Research on a visualized real-time monitoring system for the slurry chamber of a slurry shield

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Abstract. In this study, a visualized real-time monitoring system was established to monitor the working conditions of the slurry chamber and collect rotation situations of the cutter head, wear conditions of the disc cutters, image information of the excavated strata and flow characteristics of the slurry. The operating condition of the front-end equipment is shown on the upper computer, and the signal collected by the camera is transmitted to the video acquisition system in real-time. Hence, this paper presents solutions to the system with an emphasis on the system structure, hardware, and software design, and verification. The system verification was conducted through a field test in a project site, where the system could reliably monitor the slurry chamber.

1. Introduction
With the continuous development of the economy and wide application of high technology in China, China is ranked first in terms of the scale and number of tunnels and underground projects, the complexity of geological conditions, and structural style as well as the development of construction technology [1, 2]. Shield machine, as a piece of engineering equipment for mechanized excavation, has been widely used in the excavation of tunnels and underground spaces in China [3]. For smooth construction progress, it is necessary to obtain the working conditions in the slurry chamber during excavation, including the rotation status of the cutter head, wear conditions of the cutter, image information of the excavated stratum, and flow characteristics of the slurry. Such information can provide an important technical basis for the adjustment of tunneling parameters and strategies to ensure smooth construction.

Presently, opening and video monitoring methods are commonly applied because of the acquisition of the working conditions in the slurry chamber. The former is the most direct and effective approach. However, it is costly and time-consuming, which affects the construction progress and poses high safety risks [4, 5]. The latter performs its function by employing the monitor and lighting devices installed in the slurry chamber. When the slurry chamber needs to be checked, the slurry level is reduced and then the video monitoring starts. However, the video monitoring window is prone to coverage by the slurry and its monitoring area is limited [6]. Thus, in this study, a visualized real-time monitoring system (the “system”) is developed to overcome the shortcomings of the abovementioned methods.

2. System solutions
The system, as shown in Figure 1, is composed of a front-end equipment, a piece of network equipment, an upper computer, an actuator (water and air valve) and a programmable logic controller (PLC). The front-end equipment comprises the control unit, a camera, and fill light.
Figure 1. Schematic of the system structure.

The front-end equipment is installed on the slurry chamber bulkhead while the upper computer is installed on the operator cabin. Moreover, the PLC, the network equipment, and the actuator are installed on the relevant operating platforms. The upper computer communicates with the front-end equipment through the serial port to monitor the working status of the front-end equipment (such as the fill light, camera, fan, and motor) in real-time. The cleanliness of the monitoring window and the active cooling of the front-end equipment is achieved through the opening of the water and air valve by the PLC. The video signals collected by the camera are transmitted to the upper computer through an ethernet communication, which provides real-time video surveillance, recording, and playback as well as monitoring the temperature, humidity, and pressure of the system.

3. Structural design
Because of the severe working conditions of the slurry chamber, the front panel of the front-end equipment is protected with a special concave design to reduce the impact of the slurry on the monitoring window. The monitoring window is made of a special tempered glass, which is 20 mm thick. The shell of the front-end device is 70 mm thick and the rear panel which is made of steel is 20mm thick. The rear panel is designed as a cooling water tank, which is connected to the shell by bolts and sealed with rubber strips to ensure complete airtightness. A bracket is installed under the front-end device to reduce vibration.

The camera is a combination of an industrial camera and a wide-angle lens, equipped with an up-down swinging and rotary device. The camera is designed to maximize the monitoring area.

A vortex tube is installed on the rear panel for cooling water supply to reduce the excessive temperature of the camera and circuit board because the slurry chamber operates in a closed space and at a high temperature. Additionally, a fan is installed inside the system to circulate the internal airflow. To keep the monitoring window clean from the slurry for visual monitoring, high-pressure water and air nozzle are installed above the front-end equipment. The axonometric view of the front-end equipment is shown in Figure 2.
4. Hardware design
The hardware system comprises a microprocessor module, sensor module, power module, fill light, camera, RS485 module, upper computer, and JTAG. The hardware structure of the system is shown in Figure 3.

5. Software design
The software system primarily includes the communication protocol between the control unit and the upper computer, together with the monitoring system and the video acquisition system.

5.1 Communication protocol design
RS-485 serial communication with a band rate of 9600 is adopted between the upper computer and the control unit. The length of a complete protocol frame is seven bytes, which include six parts, namely, frame header, command code / answer-back code, address code, parameter, check, and frame tail.

1) Table 1 shows the command data frame format of the upper computer.
Table 1. The command data frame format of the upper computer.

| Frame header | Command code | Address code | Parameter | Check | Frame tail |
|--------------|--------------|--------------|-----------|-------|------------|
| FB           | 1B           | 01           | 1B        | 2B    | FE         |

Frame header = 0xFB, address code = 0x01 (only for one device), and frame tail = 0xFE.
The parameter format is 8421-BCD code which depends on the command code.
The check code equals the sum (hexadecimal) of the command code, the address code, and the parameter, with the elimination of carry bit carried out Bitwise AND calculation with 0x7F (to ensure difference from frame header and tail).

2) Table 2 shows the answer-back data frame format of the control unit.

Table 2. Data frame format of the control unit.

| Frame header | Answer-back code | Address code | Parameter | Check | Frame tail |
|--------------|------------------|--------------|-----------|-------|------------|
| 1B           | 1B               | 1B           | 2B        | 1B    | 1B         |

Frame header = 0xFB, address code = 0x01 (only for one device), and frame tail = 0xFE.
The parameter format is 8421-BCD code which depends on the answer-back code.
The check code equals the sum (hexadecimal) of the answer-back code, the address code, and the parameter, with the elimination of carry bit (hexadecimal) carried out Bitwise AND calculation with 0x7F (to ensure difference from frame header and tail).

5.2 Monitoring of the system design

The application software is a three-layer structure consisting of the interface, logic, and data layers. Although the upper computer software has no logic layer, all the objects of its operation come directly or indirectly from the PLC which is equivalent to an extra PLC communication layer at the lower end of the data layer because the system is designed to monitor control parameters, store historical data, and perform statistical analysis. The software architecture of the monitoring system is shown in Figure 4.

Figure 4. The software architecture of the monitoring system.

The interface of the system is designed with C# under the Microsoft.NET Framework. The OPC server is the station configuration after the successful installation of the SIMATIC NET software provided by Siemens. The OPC server reads the data in the PLC through a proprietary communication protocol of the PLC manufacturer and converts such data into a data structure compatible with the OPC specification. The OPC client reads the data in the OPC server and the data is displayed on the screen.
through a visual display. On the other hand, the key data is stored in the database for subsequent fault queries and statistical analysis. The connection principle of the program and the OPC server is shown in Figure 5 [7–8].

![Figure 5. The connection principle of the C# program and the OPC server.](image)

**5.3 Video acquisition system design**

The video acquisition system adopts the C++ and Visio Studio 2010 development environment for graphical interface development, video signal transmission, and processing [9]. As shown in Figure 6, the overall software framework uses a coordinated multi-task architecture to disintegrate the control unit functions into several finite state machines. Each task is completed within a given time.

![Figure 6. A tree structure representation of the architecture of the control unit.](image)

Shown in Figure 7 is the object-oriented process of the control model. The object-oriented process management method is adopted, which describes the data structure of each module as an object. The main functions are treated as relevant actuators. The task process of each module is disintegrated further based on the state migration (the signal acquisition module), the excitation source (the fill light and fan module), or the actuator (the motor module).
6. Verification test and engineering cases

6.1 Verification test

Given that the slurry chamber operates in a closed space at high temperatures, a vortex tube for cooling water circulation is installed to reduce the high temperature of the front-end equipment, camera, and the circuit board as well [10].

The vortex tube is an instantaneous energy separation device. During operation, the compressed air expands through the nozzle and enters the vortex chamber tangentially. A high-speed rotating vortex is generated in the vortex chamber, forming a low-temperature airflow in the central area and a high-temperature airflow in the peripheral area [11]. The vortex tube, with a small size and simple structure, has been widely used in industrial and scientific research areas such as refrigeration, heating, mixture separation, and air conditioning [12].

To verify the cooling effect of the vortex tube, a verification test was carried out. The tested device was placed in a high-low temperature test chamber, and compressed air was forced into the test chamber through the vortex tube. As shown in Figure 8, the temperature of the test chamber was continuously increased at a heating rate not exceeding 2 °C/min. The test chamber was heated up to 45, 50, 60, 70, and 80 °C, and each temperature was kept constant for 0.5 hours. The operating conditions of the tested device under each temperature range were observed and recorded. Subsequently, a data curve was drawn, as shown in Figure 9. The upper curve represents the external temperature variation (the temperature of the test chamber), and the lower curve shows the internal temperature variation of the tested device (circuit board acquisition).

Figure 8. The temperature of the test chamber.
Through the verification test, it can be seen that the vortex tube could reduce the temperature of the device to some extent. Also, the closer the tested device is to the vortex tube, the better the cooling effect. Therefore, a flow guide device is installed to extend the air inlet of the vortex tube within 100 mm of the camera and the circuit board.

### 6.2 Engineering cases

An industrial test was carried out on a slurry shield manufactured by CREG. As shown in Figure 10, high-pressure water and air nozzles were installed for flushing the monitoring window to remove any slurry deposit in the slurry chamber. As shown in Figure 11, the front-end equipment is installed in the sealed chamber, and the water and air pipelines are connected to the spare water and air pipelines, respectively.

As shown in Figure 12, the monitoring interface of the system is developed by using C# and integrated into the upper computer monitoring system. The video acquisition interface of the system is developed by using C++ and integrated into the video acquisition system of the upper computer [13] as shown in Figure 13.
Figure 11. Rear installation view of the front-end equipment.

Figure 12. Monitoring interface of the system.
Figure 13. The video acquisition interface of the system.

7. Conclusion
This paper introduces a visualized real-time monitoring system for the slurry chamber of the slurry shield. Due to the severe working environment of the slurry chamber, a compact-structured camera with excellent performance was selected, and in conjunction with a specific structural design, a cooling effect verification test was conducted. The verification and field tests show that the system can monitor the operating status of the slurry chamber in real-time, and also produce realize real-time video monitoring, recording, and playback. However, owing to the complexity of the working conditions of the slurry shield and the humanized needs concerning tunneling, the system needs to be further optimized in the following aspects:
The flushing system needs to be optimized because, in the case of tunneling with a full chamber of slurry, the monitoring window will be covered by slurry.
Intelligent tunneling could be used such that the upper computer can trigger an alarm based on the analysis of the collected pictures and video signals and thus, control tunneling together with PLC when an abnormal situation occurs in the slurry chamber.

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