on computers in each compartment of the system. Fig. 8 shows an example of the software interfaces. Algorithms described in Section 3 are loaded and tested on industrial computer modules (configuration: Atom 1.7 GHz CPU, 4 GB RAM, 8 GB c-FAST hard disk).

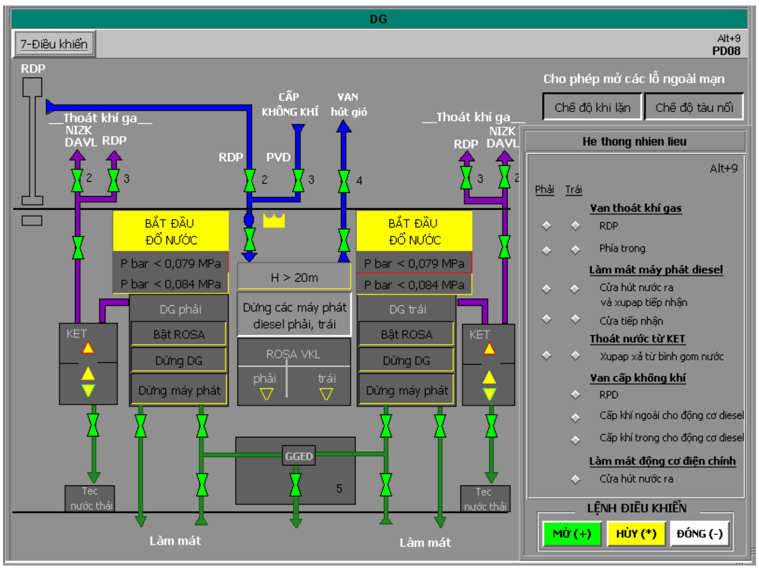

Figure 8. *SCADA software interface in underground vehicle compartment.*

Major parameters and results of software testing on the QNX operating system are consolidated in Fig. 9. It could be seen that the running of the communication protocol management process (netman), discrete signals management process (pd_io.srv), the control process (ld_dg), and its child processes (pd_cpm, ls_state, ls_msk..), all are invoked within OS kernel (proc32). The priority of the proc32 microkernel is the highest (PRI=30), and the installation processes of the CSM-SM are set to the appropriate level for the root user account. A process can be invoked multiple times in parallel (multi-instance) without affecting the overall system performance.

When implementing the algorithm with the same FIFO scheduling algorithm with different priorities, the resulting time consumed by the process itself, its child processes, and the microkernel are presented in tables 1 and 2.

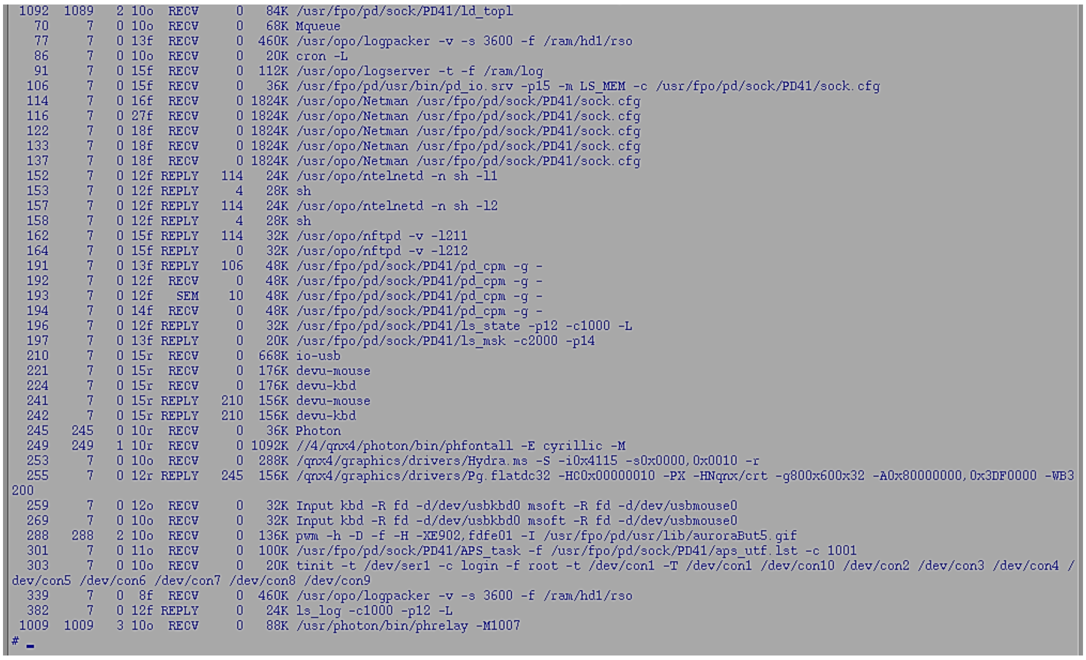

Figure 9. *System parameters of software launched on the QNX operating system.*

Table 1. *Software timing report with the low-priority setting.*

	Parameters/indicators	(a)	(b)	(c)	(d)
1	Priority level	15	16	13	13
2	Scheduling algorithm	FIFO	FIFO	FIFO	FIFO
3	CPU occupied time by process (ms)	10	4	25	13
4	CPU occupied time by child process (ms)	0	10	30	8
5	CPU occupied time by system services (ms)	12	11	60	14
6	System delay	15	60	35	10

Table 2. *Software timing report with the high-priority setting.*

	Parameters/indicators	(a)	(b)	(c)	(d)
1	Priority level	16	18	12	11
2	Scheduling algorithm	FIFO	FIFO	FIFO	FIFO
3	CPU occupied time by process (ms)	13	8	25	13
4	CPU occupied time by child process (ms)	0	12	40	10
5	CPU occupied time by system services (ms)	14	15	80	14
6	System delay	13	48	39	17

4. CONCLUSIONS

This work conducted a systematic study on the operation of the CSM-SM on submarines and proposed a design of a SCADA system to monitor, control, and interface with the actual onboard equipment. The testing results show that the use of process programming and synchronization on the QNX real-time operating system suited and meets the real-time requirements of the practical system. In future work, the authors would work toward improving the calculation and control algorithms, as well as adopting more powerful and reliable hardware devices.

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TÓM TẮT

Một hướng tiếp cận mô hình điều khiển giám sát và thu thập dữ liệu cho phương tiện ngầm

Trong bài báo này, nhóm tác giả đã nghiên cứu, thiết kế hệ thống SCADA nhằm mục đích điều khiển giám sát và thu thập thông tin toàn bộ tham số hoạt động trên phương tiện ngầm có người lái. Điều đó giúp cho việc quản lý giám sát cũng như vận hành phương tiện ngầm một cách nhanh chóng và an toàn. Mô hình điều khiển và giám sát toàn tàu (CSM-SM) được thực hiện theo phương án chia hệ thống điều khiển giám sát thành các phân hệ con, mỗi phân hệ con có một máy tính cài đặt chương trình phần mềm điều khiển trên hệ điều hành QNX, đảm nhiệm điều khiển giám sát độc lập tại vị trí theo khu vực được lắp đặt, đồng thời có thể thực hiện điều khiển các cơ cấu chấp hành tại các khoang khác trong hệ thống. Các thành phần trong hệ thống được kết nối mạng với nhau thông qua mạng trao đổi dữ liệu thông qua chuẩn truyền quân sự MIL-STD-1553B, chúng tạo thành một hệ thống điều khiển giám sát thống nhất. Mô hình được thực nghiệm trong phòng thí nghiệm và trên phương tiện ngầm, được đơn vị sử dụng đánh giá tốt.

Từ khóa: CSM-SM; SCADA; SUB-SCADA; QNX.