First Field-Test of Seabed Walking Robot CR200

Bong-Huan Jun, Hyungwon Shim, Banghyun Kim, Jin-Yeong Park, Hyuk Baek, Seongyeol Yoo, Hangoo Kang, Gyeong-mok Lee, Pan-Mook Lee
Ocean System Engineering Research Division
Korea Institute of Ocean Science and Technology
Daejeon, Korea
{bhjeon, hwshim, bhkim, jinyeong96, hbaek, usyeol, kang, lkm0724, pmlee}@kiost.ac

Abstract—**This paper reports the results of underwater test of the CR200 seabed walking robot (Crabster) conducted from 24 June to 12 July 2013 in the pier of South Sea Research Institute of KIOST. Through the test, we have successfully brought the concept of Crabster to reality, which is six-legged seabed walking robot designed to work in high current and low visibility environment. For the initial tests, the CR200 was only submerged 7 meters, so we checked the watertight, ballast and test its main capabilities. Then over the next several days we gathered data from its sensors including sonar scans and acoustic camera. In order to detect the disturbance from the current, the CR200 was equipped with an acoustic Doppler current profiler (ADCP), an attitude heading reference system (AHRS) on the body and a contact force sensor on each foot. Acoustic camera and scanning sonar were installed for the inspection of the low visibility environment. The pressure canister and electric-driven six legs/arms guarantee the 200m pressure-resistant and watertight performance. The main frame was made of carbon fiber reinforced plastic (CFRP) in order to reduce the total weight. This paper reports brief overview of the CR200 robot design, and introduces the results of first underwater test.**

Keywords— CR200; Crabster; underwater walking robot; survey and inspection of seafloor; hexapod robot; field-test

I. Introduction

The underwater walking robot CR200 was built based on the concept of Crabster [1][2]. The main mission of CR200 is inspection of shipwrecks or scour and survey of seafloor tomography in high current and turbid environment. The CR200 controls attitude and gets mobility from the six legs instead of screws. In high current area, the CR200 aligns its heading to the direction of current and keeps nose down and tail up. Therefore, the downward lift force is increased and the robot gets enough contact forces between feet and seafloor to guarantee the tumble stability. The shapes of body and legs are streamlined to enhance the hydrodynamic characteristics in high current environment. Based on the stable posture, the CR200 is able to get clear acoustic images from the high resolution scanning sonar even though in the highly turbid environment. The numerical simulations were performed for the evaluation of current loads acting on the CR200 with a variety of incident angles. The estimated current load is used to evaluate the stability of CR200 [1]. we considers the hydro static and dynamic forces on the existing stability criteria of on-land walking robot described in [3][4][5]. The stability of CR200 in current environment was analyzed based on the dynamic stability margin (DSM) [3] criteria. After the preliminary design based on the operational strategy and simulation results, we have built the CR200. The appearance of CR200 is shown in Fig. 1.

In this paper, we report the building and first field-test results of the CR200. The overview of design and implementation is presented in section II. The on-land and underwater test results are described in section III. Section IV denotes concluding remarks and future works.

II. Overview of CR200

A. Configuration of Equipment

The Fig.2 shows the equipment configuration of CR200. The six legs are installed along the both sides of body. Control and electric systems are contained in the two pressure housings. The two oil-filled junction boxes installed in the both sides of the body distribute the power and signal from pressure housing to the devices. The extendibility of CR200 is achieved by the large junction boxes which support various equipment such as

Fig. 1 Appearance of subsea walking robot CR200.

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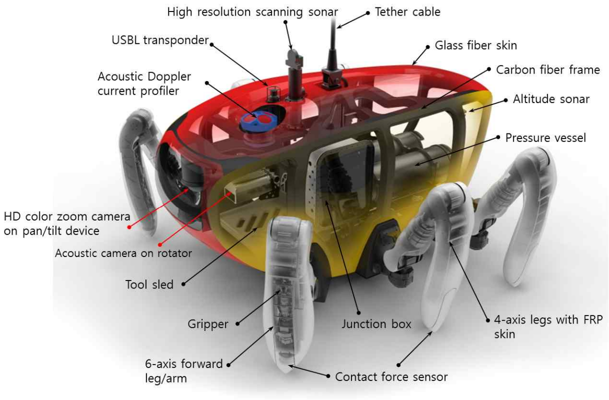

Fig. 2. Equipment configuration of CR20.

legs/arms, sensors, cameras, lamps, drawer actuator and pan/tilt device. The acoustic current profiler is installed on the upside of body to detect the speed and direction of current of water column. The CR200 estimates the external forces based on the ADCP data and contact forces of feet. The high resolution scanning sonar and the ultra-short-base-line (USBL) responder are installed on the top of the body. The scanning sonar provides the high resolution acoustic images around the robot. The USBL responder provides return pings to the surface system so that the underwater position of the robot is traced. The color HD zoom camera and acoustic camera installed on the pan/tilt device provide the optic and acoustic images in real-time respectively. The six optical cameras are attached on each side of the body for the visual inspection around the body. The links and joints of legs are made of aluminum. All of the electric motors and harmonic drives are contained in the watertight aluminum housing [7]. The legs and body are covered by fiber-reinforce-plastic skins. The specifications of CR200 are listed in Table I.

The body frame of CR200 is made of carbon fiber reinforced plastic(CFRP) so that it is lighter and stronger than other types of multi-legged robots. Since CFRP has higher specific stiffness, strength and material damping than conventional materials, the structure which is made of CFRP not only absorbs the noise and vibration of the structure but also improves the settling time and the fatigue[8][9][10]. According to the specimen test we have performed, specific stiffness and strength of the CFRP are 1.5 and 4.4 times higher than Aluminum 6061 T6 and the data from the test is described in Table I. Adopting CFRP as a body frame, CR200 reduced loads for legs and achieved improvement in strength. In the modal analysis of the frame, the deformation was concentrated on the front part in 41.2Hz.

TABLE I. SPECIFICATIONS OF CR200

Items	*Value*	*Unit*	*Remarks*
Dimension(L/W/H)	2.4 X 2.4 X 1.3(2.0)	m	sit(stand)
Weight	600(300)	kg	
Max. depth	200	m	
Max. power	20	kW	
Num. of legs(arms)	6(2)	EA	
Max. walking speed	0.5	m/s	
Equipment	acoustic camera, scanning sonar, ADCP, CTD, AHRS, USBL, alt. sonar, tool sled, pan/tilt optical HD camera, analog cameras, contact force sensors		

The CR200 has six legs; two of them are arm-combined legs and four of them are dedicated legs. The arm-combined legs have seven joints and dedicated legs have four joints. The arm-combined legs use four joints in hexapod walking and use seven joints in manipulation. The three joints for each leg are usually sufficient for the hexapod gait. However, adopting four-joints-leg, which has one redundant joint, we can optimize the robot posture for the current or uneven seafloor with redundancy. The length ratio of thigh to shank was determined as 3:4 from biological data of creatures such as lobsters, crabs, and insects. Adopted frameless hollow motors and harmonic gears, we could satisfy the requirements of downsizing, lightweight and zero backlash. The absolute encoder was attached to the each joint for the initial angle of each joint. All of the parts of joint are contained in the aluminum casing for the pressure resistance and watertight. The fabricated leg and arm are tested in the pressure chamber up to 25bar pressure.

All of the electrical system including interface boards, power boards and communication devices are contained in the two pressure canisters. The pressure canisters were made of aluminum and tested in the pressure chamber up to 25 bars. The large junction boxes located both side of body are oil filled type and were made of FRP. Tool sled which is also made of FRP is driven by BLDC motor and pulley belt mechanism. The body and leg/arm have fairing skins to enhance the hydrodynamic characteristics. The skins and brackets for equipment were also made of FRP. Adopting the composite materials widely, we could keep the weight of body under 300kg which is design load of legs.

B. Remote Control System

After the CR200 is launched, all of the control and monitoring are conducted in the control room. A twenty feet standard shipping container contains all of the equipment for controlling of CR200 like power supply, communication system, control and monitoring system. In this section, the remote control system is discussed.

The mother ship supplies 440VAC power to the remote control room. The supplied power is converted to 150~200VDC and supplied to the CR200 via tether cable. By supplying DC power instead of AC, we could remove the power conversion devices in CR200 which dramatically reduce

TABLE II. COMPARISON BETWEEN CFRP AND ALUMINUM

Parameter	CFRP	Aluminum
Specific stiffness [Mpa/kg]	936	621
Specific strength [Mpa/kg]	11.064	2.489

the total weight of CR200. The capacity of supplied power is 30kW.

The local networks in the CR200 and the remote control room are Gigabit Ethernet with 1,000 Mbps bandwidth[11]. All devices with Ethernet interface are interconnected by Gigabit switching hub. The remote control room communicates to the CR200 through single mode optical fiber lines with 1,000 Mbps bandwidth. Fiber optic Gigabit media converter interfaces between optical link and Ethernet network. Solteck SFC2000-TWL was chosen as fiber optic converter. It supports maximum 10 km transmission distance, 1,000 Mbps bandwidth, and wavelength-division multiplexing (WDM) technology. The WDM is a technology which multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths of laser light. This technique enables bidirectional communications over one strand of fiber, as well as multiplication of capacity.

In the remote control room, seven computers share all of the data from CR200 by TCP/IP protocol. Two network HD cameras and a GPS receiver are connected to the Gigabit Ethernet line directly. The USBL system is connected to agent computer by RS232C serial communication line. In the CR200, an acoustic camera and two HD cameras are connected to Gigabit Ethernet directly. Since the interface boards and legs/arms communicate using controller area network (CAN) protocol, Ethernet to CAN converters were used to connect them to the network line. The Ethernet to serial converter supports the serial devices to connect to the Ethernet. The serial devices of CR200 include altitude sonar, scanning sonar, CTD, ADCP and AHRS. The analog cameras are connected to the Ethernet line via video encoder. The structure of communication system is depicted in Fig. 3.

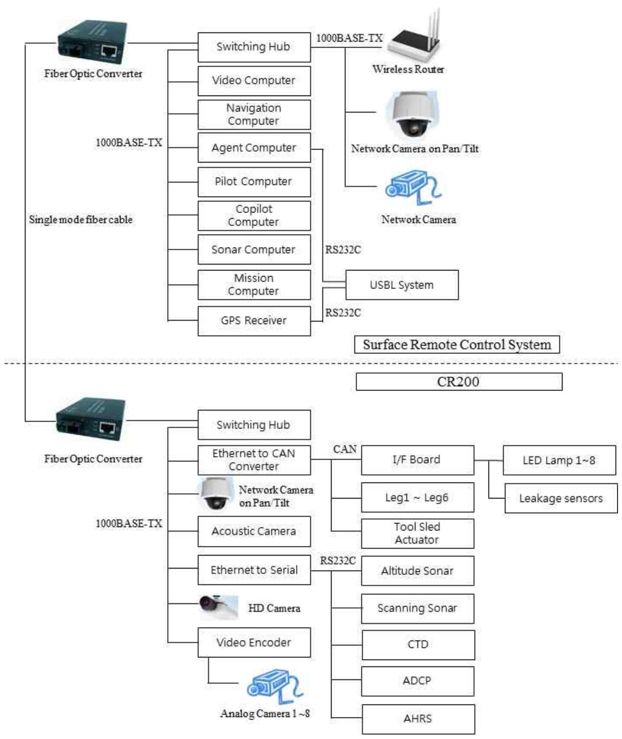

Fig. 3 Communication system of CR200 based on Gigabit Ethernet.

Fig. 4 Control and monitoring system of CR200.

The seven computers and nine LCD monitors are dedicated to the control and monitoring of CR200. The agent computer is real-time controller based on Linux operating system. The pilot and copilot computers provide the graphic user interface (GUI) and joystick interface to the operators. The video computer displays and saves all of the video data from CR200 and onboard cameras. The navigation computer displays the locations of CR200, mother ship and target point on the map data using the GPS and USBL data. The navigation computer also provides planning functions for survey and inspection of target area. The sonar computer displays real-time acoustic images from the acoustic camera and scanning sonar. The mission computer is reserved for special mission sensors to be installed in a future.

The agent computer, which is center of the real-time control, requests feedback data to the CR200 periodically. The agent computer shares the received data to other computers via network and computes the new commands for each leg of CR200 by the gait and posture control algorithms. The core of control algorithms are gait and posture control against to the external disturbances based on the center of pressure and tumble stability criteria. The algorithms estimate the environmental disturbance using the contact force on each foot, current from ADCP and attitude and motion of CR200 from AHRS. The control frequency of gait is 100 Hz so the computed new commands are sent to CR200 every 0.01 second. The operator can command the posture and gait pattern by joystick or GUI in pilot and copilot computers. The operator can identify the posture of each leg and CR200 using the graphic model of CR200 displayed graphically in the one of the pilot monitors.

C. Survey and Inspection System

There are three solutions in CR200 for the underwater inspection; 1) acoustic camera, 2) high resolution scanning sonar, 3) optical cameras. The acoustic devices of CR200 and some experiments using them are introduced in this section.

The CR200 is equipped with a high resolution scanning sonar for seafloor tomography which covers 3~150m range. The update rate of scanning sonar is less than acoustic camera. However it provides precise and clear acoustic images in the seafloor. Moreover, we can make a map of sea bottom by mosaicking the images. The update rate depends on the scanning rage and width. For the high resolution scan, it takes about 30 minutes. The CR200 can provides stable keeping of sonar head during scan based on the mechanical contact between six feet and sea bottom

The CR200 is equipped with an acoustic camera for real-time images in the turbid water. The acoustic camera covers 1~15m range at 1.8Mhz and 0.5~5m range at 3.0MHz. It provides 4~30 frames/sec. However, the sonar image is not identical to the optical image. The operators have to imagine the status of object in real-time based on both of acoustic and optical images.

There are 10 cameras in the CR200. A HD camera with pan/tile device on forehead frame provides optical images of outside and inside of CR200. Another HD camera is dedicated for forward inspection. The wide view color cameras installed both side of body inspect the 6 legs and side field of robot. The other analog cameras inspect the tether cable and forward and backward of the CR200. The ten LED lamps with dimming control support the camera.

III. Field-Test Results

The first field-test was conducted from 24 Jun to 12 July 2013 in the pier of South Sea Research Institute of KIOST. The results are described in this chapter

A. On-land test

The on-land test is focused on the validation of 1) overall functions of CR200, 2) validity of communication system, 3) validity of control algorithm and capacity of joint power.

The posture controller of CR200 was implemented based on the kinematics of the body and each joint of legs. Solving the forward and inverse kinematics of CR200, we generated the joint paths from the reference posture. The posture was controlled in 6 degrees-of-freedom by synchronized controlling of each joint[13]. The snap shots of posture control are shown in Fig. 5 and Fig. 6. The posture control of CR200 will be used as the means to overcome the sea current and keep the attitude stable. Moreover, it gives more degrees of freedom to the sensors on the CR200. Through the on-land test, we verified

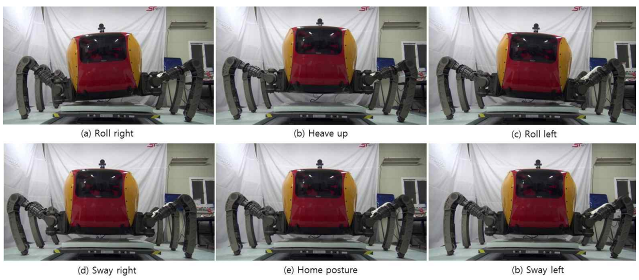

Fig. 5 Posture control of CR200 in yz-plan.

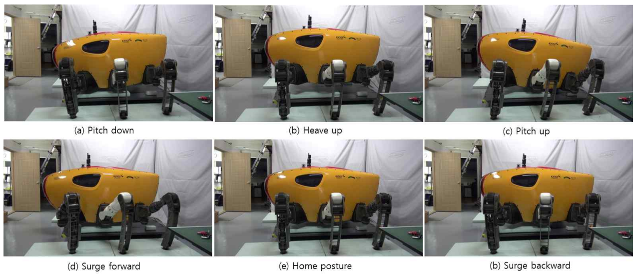

Fig. 6 Posture control of CR200 in xz-plan.

the legs have enough payload capacity in the extreme motion with full loads[14] shown in Fig. 7. Figures 8 shows the 10kg lift test when the front leg is used as arm[15].

For the initial test, we chose the discrete 8-phases hexapod gait which guarantees the highest tumble stability[16]. The operator can easily intervene in gait control during the robot walks on the unknown and obstructive area. Figure 9 shows the eight phases of discrete 8-phases hexapod gait during walking on land[17]. The communications with all the equipment were established and verified before the first diving.

Fig. 7 Extreme motion with full loads to verify the capacity of legs.

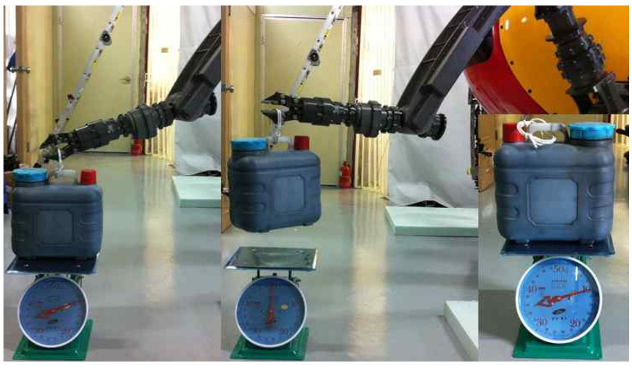

Fig. 8 Lift test of front arm (10kg load).

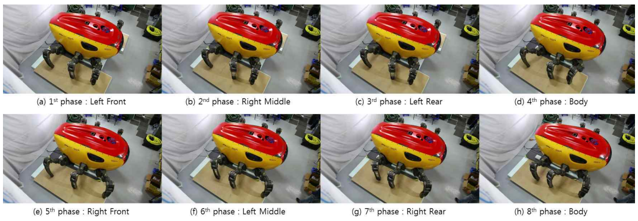

Fig. 9 Discrete 8-phases hexapod gait of CR200.

B. Underwater test

The field operation of CR200 is supported by a remote control van, a hanger & tool van and a crane & winch system which is depicted in Fig. 10. After the CR200 was launched, we checked 1) the watertight of dynamic seals of thirty joints 2) identification of topography and underwater structures in 100m range with scanning sonar and analysis the effect of posture changing on the scanning image. 3) real-time identification of objects in the 15m range with acoustic camera 4) real-time identification of object in the 2m range with combination of optical camera and LED lamps 5) underwater position tracking with GPS-USBL 6) acquisition and recording of conductivity, temperature and depth 7) posture and walking control with six-legs 8) attitude acquisition with Attitude Heading Reference System.

The strategy to overcome the high turbid environment by combination of the vision systems was verified in the underwater test. Scanning sonar identifies underwater structures and topography in 5~150m range and acoustic camera visualize the objects in 0.5~15m range and the optical camera covers 0.2~1m range in turbid water. The scanned images in 100m and 15m ranges are shown in Fig. 11 and Fig. 12 respectively. The piles under pier are identified in 100m range scan of Fig. 11. In the 15m range scan of Fig.12, the rocks and CR200 itself were identified. Acoustic image in Fig. 13 shows the swimming fishes in addition to the rocks observed in Fig. 12. The swimming fishes and star fishes on the rock were identified in the optical image in Fig. 14[18]. In the experiment, we got clear acoustic images based on the stable posture of CR200 and observed easily many fishes than when we use the propeller-typed vehicle due to the silence of CR200.

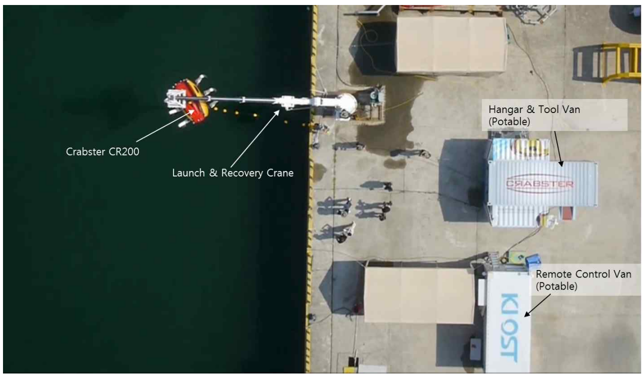

Fig. 10 Configuration of supporting system in the field test.

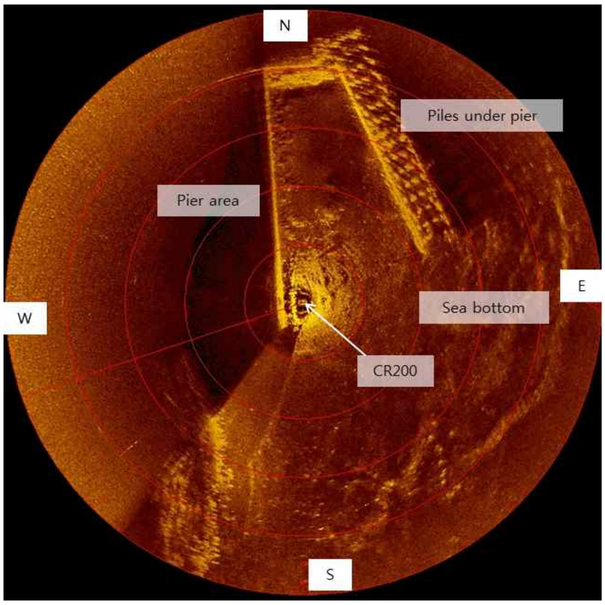

Fig. 11 Scanned image in 100m range (20m/div).

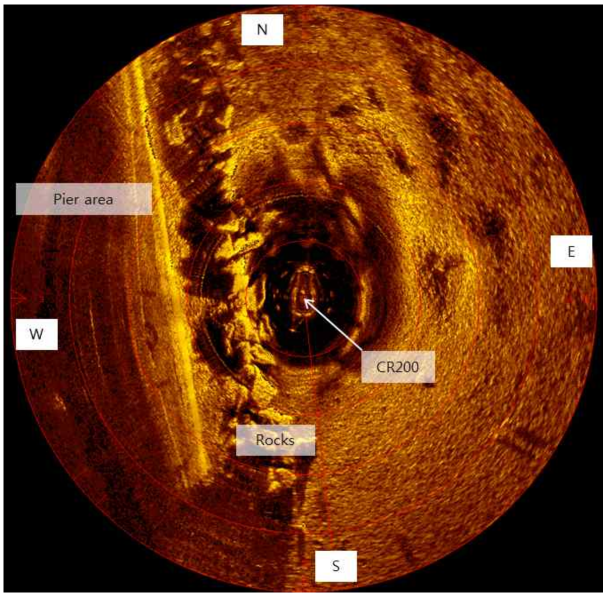

Fig. 12 Scanned image in 15m range (3m/div).

We verified in the first field-test of CR200 that the overall functions and performance of CR200 work as designed and the effectiveness of the strategy to overcome the turbid environment.

IV. CONCLUSION

The design and first field-test result of CR200 is described. The overview of CR200 was presented which includes configuration of equipment, remote control system and survey and inspection system. The weight of walking robot affects

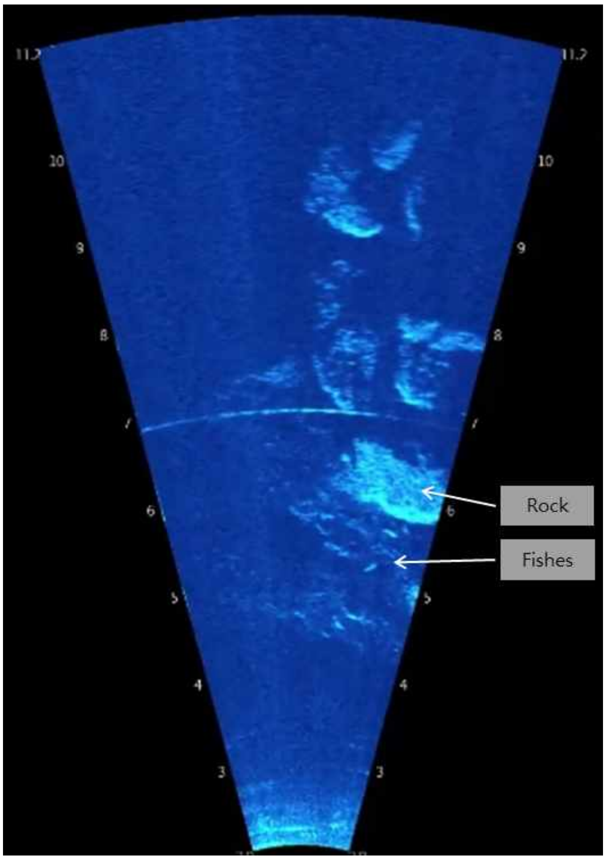

Fig. 13 Acoustic camera image in 11.2m range.

Fig. 14 Optical camera image in 1~1.5m range.

seriously to the mobile ability. We could keep the weight under the goal by 1) adopting the composite materials widely to various parts, 2) supplying DC power directly to CR200, 3) using frameless motors for legs. The remote control system based on the Gigabit Ethernet dramatically simplified the communication wire in control room. The digitized data and video were robust to the noisy. The Linux based agent computer keeps the synchronization with CR200 and implement real-time control. The survey and inspection system includes the acoustic camera, scanning sonar and optical cameras. The function tests of acoustic equipment were carried out for the verification of the operating strategy with CR200 in turbid area. After integration of CR200 subsystems, we conducted on-land and underwater test. Some of the results were described in this paper.

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