PAPER

Research on 3-D Precise Mapping System for Deformation Defects of Submarine Pipeline

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ABSTRACT

The submarine oil pipeline has many advantages, such as large oil transportation capacity, and being fast and economical. However, long-term laid submarine oil pipelines are affected by reciprocating load of water flow, subsidence caused by soil liquefaction, ship anchorage operation, etc. In severe cases, it causes overall distortion of a small section of the submarine pipeline, profoundly affecting the safety of the submarine pipeline, which is a significant safety hazard for the health of the marine environment and potentially impacting social and economic benefits. Taking the Cezi-Zhenhai submarine pipeline in the sea area between Ningbo and Zhoushan as an example, many deformation defects in the pipeline have been found through internal inspection, and there is a trend of further deterioration. However, the existing external detection of submarine pipeline deformation can only collect limited data through mechanical dots for rough inversion. This does not meet the accuracy requirements of repairing existing submarine pipeline clamps. Therefore, we propose a real-time visualization surveying and mapping system for the submarine pipeline based on a 3-D laser and a separately designed electronic control system. Our research team performed actual mapping work for the Cezi-Zhenhai submarine pipeline and achieved an excellent mapping control effect. A steady monitoring image and good control effect of moving parts are obtained, and the data obtained by 3-D laser processing perfectly represent the actual state of the submarine pipeline. Predictably, the large-scale application of this system will provide a solid technical guarantee for the health of submarine pipelines.

Keywords: submarine pipeline, electronic control system, external detection

Introduction

With the rapid development of China's economy, the demand for energy is increasing (Ho et al., 2020), and the number of crude oil pipelines laid under the seabed is growing year by year. It is increasingly essential to map the deformation defects of damaged pipelines and carry out pipeline reinforcement and repair. Because of its good geographical location and water depth conditions, Zhoushan City plays a vital role in importing and transferring crude oil. The Zhoushan Islands New Area establishment in Zhejiang province has also made the site attract increasing attention (Jin et al., 2019). The Cezi-Zhenhai submarine pipeline is located in the junction area between the southeastern part of Hangzhou Bay Estuary and the western part of Zhoushan Islands. The unique geographical environment creates special hydrological and sediment conditions and complex surrounding dynamic and geomorphic features. In addition, with the vigorous development of the marine economy in recent years, the artificial transformation of the marine environment has become increasingly apparent, which complicates the sea bed where the submarine pipelines are located, resulting in many pipeline deformation defects in the submarine pipelines in this area (Wang, 2018; Zhu et al., 2014). To successfully install submarine pipe clamps, it is urgent to have working tooling that can quickly and accurately map the deformation of the submarine pipeline and formulate the repair plan of the pipeline according to the results of accurate mapping to avoid further damage and even fracture of the submarine pipeline.

Detecting a submarine pipeline mainly includes two aspects: pipeline internal inspection and pipeline external inspection. Internal inspection specifically detects the internal condition of the pipelines; obtains the data on pipeline corrosion, cracks, and other defects; calculates the growth rate of defect corrosion; evaluates the remaining strength of the pipeline; and predicts the re-inspection cycle. At present, advanced internal detection technology includes magnetic leakage internal detection technology (Zeng et al., 2019; Chen et al., 2008), ultrasonic internal detection technology, and internal eddy current detection technology (Bao & Shuai, 2017); the more traditional method is the mechanical internal detection technology. External inspection is carried out outside the pipeline. The primary purpose is to master the external condition of the pipeline and check whether there is any external force damage and damage to the outer wall of the pipeline (Zuo et al., 2011). For submarine pipelines that cannot conduct internal detection or those that require appearance data, external detection technology is a crucial way to understand the operation status of the pipelines and find pipeline defects. External pipeline detection technology includes magnetic eddy current detection technology, pulse eddy current method (Wu et al., 2016; Zhang, 2017), electromagnetic ultrasonic detection technology, external radiographic testing technology, etc. (Hou, 2017; Yao, 2013; Kalogerakis et al., 2009).

The above external inspection techniques suit waters with low flow rates and high visibility. There is significant uncertainty about whether they can generally work in waters with complex sea conditions (high current rates and extremely low visibility). Similarly, under similar sea conditions, if technical equipment is employed in seawater, it is inevitable to face problems of maintaining equipment stability under rapid water flow, low visibility, and large amounts of impurities that will result in a low signal-to-noise ratio of the detected data. To repair and reinforce the submarine pipeline in a timely way to avoid oil leakage due to its breakage, it is necessary to conduct accurate appearance scanning of the submarine pipeline, judge the danger level based on the scanning results, and formulate corresponding response strategies (Guo et al., 2020). To this end, we innovatively create a dry environment and visualize it so that the pipe deformation defects can be quickly and accurately mapped in 3-D form. The real-time uploading of surveyed data also solves the interference caused by complex sea conditions to pipeline detection.

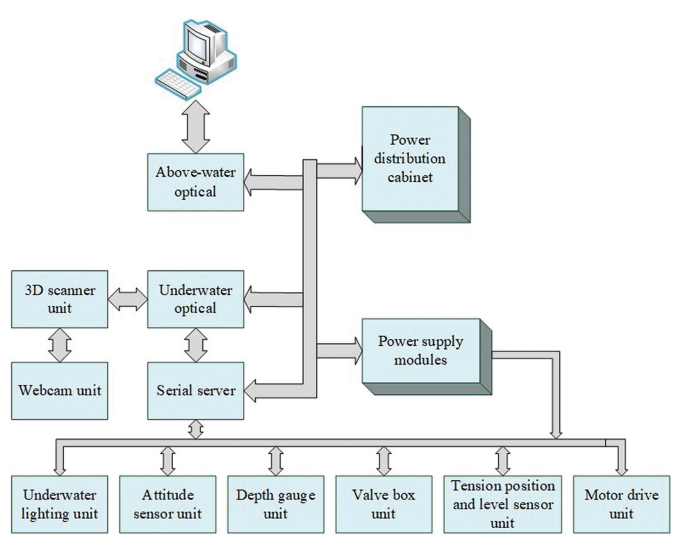
We have designed a separate electronic control system for submarine pipeline surveying and mapping, mainly responsible for communication and control. The real-time online monitoring of underwater equipment status and the condition in the cabin by the onboard equipment lays a foundation for improving the stability and accuracy of the motion of the 3-D scanning drive mechanism. The monitoring and control system proposed in this paper enables the mapping device to achieve a more accurate and faster 3-D mapping function, which is of great significance to real-time monitoring of the deformation of submarine pipelines.

Overall System Design

The overall system structure of the chamber-based 3-D accurate mapping device for submarine pipeline deformation defects is shown in Figure 1. The system mainly consists of a control and mapping host computer unit, a power distribution unit, an above-water optical unit, an underwater optical unit, a power supply unit, a

FIGURE 1

System block diagram.



serial server unit, a 3-D scanner unit, a webcam unit, an underwater lighting unit, an attitude sensor unit, a depth gauge unit, a valve box unit, a tension position and level sensor unit, and a motor drive unit.

The control and mapping host computer unit is responsible for controlling the entire mapping device motion actuator, displaying the underwater device's status and each sensor's status, controlling the 3-D laser scanner, uploading scanned submarine pipeline profile data timely, etc. The above-water power distribution unit is responsible for the power supply of the underwater mapping device while providing power for the above-water oil source and air compressor, underwater submersible pump, monitoring the operational status of the underwater device, and providing corresponding protection functions. The serial server provides an eight-way serial to network port conversion through its RS485 signal to network signal port. It sets different communication rates and port numbers for serial communication through the corresponding configuration function. The 3-D scanner unit uploads the 3-D profile data of the mapping device to the host computer in real time through the network signal. It extracts the required relevant feature values through the data processing software to provide data support for the later work of repairing the defects of the submarine pipeline (Zhao et al., 2010; Vasquez et al., 1997). The webcam unit and the underwater lighting unit provide real-time image information of the empty underwater chamber. The attitude sensor and depth gauge are responsible for delivering real-time attitude and equipment depth information when the mapping device is lifted and recovered underwater. The valve box unit controls the opening and closing action of the mapping device's left and right half chambers and the tightening and releasing action of the four positioning winches of the mapping device. The tension sensor unit provides the tension data of the four positioning winches when the mapping device is installed and positioned underwater. The position sensors provide position data of the mapping device's left and right half tanks in the closed position. The level sensors feedback liquid level data of the top floating tank and lower empty tank of the mapping device in real time. According to the established movement path, the motor drive unit is responsible for the type conversion of the communication data and the driving force of the four actuator motors.

System Unit Design

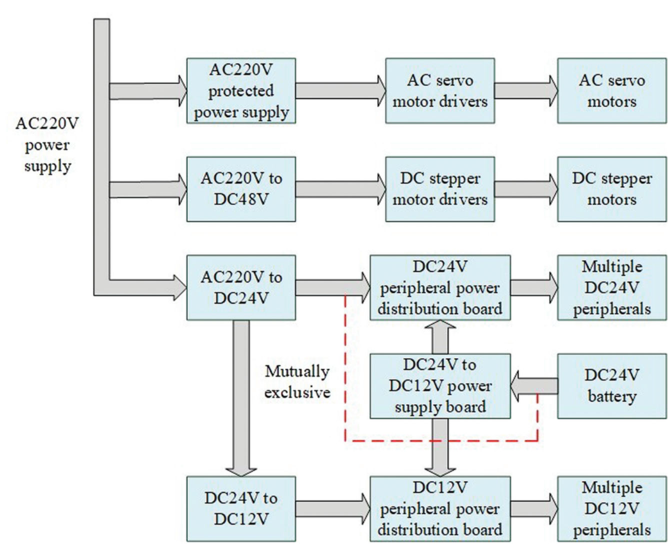
Design of the Power Supply Distribution Unit

The chamber-based submarine pipeline deformation defect 3-D accurate mapping system is equipped with a variety of models of external equipment with power supplies of 12V, 24V, and 48V, and individual equipment requires an independent power supply to ensure that, in the event of external equipment failure, it can be isolated and does not affect the use of other equipment. The power distribution unit design structure is shown in Figure 2. The AC220V to DC24V power supply module and DC24V to DC12V power conversion module provide isolated power for the underwater DC24V and DC12V peripherals, respectively. At the same time, the DC24V battery and AC-DC converter switch the power supply of underwater DC24V and DC12V peripheral loads through the ship power self-test relay, which also automatically switches to the underwater DC battery power supply when a ship's power failure is detected, ensuring that the necessary peripheral loads can work appropriately in emergencies.

The block diagram of the peripheral power control circuit of the

FIGURE 2

Block diagram of the power distribution unit.

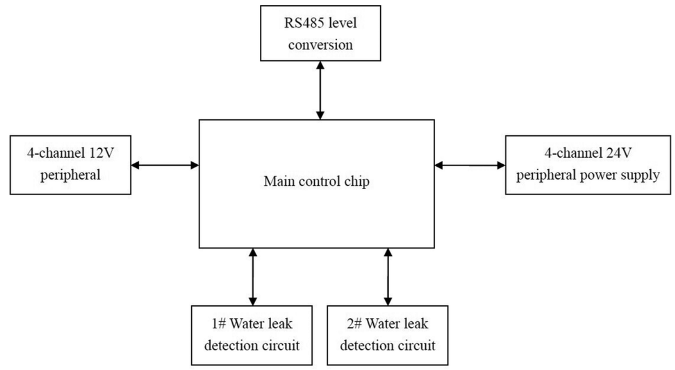


power distribution unit is shown in Figure 3. The circuit uses an STM32F103C8T6 microcontroller (Zhao, 2017; Shi & She, 2020), which is networked with the RS485 communication bus through a TTL (Transistor-Transistor Logic) to RS485 level conversion circuit (Bai & Wang, 2020). Four-channel 24V and 12V power supply circuits can supply power to equipment with a rated capacity of 100 W and 60 W or less, and both have overload protection functions. Two water leak detection circuits provide real-time leak detection in sealed compartments.

The software design of the peripheral power control circuit mainly completes the following functions: (1) The system is predefined and initialized; (2) open the serial port to receive interrupts; (3) receive data and judge the correctness of the data; if the correct data is received, then judge whether the data frame ID is the ID of the peripheral power control board—if not, then discard the data frame; if yes, then judge the instruction byte of the data frame and operate the corresponding IO port according to the instruction byte; (4) if the received data frame is an interrogation command, then send the system collected water leakage detection data to the host computer; (5) if the system does not receive another execution operation command from the host computer within the time interval of the independent watchdog reload value, the system automatically performs a reset (to ensure that the control unit of the peripheral power supply can be automatically reset in case of communication abnormalities) (Chen et al., 2009; Cui & Yang, 2021; Yang, 2015). The software flowchart of the peripheral power control circuit is shown in Figure 4.

FIGURE 3

Structure diagram of the peripheral power control circuit.

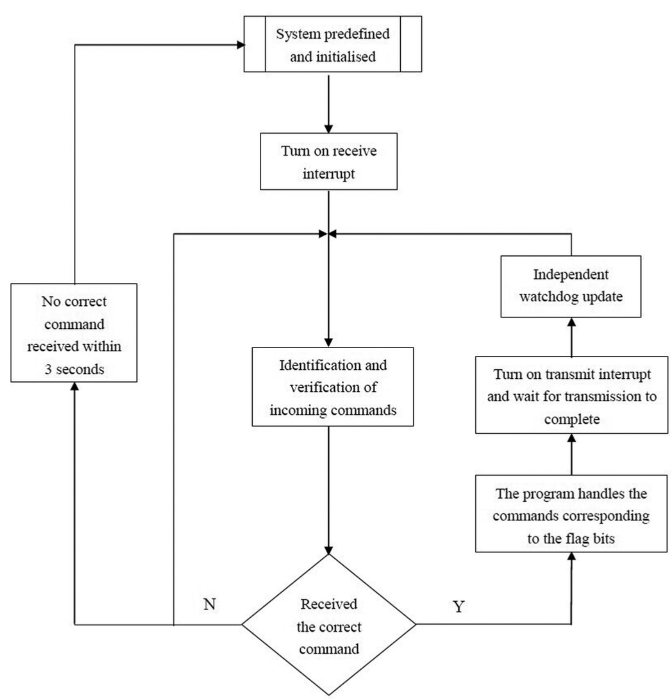


Design of the Analog Quantity Acquisition Unit

The chamber-based 3-D accurate mapping system for submarine pipeline deformation defects requires a variety of sensors for attitude, pressure, depth, and liquid level to collect signals from the underwater lifting attitude of the mapping device, the system pressure of the empty chamber, and some of the primary actuators, the working seawater depth, and the liquid level in the chamber, and to transmit signals to the deck operator's host computer in real-time through the communication unit for the monitoring system to grasp the real-time signal, which is sent to the deck operator via the communication unit in real-time. A block diagram of the sensor signal acquisition circuit is shown in Figure 5.

FIGURE 4

Software flow chart of the peripheral power control circuit.

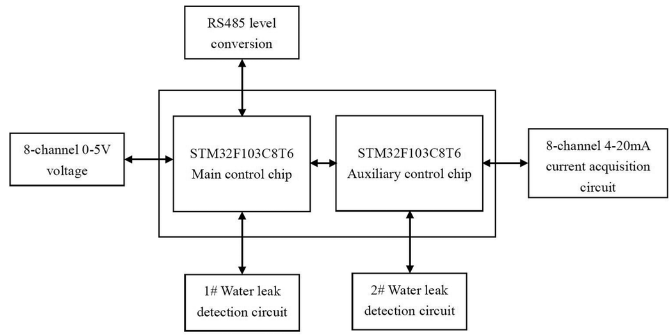


The STM32F103C8T6 is used as the microcontroller for this circuit. The controller is networked using the RS485 bus and communicates via the communication unit with the main deck control computer (Du, 2021). The sensors of the mapping device have two forms of voltage output and current output, so to reduce the space occupied by the circuit, two acquisition modules for voltage and current signals are integrated on one circuit board, and the information between the two is transferred through the communication port between the chips. In addition, two water leakage detection circuits are used to detect whether the interface box of the mapping device is leaking and to upload status information in real-time.

The analog acquisition unit software mainly includes the following functions: (1) initialization of the master and auxiliary control chip; (2) the auxiliary control chip collects analog data and sends it to the master chip through the serial port according to a specific time interval; (3) the auxiliary control chip judges the watchdog flag bit and updates the watchdog if the watchdog flag bit is obtained within the reload time, otherwise the auxiliary control chip resets the system; (4) the master chip serial port interrupt receives the data and checks the data frame. If the auxiliary control chip sends the data, it is stored in the cache. Suppose the data sent by the auxiliary chip are stored in the cache. In that case, if the query instruction sent by the upper computer is correct, the data collected by the auxiliary chip or the query instruction sent by the upper computer is stored. The latest data status is then written to the uploaded data frame and sent to the upper computer through the serial port (Zhou et al., 2020). The software flow diagram of the sensor signal acquisition unit is shown in Figure 6.

FIGURE 5

Block diagram of the sensor signal acquisition circuit.



Design of Motor Drive Unit

The scanner unit of the chamber-based 3-D accurate mapping system for submarine pipeline deformation defects is controlled by two straight track motors to realize fore-and-aft reciprocating motion, two ring track motors to drive the scanner to perform 36° rotation in the circumference direction, the scanner angle motor through the reducer and rack, and pinion to complete its slight angle rotation. Since the communication interfaces of the five drives are RS485 and CAN, and their communication data formats differ significantly, two RS48 to CAN modules are configured here. The first conversion module enables the conversion from the control RS485 bus to the CAN bus, and the second conversion module enables the conversion from the CAN bus to the drive RS485 bus; this configuration is conducive to simplifying the communication

FIGURE 6

Software flow chart of sensor signal acquisition unit.

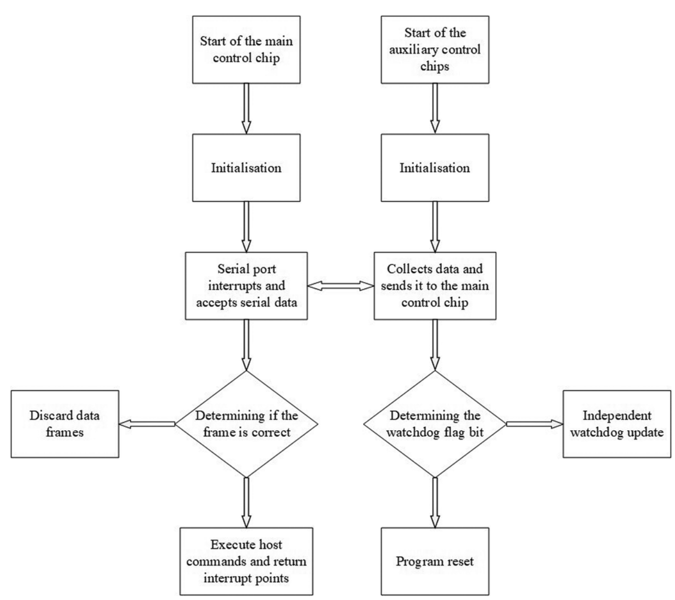
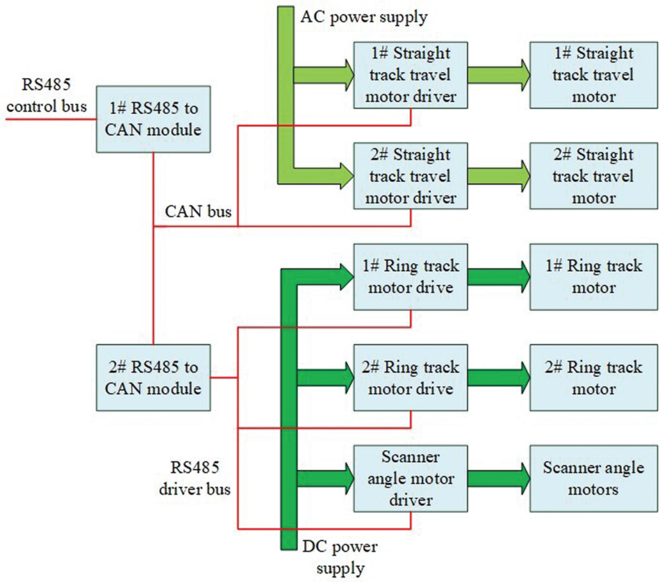


FIGURE 7

Diagram of the motor drive unit.



data frame format between the host computer and the drives and improving the stability of the communication system (Figure 7).

System Debug

As shown in Figure 8, based on the designed and processed mapping device, the whole precision mapping system is debugged, and all functional modules work correctly. Stability and waterproof seal are the critical points in commissioning. The harsh sea environment puts forward very high requirements on the interface stability and waterproof seal of the electric control system. Especially in Hangzhou Bay, a large amount of sediment is carried in the seawater, which increases the difficulty significantly. The entire commissioning cycle has reached 30 days. The system debugging improves the upper computer interface, enhances the protection ability of the system to deal with water leakage in the cabin, and improves safety and stability.

FIGURE 8

Test site map of electric control system.

On-site system commissioning is divided into three main stages, starting with full functionality on land, followed by underwater testing offshore, remediation for emerging new problems, and finally, carrying the entire system to target seas for actual operations, verifying its functionality. Through the actual assessment and verification of the three stages, the whole measurement and control system can effectively supply power to the whole system, provide monitoring and lighting, control the movement parts, realize the remote data upload, and monitor the posture and each partial state of the surveying and mapping device.

Verified by multiple launches, the mapping device realizes the maximum seal of 33 m underwater, creating an empty cabin environment that provides the conditions for laser 3-D mapping. Utilizing the dry compartment environment, the camera and underwater illumination cooperate to manipulate the in-chamber 3-D scanner actuation mechanism for turning; the control center controls the scanner movement to the corresponding position to meet the imaging requirements of the laser 3-D scanner.

Sea Test Certificate

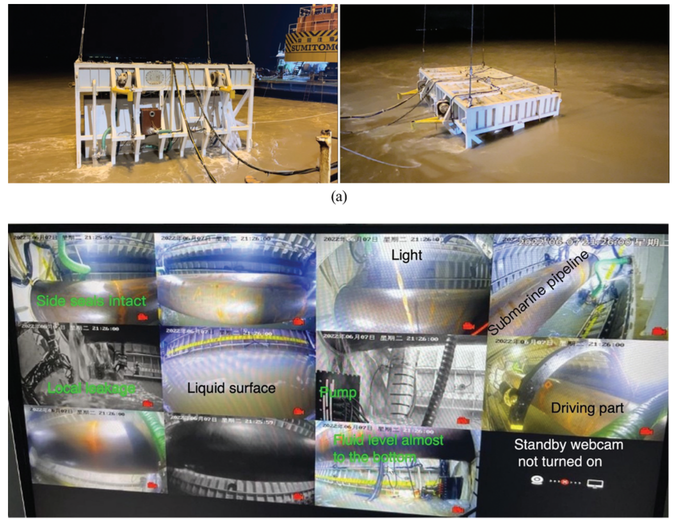
All chamber-based submarine pipeline deformation defect 3-D accurate mapping system components were tested in the Taohua Island sea, Zhoushan, on June 2, 2022. Due to various control and mechanical structure problems encountered in the structural transformation and sea test, the whole commissioning test took 2 weeks. On June 18, 2022, a sea test was conducted in the target sea area near Cezi Island, Zhoushan. A 6-m-long 12° curved angle submarine pipeline was used for the mock trial.

Figure 9(b) shows the underwater space cabin's monitoring interface; the interface includes 11 perspectives to observe the cabin's condition, mainly including the liquid level, moving parts, and leakage in the cabin. To monitor the water level in the cabin, the water level line is set on the side wall. A scale line is also set in the fore-tail to monitor the progress of moving parts in the cabin. After a period of emptying, the water level in the cabin meets the mapping needs. The control and communication of the surveying and mapping system are normal, and the power supply is expected, which can ultimately drive all the functions of the complete surveying and mapping device and realize all the preset functions. The final 3-D scanning results are shown in Figure 10. Because of the limitation of the scanning angle, the scanning is stopped at any time when the undersea pipes are out of the scanning range. In addition, a single, long scan will bring a vast amount of data, resulting in a substantial prolongation of data import time and difficulties in postprocessing, so mapping the undersea pipeline cannot be done at once. The merging of the individual scans resulted in the presentation of Figure 10, with each color representing the data from each scan. The bending angle of the submarine pipeline is set to 12° according to the requirements of test and processing. After processing the scanning results, the angles of different spans are measured as 11.4812°, 11.4565°, 11.4903°, 12.0609°, and 12.2065°, respectively.

The successful development of this system provides the primary conditions for the practical application of underwater cabins, fills the blank of cabin detection of submarine pipeline detection, and improves the accuracy of external detection to an unprecedented degree. The systematic and large-scale application will further enhance China's ability to accurately survey and map submarine pipeline

FIGURE 9

Sea trial site at Cezi Island, Zhoushan. (a) Field experimental diagram of the unit in the water; (b) monitoring unit of the electric control system for sea test in the target area.

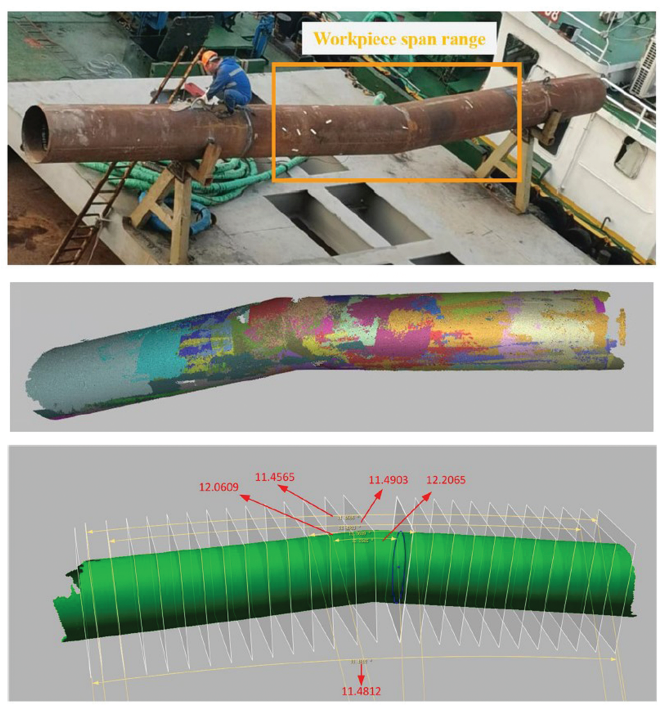


(a)

(b)

FIGURE 10

3-D scanning results of the test pipeline and seabed used in the operation area.



detection and narrow the technology and equipment gap with foreign countries.

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