Experiment On Teleoperation Of Underwater Backhoe With Haptic Information

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Abstract: *There has already been progress in the development of unmanned construction and inspections of structures on land, mainly because it is possible to use radio waves and optical images that are effective ways to remotely control work and operate robots. In contrast it is not easy to develop unmanned work methods for use underwater, because it is a special work environment, where underwater turbidity and suspended solids obstruct the operator's view of the object of work by scattering light. This report introduces the remote operation of an underwater backhoe based on bilateral operation that was developed to overcome such difficulties*

Keywords: Bilateral control, Underwater backhoe, Teleoperation

1. INTRODUCTION

Because many port and harbor structures are constructed under the surface of the water, most of their construction, inspections and diagnoses, and maintenance and repair are done underwater, and much of this requires manual work by divers. Technology that can enable this underwater work to be performed more safely and efficiently is required to be established as quickly as possible. This research institute is conducting research and development on unmanned underwater work that can be applied to overcome these problems to construct, inspect and diagnose, maintain and repair, and according to circumstances, perform damage restoration of port and harbor structures.

2. PROPOSAL OF A REMOTE OPERATING METHOD

When the remote operation of this underwater work was considered, it was necessary to overcome the limitations on the operator's ability to see the state of the work relying only on images obtained by TV cameras or ultrasonic waves by developing a new visual confirmation method. Many underwater visual confirmation technologies have been developed and it is generally effective to obtain visual images using ultrasonic waves. This approach is suitable for clarifying the topography over a wide range, but to operate construction machinery, a range of only a few meters from the machine is necessary. However, applying ultrasonic wave visual confirmation technology in this way is hampered by problems such as the effects of the shadow of the machine and the diffuse reflection of the ultrasonic waves. Present ultrasonic wave visual confirmation systems suffer from low real-time capability and still cannot be used to continuously revise the topography as its shape is changed by the work.

This study proposes a man-machine interface that uses contact information as a technology that can confirm the shape of a mound beside work machinery in real time, a function that has been impossible using ultrasonic visual confirmation technology. By installing a pressure sensor on the bucket of a backhoe, it is possible to detect whether or not the bucket has contacted a riprap mound or whether or not the bucket receives large reaction force from the riprap mound when it is operated, and feeding this information back to the operator in easily understood form increases the operator's ability to confirm the state of the work to prevent a fall in operating efficiency as during the offshore trial.
Specifically, the system has been constructed so that each part of the backhoe moves in response to remote control commands from the operator, and at the same time, the stroke of each part of the backhoe and the reaction force received when its bucket contacts objects such as a mound of rocks are detected and this information is fed back to the operator.

In other words, mechanisms that permit the operator to move the operating lever while watching attitude display screens of each part of the backhoe obtained by detecting the strokes of the arm and boom, and that feed back the reaction force received from the bucket to the operator as resistance to the motion of the operating lever were considered. The operator can be informed of the state of the bucket because, when this resistance is small, the arm and boom are moving, and when the resistance is large, the bucket is attempting to move rocks on the mound. And computer graphic images prepared by accumulating a history of the attitude of the bucket as reaction force acts on it can inform the operator of the shape of the mound during smoothing work. In brief, using this operating system, an operator can remain directly aware of the attitude of the backhoe and the types of loads it is bearing as it smoothes a mound and how the shape of the mound is changed by the progress of the work.

2.1 Visually indicating tactile information

A human can move without visual information by confirming its surroundings by touch (tactile sense) to form an image (haptic image) in its brain. Applying this principle to the remote operation of an underwater backhoe can pioneer a way to confirm the state of work performed underwater in real time by processing multiple, but not too many, types of information into easily understood form premised on the superior confirmation capabilities of a human. This is a method called augmented reality. This method is applied to conduct research on haptic image visualization.

As one method, when the system detects contact with the object by the manipulator on the underwater work machine, it determines its coordinate position and displays this visually as computer graphics to provide information necessary for remote operation. Specifically, a contact sensor or a force sensor installed on the tip of the working arm detect contact with the object of the work, then this contact position is calculated based on the angle of each movable part of the work arm and on the stroke of its cylinder. Furthermore, the three-dimensional coordinate position of the contact point is obtained by measuring the position coordinates of the work machine itself with an underwater coordinate position measurement system. By repeating this method, it is possible to portray a more realistic image on three dimensional coordinates by gradually clarifying the form etc. of the object. Figure 1 shows how the haptic image is formed, and Figure 2 shows the topography display computer graphic.

2.2 Operating entry interface

The purpose of this research is to remotely operate an underwater backhoe to perform work such as smoothing riprap, but because the machine is on the ocean floor where its position cannot be visually confirmed, it is necessary to be able to confirm the attitude etc. of the backhoe at a glance. It is predicted that using the operating interface with a conventional joystick will provide poor operability, because of the difficulty of clarifying shapes.

The operating interface used for this research is analogous entry that can be counted on to let an operator remotely operating a backhoe with many joints perform operations easily and intuitively understand the angles of the joints. This means that the operator can understand the shape by watching the interface, and by moving it, intuitively respond to each action of the actual machine one after another. And because the actual system presents information as computer graphic images on an ordinary display device, it is material useful in mutually reinforcing the information.

And the functions and conditions necessary for an analogous interface are that it achieve good operability, indicates reaction forces produced when the machine contacts the object, and ensures safety and reliability.

It is important that it be possible to easily enter operations in order to achieve good operability. Therefore, the operator holds a part of the operating interface corresponding to the bucket. So the purpose of the interface is to move the bucket

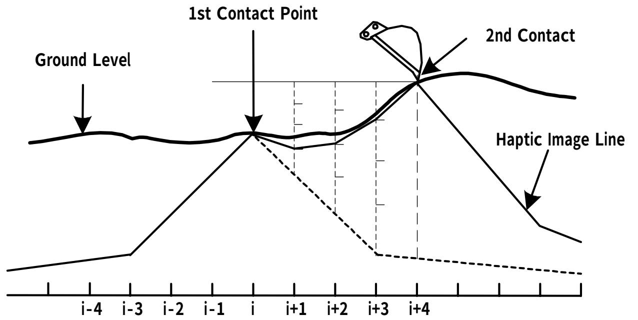

Figure 1 Formation of a Haptic Image

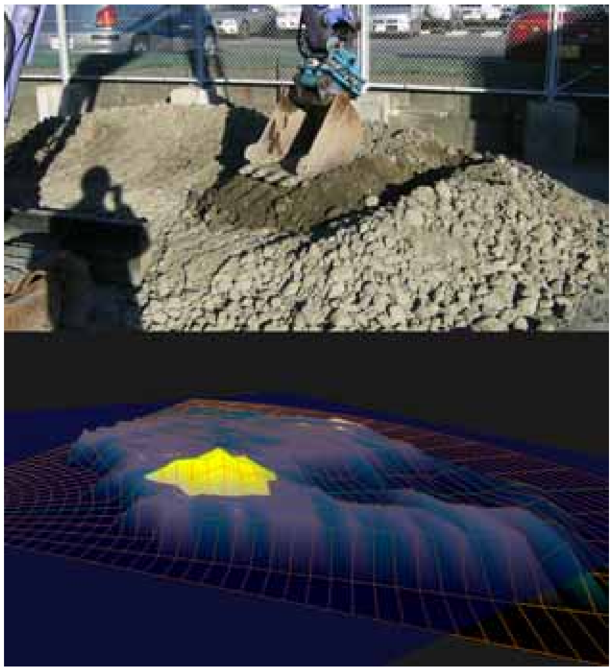

Figure 2 Topography Display Computer Graphic

any way the operator wishes, and the simplest way to do this is to hold the bucket itself. But the range of mobility of the bucket is large at about 300°, and it is presumably necessary to shift the bucket during operation without changing its shape.

Operating this interface as if the part held is a cylinder, a pen for example, lets the operator enter operations as he wishes and ensures the entry range. The scale of the analogous interface is 1/20 of the underwater machine. Presuming that the mobile range is within about 400mm premised on its desktop use and that the precision required to operate an actual machine is approximately 50mm, this scale was set because the precision of the actual work is about 2.5 mm that is 1/20, and combined with the display of the reaction force described below, this is can be fully achieved.

It is necessary to incorporate a reaction force indicator mechanism in the analogous interface constructed through this research. Because the major task of this machine is to smooth riprap, it must be able to sense that it has contacted hard material. The tactile force that obtains the feeling of having contacted hard material may be 1 kgf if the response is adequately far, and a condition for applying this system is that it be able to output 1 kgf or more in any direction.

The degree of freedom of a backhoe consists of four degrees of freedom: that of the bucket axis, arm axis, boom axis, and rotating axis, but work using the rotation around the pivot (yaw rotation) is mainly changing direction, so it is not installed at the prototype stage of the operating interface. The yaw rotation will be incorporated in the movement operating system of the actual machine.

3. DEVELOPMENT OF THE REMOTELY CONTROLLED UNDERWATER BACKHOE

3.1 Development of the test machine for the offshore trial

The basic trial of this remote operating system was performed by a land based test machine equipped with a mini-shovel, but because of engine output problems, the trial was performed using material with diameter of about 150mm that is smaller than the riprap used to construct actual mounds, so it was necessary to perform a smoothing test to actual scale. Therefore, a test machine was manufactured for use in trial smoothing work performed in real ocean water in 2004. The underwater test machine was based on the underwater backhoe BIGCRAB (Fig. 3) owned by Saeki Kogyo Co., Ltd. that conducted research jointly with this research institute. The BC3 was originally constructed for underwater remote control operation, and its basic equipment includes proportional electromagnetic valves etc. The test machine prepared for this trial was equipped with a control PC and control use sealed vessels containing the sensor amplifiers etc. The control use sealed vessels had a double structure and were equipped with float switch type underwater sensors. Internally, in addition to the control devices, it was equipped with an uninterruptible power source device in case of broken cables or a power failure. And to monitor the major data obtained by backhoe sensors from above the water, a console extension device that allows the use of a monitor, keyboard, and mouse at a remote location was installed to be used to permit the rebooting of the on-board PC and to correct its program. The waterproof vessel containing the control devices is shown in Figure 4.

As a waterproofing measure, the angle sensor's potentiometer that is its mechanically rotating part is omitted, the magnetostriction sensor is installed on the side of the hydraulic cylinder. It is also equipped with an SBL transponder and water pressure gauge to measure the position of the underwater backhoe. To measure the depth of the backhoe based on data obtained by the water pressure gauge, it is equipped with a high precision water pressure gauge with error of 0.15% in the 20m measurement gauge. The impact of the tide level when a water pressure gauge is used is corrected by entering the tide level at the time to the database. The machine body orientation and angle of inclination are detected by a magnetic orientation sensor and a FOG (Fiber Optic Gyro). The magnetic orientation sensor is sealed with urethane resin and the FOG is installed in the control use sealed container.

A new reaction force sensor was made by equipping it with a ±200kN load cell to match the backhoe output. This reaction force sensor was equipped with a new mechanism that senses force through a spring washer considering the impact load. Figure 5 shows the reaction force sensor.

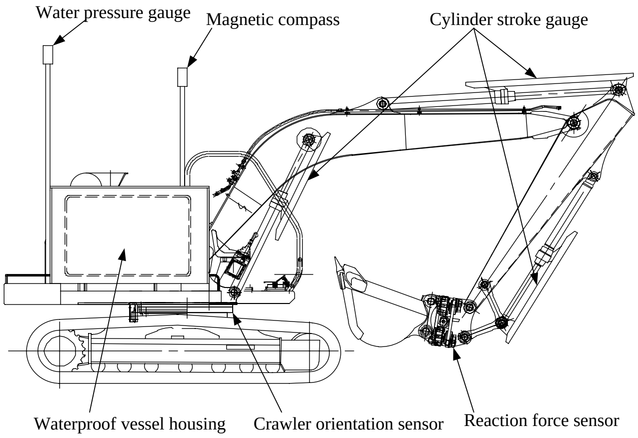

Figure 3 Underwater backhoe BC-3

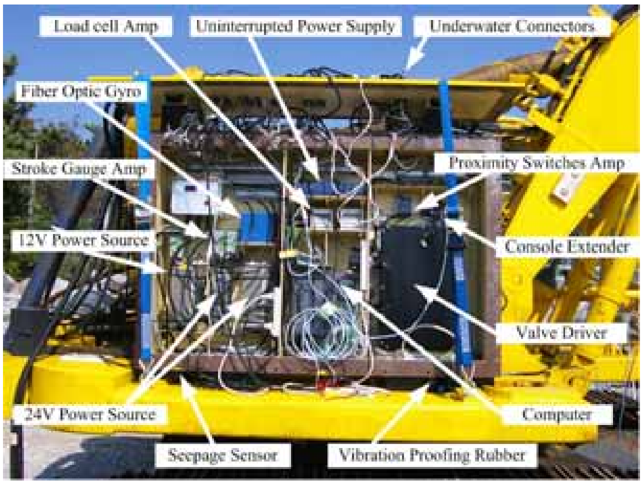

Figure 4 Equipment Housed in the Sealed Container

Figure 5 Reaction Force Sensor

3.2 Development of the similar figure interface

Figure 6 shows the backhoe use similar figure interface used to control the backhoe. It is equipped with actuators that have an analogous relationship with the front of the test machine used for the trial, and that transmits output attitude constraining force and tactility feedback independently to each joint, and a rotary encoder that monitors the joint angle, and the remote control computer controls these devices and obtains data. The remote control computer calculates the tip coordinates based on the joint angles then transmits these to the PC on the backhoe as command values. tactility is displayed to the operator according to feedback information that is transmitted from the PC on the backhoe.

Figure 6 Similar Figure Interface

3.3 Bilateral control

Position symmetrical bilateral control that restricts the difference between entered attitude and machine body attitude is an effective way to obtain stability when remotely controlling construction machinery. But in cases of large output as that of a backhoe, it is difficult to sense contact because a small load does not cause displacement between the Master and Slave. And with a force feedback type, the delay between signal entry and operation and operating speed are problems that make it difficult to maintain the analogous relationship between the Master and Slave. So the trial machine simplified the detection of loads by performing position symmetrical bilateral control during no-load, and when the force sensors detected contact, performing control to increase the position constraint gain. And it displayed the scale of the excavation reaction force by performing force feedback bilateral control only of the bucket axis.

A control method of this kind changes the proportional correction gain and power transmission gain based on the contact sensor entry, so it is called variable gain position symmetrical bilateral control.

3.4 Topography database

A database to store the topography over a wide range was built presuming it would be used for the offshore trial. This database can store topographical elevation information for a total of 500,000 (50m×100m) at 10cm intervals, and can simultaneously store the same number of target elevation data that replace finishing stakes It displays the positions of work-boats, caissons, and other nearby structures, and plots the position, orientation, attitude etc. of the backhoe in real time. This database is also linked to an LAN and usually contains bucket contact elevation data that has been transmitted from the remote control PC, but during movement and other times that it is required, the required range is framed and topography data is transmitted to the remote control computer. It is also equipped with a function that reads in topographical data based on ultrasonic images, a function that receives backhoe positioning data obtained by the SBL from the RS232C port, and a function that outputs topography data after the work is completed from a text file.

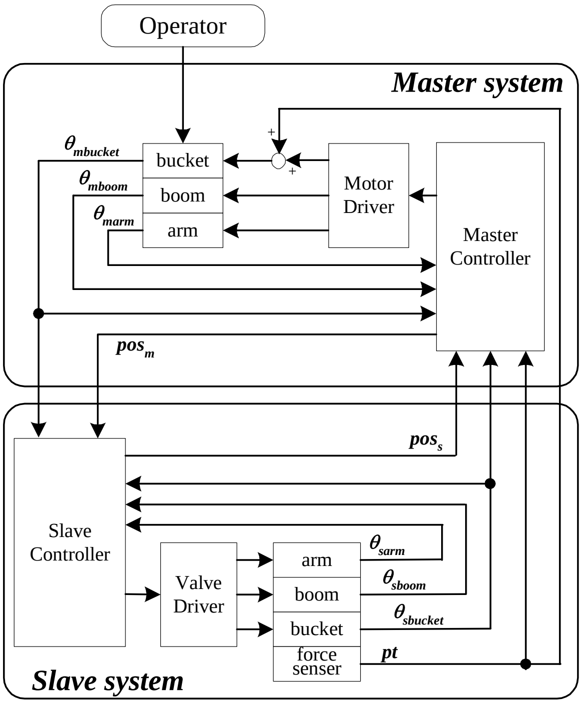

Figure 7 Variable Gain Position Symmetrical Bilateral Control

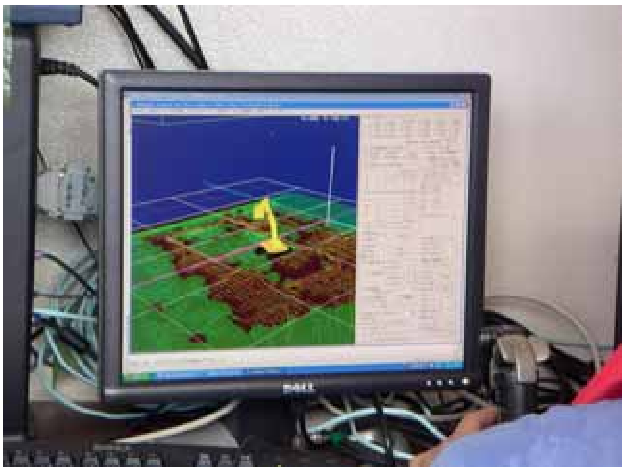

Figure 8 Topography Database Screen

4. OFFSHORE TRIAL

4.1 Offshore trial area

The trial was performed on top of a – 16.5 riprap mount at a breakwater offshore from Kaminoshima Island in Nagasaki City in Nagasaki Prefecture for 5 days from October 4 to 8, 2004 (cancelled 1 day because of bad weather). The size of the riprap was between 5 and 100kg each, the evaluation range was 10m×10m, and the work that was the object was smoothing the riprap to ±30cm. For comparison, the same smoothing work was performed by a backhoe operated by a diver seated on the backhoe. Figure 9 shows the trial evaluation range. Excluding the day the trial was cancelled, the maritime conditions were extremely gentle: wave height of 50cm or less, visibility of 5m and tide flow from 0 to 0.3 knots.

4.2 Preparing for the trial

After the work-boat was towed to the trial area, the topography was measured by an ultrasonic sounding device to confirm the shape of the evaluation range. This data was entered to the database and the operator determined the location to lower the backhoe and prepared a work plan for the day by viewing a screen that portrayed the topography.

As the backhoe was lowered, the control cable used to supply power and transmit signals to the on-board PC was lowered along the power hydraulic hose and anchored with the buoy cable. After the backhoe was on the seabed, the wire sling was removed by a diver.

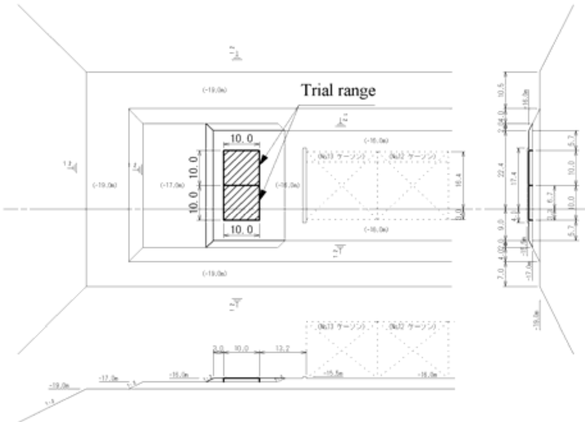

Figure 9 Trial Evaluation Range

4.3 Smoothing by remote control

After confirming the operation underwater, the smoothing trial under zero-visibility conditions was performed. The trial was performed by an experienced underwater backhoe operator extremely knowledgeable about the characteristics of underwater backhoes. The operator performed the work without a TV camera by using only information from the computer graphics images described above.

The basic operation was excavating the mound to the required height then discarding the material removed outside the work range. The plane coordinates of the backhoe were obtained by performing ultrasonic positioning with the SBL, but the vertical coordinates were obtained by data obtained from the water pressure gauge installed on the backhoe. The bucket tip coordinates were calculated as the absolute coordinate system by adding the angle of inclination, and the boom, arm and bucket angle information to this coordinate. The operator performed the work without relying on the finishing stakes by entering this coordinate system to the database and comparing it with the design elevation coordinates that are an absolute coordinate system.

4.4 Completing the offshore trial

Figure 10 shows the state of the mound photographed after the work. The state of the mound before the work included irregularities of approximately 80cm, but after the work it was smoothed almost flat as shown by the staff.

After the work, a survey was done using an underwater level. The result of the survey is shown in Figure 11. This result was based on measurements of the range where the remotely controlled work was done at intervals of 1m, and the numbers are the discrepancy with the target height.

Averaging all the survey points within the execution range obtains +17, and its standard differential was ±8.1cm. The execution control standard of ±30cm was exceeded at 2 points, but it was below the target elevation at 1 point. At more than half of the survey points, it was between +10cm and +20cm. However, it can be stated that the work that was smoothing the mound flat was performed adequately as indicated by the standard differential.

The topographical data recorded based on the system's contact information were compared with the results of measurements by a level measuring device. The result showed that the topographical data recorded by the system was an average of 4cm or more above the actual height based on the level survey, so that the standard differential of this difference was ±14cm. It is assumed that this scattering occurred because the system uses the bucket as its contact unit, that means it is wide at contact time. Therefore it is possible for the coordinates measured by the contact to fail to conform with the survey coordinates obtained using the underwater level. However averaging obtains a difference of 4cm, and considering the fact that the riprap used for this trial weighed 100kg each, its measurement precision is presumed to be adequate for rough smoothing.

Figure 10 View of the Mound after the Work

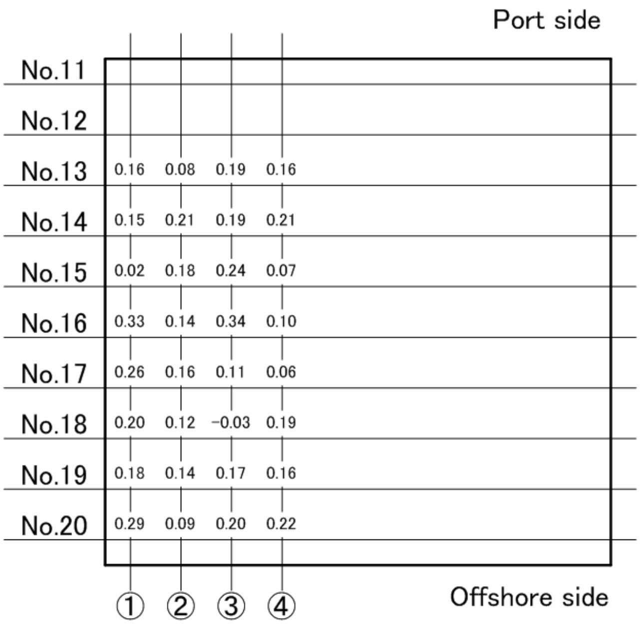

Figure 11 Mound Survey Results (Teleoperated)

5. FINDINGS

This research, that was undertaken with achieving safe and efficient underwater work as its basic goal, has proposed a method of feeding back contact information (reaction force acting during contact and position of the contact point) received from a work machine that is being controlled remotely during underwater work where visual information is inadequate to the operator of the machine by the bilateral control method, and it has verified the practicality of the proposed method by an offshore trial of smoothing work by an underwater backhoe.

The research has clarified the following major facts.

• This entry interface that moves the operating unit (Master) and the underwater backhoe (Slave) analogously and at the same feeds back the reaction force acting on the bucket to the operating unit, is a method that lets the operator directly confirm the response of bucket operation and the attitude of each part of the backhoe, permitting remote operation without a view of the work. The bilateral control system is the control mechanism that effectively achieves this type of operation.

• Along with the response to operations described above, the system increases the operator's ability to monitor the work by providing a computer graphics image of changes to the topography accompanying the smoothing work based on the contact information that is fed back.

• The results of the offshore trial in the Port of Nagasaki of the riprap smoothing work by the underwater backhoe controlled by this remote operating system showed that the execution precision was an average of +17cm (standard differential ±8.1cm).

6. CONCLUSION

Underwater work is often dependent on manual work performed by divers directly observing the work because of a variety of technical obstacles that differ from those on land—difficulty remotely operating machinery using optical images for example—that interfere with unmanned work, but this research has opened the way to establishing a practical underwater backhoe remote operating system.

But while the riprap smoothing work that was the object of this research is heavy work that requires a stipulated execution precision, it is relatively simple work, so this system cannot be applied to detailed complex underwater work such as the inspection and repair of wharfs.

Now that many structures constructed during the period of high-speed economic growth are nearing the ends of their service lives when they must be maintained in sound condition and used effectively, the achievements of this research are a first step in establishing unmanned underwater work, and in the future, research will be continued in order to develop more advanced and more practical underwater unmanned work methods.

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