Introduction to Operations of a High-resolution Acoustic Camera on Crabster CR200 and Applications

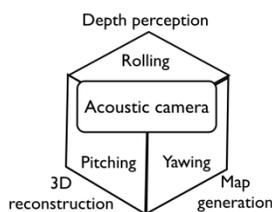Jln-Yeong Park*, Hyuk Baek, Hyungwon Shim, Bong-Huan Jun, Pan-Mook Lee

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Graphical abstract

Abstract

This paper describes operations of a high-resolution multi-beam acoustic camera installed on Crabster200 (shortened to CR200) and application researches. The CR200 is a new type of ROVs having six artificial legs driven by BLDC motors. The robot thrusts itself using the legs on seafloor and controls its body posture and attitude. Each leg has four degrees of freedom. And the robot is supposed to inspect and work in fast current flow and turbid water where visibility is very low. The name of "Crabster" came from a combination of crab and lobster because the CR200 imitates behaviors of the two creatures to keep its position against water current flow. In turbid water, performance of typical optical cameras is limited and fails. Therefore, in this case, the acoustic camera can be a good alternative to image objects of interest using acoustic beams. The CR200 is equipped with high-resolution acoustic camera using 3M Hz frequency obtaining maximum 2.9 mm resolution with a rotation which provides two degrees of freedom; roll motion and pitch motion. Yaw motion cannot be provided by the rotator. Then, the CR200 have to rotate its body in place to obtain yaw motion. From these roll motion, pitch motion and yaw motion with image processing, we extract and derive depth perception, 3-dimensional reconstruction and mosaicking, respectively. In this paper, we introduce practical uses of the acoustic camera in offshore and water basin and its application researches. The authors have tried to verify the performance of CR200 as an actively adaptable underwater mobile observant platform.

Keywords: Acoustic camera, CR200, field operations, underwater observatory

Abstrak

Kertas kerja ini menerangkan operasi kamera akustik resolusi tinggi pelbagai pancaran pada Crabster200 (dipendekkan kepada CR200) dan aplikasi penyelidikan. CR200 ialah sejenis kenderaan kawalan jauh (ROV) yang mempunyai enam kaki buatan yang digerakkan motor BLDC. Robot menujah dirinya menggunakan kaki pada dasar laut dan mengawal postur badan dan sikap. Setiap kaki mempunyai empat darjah kebebasan. Robot itu sepatutnya memeriksa dan bekerja di dalam aliran arus yang laju dan air keroh dimana penglihatan agak rendah. Nama "Crabster" terbit daripada kombinasi *crab* dan *lobster* kerana CR200 meniru tingkahlaku dua makhluk itu untuk mengekalkan kedudukannya melawan aliran arus air. Dalam air keroh, prestasi kamera optikal biasa terhad dan gagal. Oleh itu, dalam kes ini, kamera akustik boleh menjadi satu alternatif untuk objek imej menggunakan pancaran akustik. CR200 dilengkapi dengan kamera akustik resolusi tinggi menggunakan frekuensi 3 MHz mendapat resolusi 2.9 mm maksima dengan putaran yang memberikan dua darjah kebebasan; putaran roll dan pitch. Putaran yaw tidak boleh diberikan oleh pemutar. Kemudian, CR200 akan memutar badannya untuk mendapatkan putaran yaw. Daripada gerakan roll, pitch dan yaw dengan pemprosesan imej, kami ekstrak dan terbitkan persepsi kedalaman, pembinaan semula 3-dimensi dan mosaicking. Dalam kertas kerja ini, kami perkenalkan penggunaan

praktikal kamera akustik di luar pesisir dan lembangan air dan aplikasi penyelidikan. Pengarang cuba mengesahkan prestasi CR200 sebagai platfom mudahalih bawah air yang boleh memerhati dan secara aktif menyesuaikan diri.

Kata kunci: Acoustic camera, CR200, field operations, underwater observatory

1.0 INTRODUCTION

In underwater where turbidity is high, performance and valid range of conventional optical cameras become very short and limited under 20~30cm long. In the environment such like this, any underwater unmanned robot, such like a ROV (Remotely Operated Vehicle) is not able to carry out any works using the optical cameras. To overcome this low visibility in underwater, acoustic devices are adopted widely. Side-scan sonar, multi-beam sonar and pencil-beam profiler are these kinds of typical acoustic devices. A multi-beam acoustic camera is one of them. It emits multiple acoustic beams to image objects of interest. This can be a candidate for an obstacle avoidance, gap-filler aiding side-scan sonar and identification sensor as well [1]. The acoustic camera has several different titles such like "Forward-looking SONAR", "Imaging SONAR" or "Multi-beam SONAR." The word of "SONAR" is short for SOund Navigation and Range. In this paper, the name of "acoustic camera" is used because it is related imaging rather than navigation or range measurement. In addition, "acoustic camera" shows a meaning which is contrast with "optical camera." Shaking has to be minimized to get best quality of images when we are operating the acoustic camera in like manner we take a picture using any optical camera. However, it is not easy for the camera to keep stationary in strong water currents. Therefore, some platform which can control its attitude or posture and keep stationary against fast water flow becomes required. Researchers in KRISO (Korea Research Institute of Ships and Ocean Engineering) have been developing a new type and a bio-inspired underwater walking robot which has six artificial legs driven by BLDC motors [2]. The name of the robot is "Crabster," and it is a compound word of crab and lobster. It has a tether cable and wired-operated. First model is Crabster200 or CR200. The six artificial legs thrust the robot itself with maximum forward walking speed of 0.25 m/s and the robot can rotate in place and show side away movement as well. Each leg has four degrees of freedom and was designed for walking and swimming [3]. Maximum depth rating for operation is 200 m. Its body attitude can be changed while keeping its six feet contact with the ground. The CR200 is equipped with an ADCP (Acoustic Doppler Current Profiler), a CTD (Conductivity-Temperature-Depth) sensor, a single-beam scanning SONAR and one multi-beam

acoustic camera. In addition, eight analog cameras, a network HD camera with pan-tilt device and several LED lights are also installed. The acoustic camera model is ARIS Explorer 3000 (Adaptive Resolution Imaging Sonar) from Sound Metrics [4]. The ARIS operates at two frequency modes which are 3.0 MHz and 1.8 MHz. The higher frequency mode images objects with 2.9 mm of maximum downrange resolution. While the posture of the robot can be controlled subtle, it is expected that the CR200 is able to decrease shades of acoustic devices and expand valid view range or viewing volume.

Acoustic image post-processing is conducted to extract new information or clues from the collected acoustic raw images. Because properties of the acoustic camera to image objects are different from those of conventional optical cameras, novel approaches for acoustic image processing are required. Especially, depending on motions of the acoustic camera during imaging objects, we were able to extract different kinds of information. In other words, three different kinds of image processing can be conducted to three different motions; roll motion, pitch motion and yaw motion. Roll motion and pitch motion can be provided by a 2-axis rotator while yaw motion is provided by rotation movement of the CR200.

From two images with different roll angle, classic anaglyph method can be adopted to generate stereoscopic images for depth perception [5]. Using consecutively grabbed acoustic images during the camera's pitch motion, we could extract clues for 3-dimensional shape of the object [6] [7]. Park *et al.*, (2014) [7] also describes a conventional mosaic using multiple horizontally collected acoustic images. A larger map around the robot can be achieved by this mosaicking. A novel blending technique for mosaicking of acoustic images was introduced by Hurtós *et al.*, (2013) [8].

In this paper, previous researches of the motions of the acoustic camera and corresponding effects are reviewed and repeated. And then, operations of the camera on the CR200 in a water basin and sea floor are introduced. We conducted underwater experiments to verify performance of the CR200 as an actively adaptable underwater mobile observant platform in the water basin and sea.

The followings are organized in the remainder of this paper. Section 2 depicts specifications of the CR200 and the ARIS. Integration of CR200 and ARIS is described as well. In section3, we repeat our previous

research results about three kinds of image processing related to three different kinds of motions of the camera. Section 4 shows various acoustic images collected during experiments on the water basin and sea. The CR200 imaged to objects from place to place. The images taken from various points of view help us to identify the object. In addition, acoustic images to inspect a gripper of the CR200 are also included. Conclusion and future works are discussed in the last section 5.

2.0 CRABSTER CR200 AND ACOUSTIC CAMERA ARIS

2.1 Crabster–CR200

The CR200 is a bio-inspired and multi-legged underwater robot. Power and communication are supplied by tether cable such like a conventional ROV. One leg has four degrees of freedom. Shim *et al.*, (2013) [3] introduces structures and configurations of the legs. Two legs in the front of the robot include a manipulator with three degrees of freedom as well. Using these manipulators, CR200 is able to collect somethings or to release some devices or sensors on the sea floor. There are two advantages of legs as thrusters for underwater operation or inspection. The first one is that the legs make the robot be able to increase downward lift force by adapting its body posture against the water flow. It results in increasing of endurance against tidal currents than those of propeller-driven ROVs. The second advantage is to move on the seabed floor without disturbing sediment or with minimizing disturbance or destruction. In addition, at least some destruction by propeller flow can be decreased. Specifications of CR200 are listed in Table 1. Figure 1 shows external appearance of the robot. Six artificial legs covered by white skin are installed. LED lights and optical camera are installed on the back. To decrease resistance, external skin was designed to form streamline shape. Two pressure housing vessels contain electric parts and systems. Two oil-filled junction boxes are designated to distribute power and signals from the tether cable to every parts of the robot platform. The body frame is carbon fiber reinforced plastic (CRFP) material which makes weight of the robot be lighter keeping strength. The sensors and devices on the CR200 are shown in Figure 2. First tests of diving into the sea were conducted in July, 2013 [9]. To advance investigation of dynamic characteristics of the robot, experiments in the water basin were also conducted in April, 2014 and April, 2015. Figure 3 shows movement of CR200 in the water basin. The water basin is the Ocean Engineering Basin in KRISO [14].
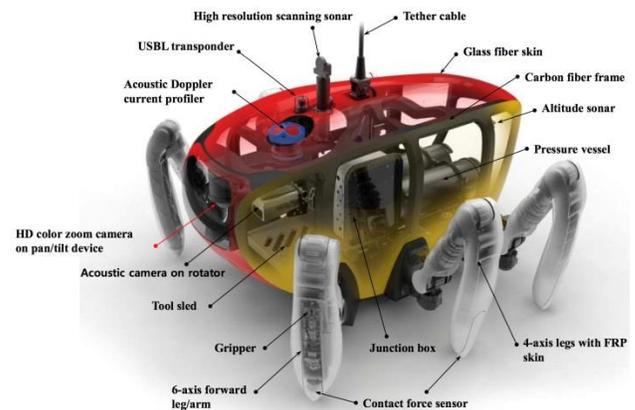

Figure 1 Crabster: CR200

Figure 2 Devices and Sensors of CR200

Figure 3 CR200 in underwater - Ocean Engineering Basin

Table 1 Specifications of CR200

Items	Value	Unit
Dimension	2.5 × 2 × 1.3	m
Weight	646kg@air, 154kg@water	Kg
Operating depth	200	m
Power requirement	20	kW
Maximum walking speed	0.25	m/s
Equippment	Acoustic camera, Scanning Sonar, ADCP, CTD, AHRS, USBL, Altimenter, Toolsled, Pan/Tilt optical HD camera	

2.2 Acoustic Camera-ARIS

Full model name is "ARIS Explorer 3000." It operates at two frequency modes; 1.8 MHz and 3.0 MHz. The higher frequency provides maximum 2.9 mm downrange resolution but valid range is limited to less than 5 m whereas the lower frequency shows longer range to 15 m with lower resolution. Table 2 is specifications of the ARIS. For more efficient and convenient operation, a 2-axis rotator is adopted. The rotator provides roll and pitch motions. Figure 4 shows the ARIS with the rotator installed on the nose of CR200 and Figure 5 describes rotation axes of the camera. In the front of the camera, a toolsled cover and a black-colored transparent acrylic cover are located.

Figure 6 shows the acoustic volume and three major terms about distance and direction relative to the acoustic image. The acoustic volume is wedge-shape which is composed of 128 acoustic sector-shape beams. Horizontal field of viewing angle and vertical field of viewing angle are 30o and 14o, respectively. Each term in Figure 6 is orthogonal to each other. The term of down-range refers to distance away from the acoustic camera along the length of the acoustic wedge whereas cross-range is distance directly across the width of the wedge. The term of perspective view is a direction perpendicular to down-range from above to down on the wedge and it becomes direction of an inspector's view at the same time [10]. Therefore, there exists a difference between a perspective view of optical camera and those of acoustic camera.

2.3 Integration

Figure 7 is a block diagram showing the integration of the ARIS and the rotator on the CR200 [6]. Kim *et al.*, (2013) [11] describes operating software and software architecture of overall CR200 system. ARIS and the rotator are connected to an Ethernet hub. Signals from the Ethernet hub is transmitted to the Acoustic Camera Interface PC in on-ship remote control units via fiber-optic converter and fiber-optic cable.
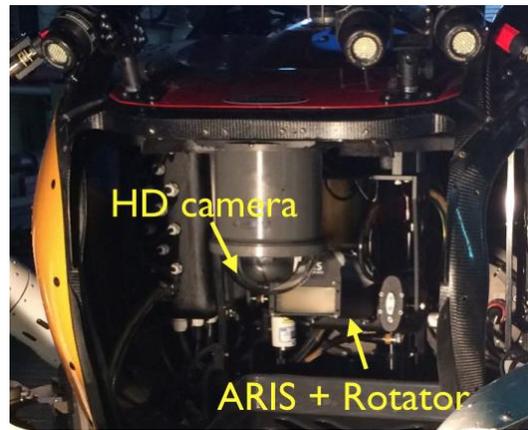

Figure 4 ARIS and its rotator installed on CR200

Table 2 Specifications of ARIS Explorer 3000

	Identification mode	Detection mode
Operating frequency	3.0MHz	1.8MHz
Beamwidth	0.25°	0.42°
Number of beams	128	128 or 64
Range	5m	15m
Frame rate	15fps (max.)	
Field of view	30°	
Power consumption	15W	
Weight in air	5kg	
Dimension	26 × 16 × 14 cm	

Figure 5 Three axes of the acoustic camera
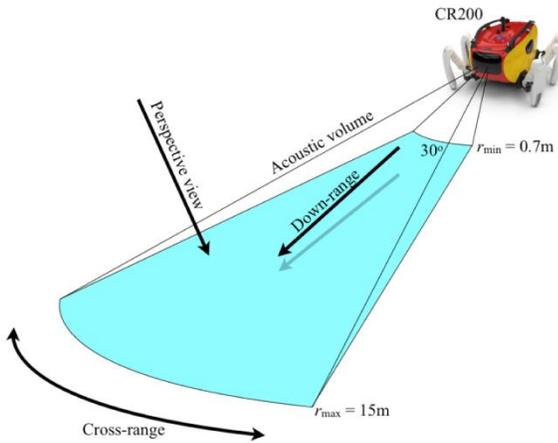
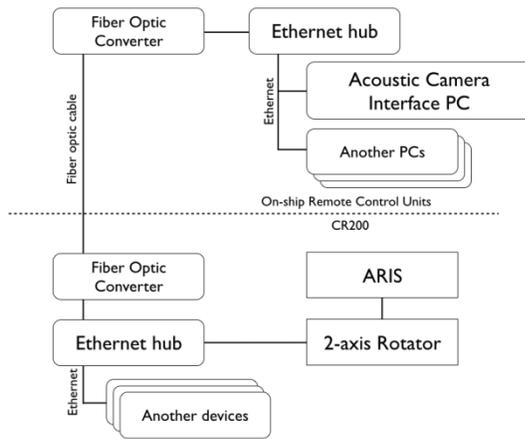**Figure 6** Acoustic volume and three major terms

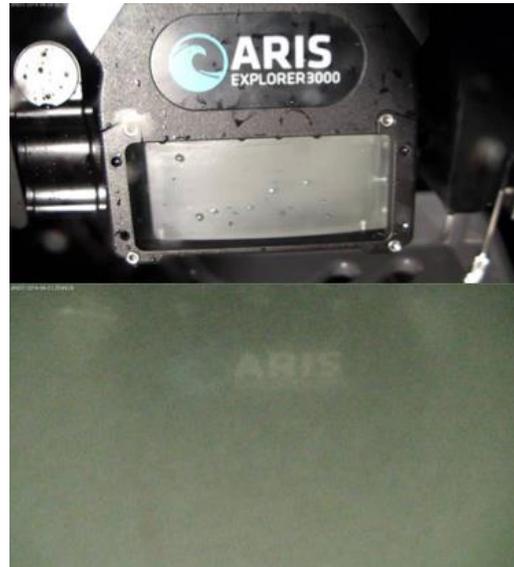**Figure 7** System block diagram-Integration of ARIS and CR200

Figure 8 Upper image: ARIS taken by the HD camera in air, Lower image: ARIS taken by the HD camera in water
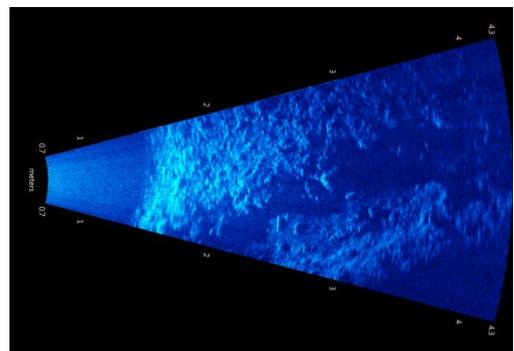

Figure 9 HD camera image in underwater

Figure 10 Acoustic image in underwater – taken at same place of Figure 9

3.0 APPLICATIONS OF ACOUSTIC CAMERA FOR CR200

In sea water, turbidity was high and view range was about 20 cm or less. Figure 8 shows two images of the HD camera installed in the front of the ARIS. The upper image was taken in air whereas the lower one was taken in sea water. The distance of the HD camera and the acoustic camera is almost about 20 cm. Figure 9 and Figure 10 show the HD camera image and the ARIS image, respectively at the same place. Although, the HD camera does not show anything, the ARIS could image the front of the robot. Stones of various sizes, mud and features of the ground could be identified. In the remainder of this section, three different kinds of motions of the camera and the related image processing are described.

3.1 Yaw Motion and Mosaicking

The 2-axis rotator does not provide a rotation with respect to yaw axis. Therefore, CR200 have to rotate in place to change the camera's view direction. During the rotation, we collected acoustic images consecutively. And then, we generated a larger

mosaicked map. Generation of a larger image using multiple smaller images is traditional and widely-used. Figure 11 is set of grabbed images and Figure 12 is the mosaicked image [12]. Using this, operators of CR200 can discriminate obstacles or objects of interest around the robot. Change of CR200's heading direction with respect to time resulted from the rotation in place is shown in Figure 13. Figure 14 shows another result of mosaicking. The images were taken during tests in the Ocean Engineering Basin. The CR200 was tracking a rope installed near the sea floor.
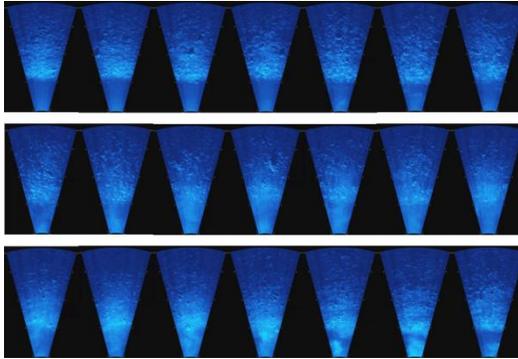
Figure 11 Set of the consecutively grabbed images during rotation
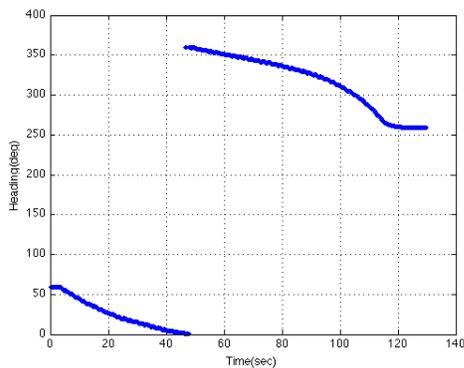
Figure 12 Heading change of CR200

Figure 13 Mosaicked image
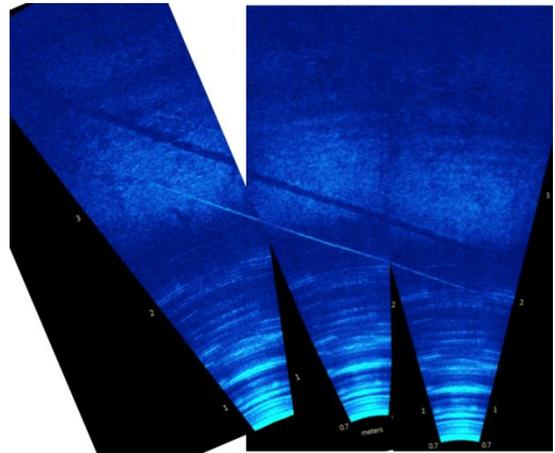
Figure 14 Mosaicked image – Rope

3.2 Pitch Motion and 3-D Reconstruction

We introduced a 3-D reconstruction of the object using multiple acoustic images [6] [7]. By extracting points corresponding to the object from consecutively grabbed images during pitch motion and by calculating geometry relationships among the images, we could reconstruct the estimated 3-D model of the object of interest. This scheme was inspired by CT (Computerized Tomography) used in medical. For this, we have to know the pitch angles of the acoustic camera when the images were taken because we cannot find out elevation of any points in the wedge-shape acoustic volume [12]. The processing is the followings.

1) Scanning with pitch motion: Figure 15 shows setup for underwater experiment and object of interest. The object was a rectangular frame structure. Imaging with pitch (tilting) motion is depicted in Figure 16. We grabbed n images of the object. Each of the images was taken with different pitch angles of the camera. Figure 17 is the consecutively grabbed images of the target. The experiment was conducted in the water basin and at that time, the acoustic camera system was separated from CR200 and was set up solely.

2) Binarization and discrimination: To discriminate the object of interest from background in each image, we binarized the image using a pre-specified threshold value. The threshold was determined by trial-and-error. Points whose intensity is higher than the threshold were selected as a part of the object in the image.

3) Coordinate conversion and calibration: Extracted points are denoted with respect to the image coordinate. These points need to be denoted with respect to the global coordinate. Coordinate conversion we used was depicted in [6]. And each acoustic beam are not very thin but has finite vertical width, therefore there are duplicated points through

consecutive images (Figure 18). To eliminate these duplicated points properly, we need further study. In this paper, we selected one point as the part of the object that has the maximum k among the duplicated point set having same range and same azimuth. Figure 19 shows result of mosaic and 3D reconstruction.

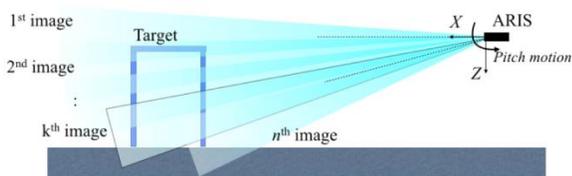**Figure 15** Experiments setup (left), Object of interest (right)
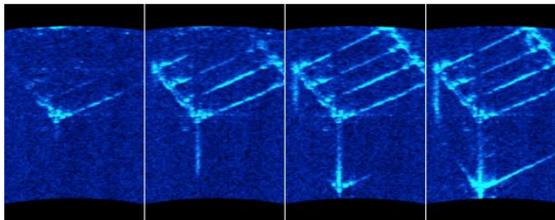

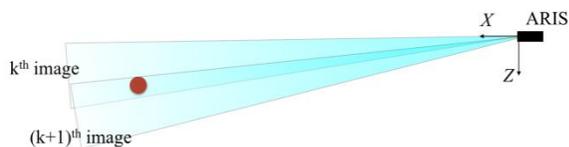**Figure 16** Object imaging with pitch motion

Figure 17 Consecutively grabbed images

Figure 18 Duplicated target point through multiple images
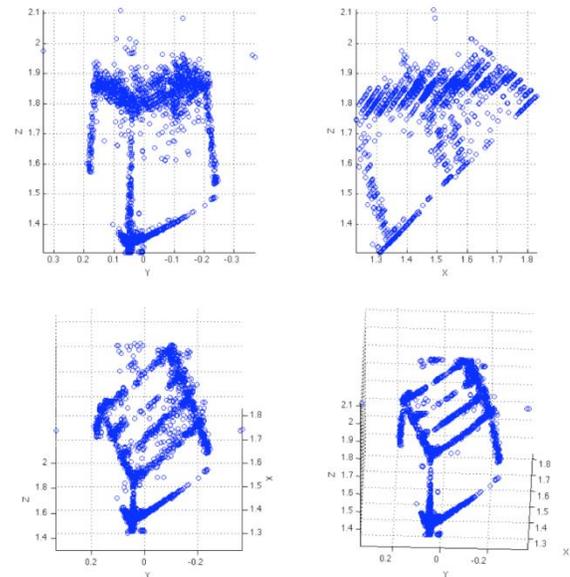
Figure 19 Reconstructed 3D model: Front view (Upper left), Side view (Upper right), Top view (Lower left) and general view (Lower right)

3.3 Roll Motion and Depth Perception

The acoustic camera provides 2-dimensional images basically. For depth perception, getting two images for each left and right eye and generating single stereoscopic image can be one of solutions. Anaglyph is one of classic methods of stereoscopic image generation. It uses two or more images filtered for different eyes using different colors. Typically, red and cyan are adopted widely. Figure 20 shows the most popular way of how to anaglyph to work [13]. To get two images for each eye using the acoustic camera, roll motion becomes required. Roll motion of the acoustic camera makes side view of the object. This is very different with the optical camera. Figure 21 shows change of perspective view with respect to change of roll angle φ of the acoustic camera. The symbols of P and P' are project planes for each roll angle. A point in the acoustic volume becomes projected to this plane. The symbols of O and O' are projected objects onto the corresponding project plane. It shows that just rolling of the acoustic camera is able to provide different side view of the objects. Therefore by rolling the camera, the viewer can obtain side views of the object of interest. The images taken with various roll angles are shown in Figure 22. The object is shown in Figure 15. Using this property, research about generation of stereoscopic images for depth perception was conducted [5]. Figure 23 and Figure 24 show examples of generated stereoscopic images. The object of interest is shown in Figure 25.
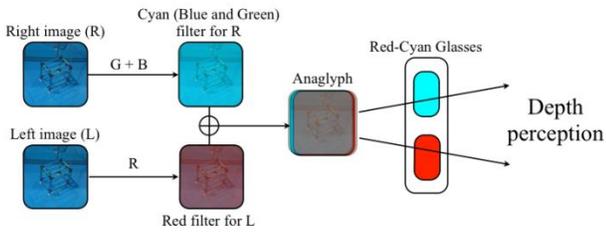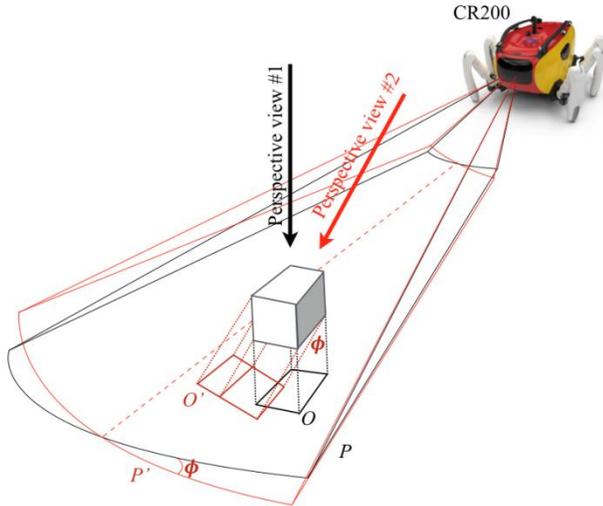
Figure 20 Generation of anaglyph

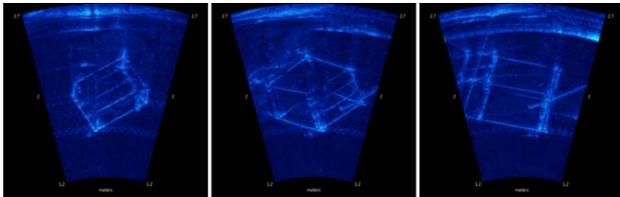**Figure 21** Change of perspective view depending on change of roll angle

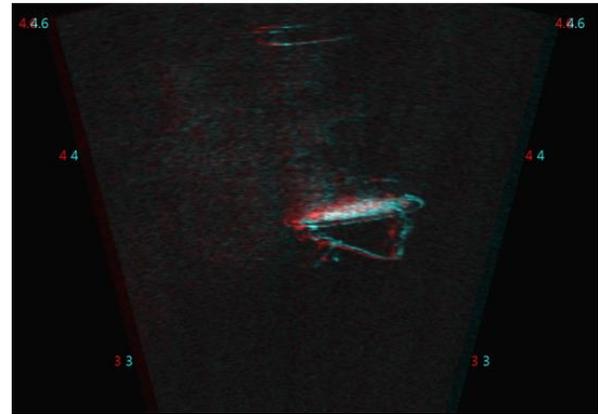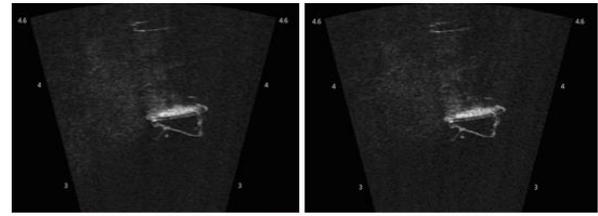**Figure 22** Roll at 0° (Left), Roll at 45° (Middle) and Roll at 90° (Right)

Figure 23 Image for left eye (Upper left), Image for right eye (Upper right), Anaglyph image (Lower center) - Red-Cyan glasses required
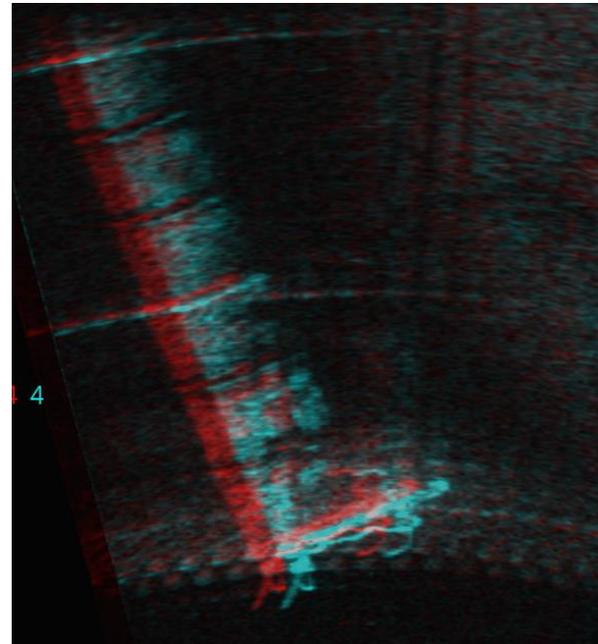

Figure 24 Anaglyph image: Red-Cyan glasses required

Figure 26 Two manipulators of CR200

Figure 25 The object of interest - Steel drum

4.0 OPERATIONS–FIELD AND WATER BASIN

In this section, acoustic images taken by the ARIS on the CR200 platform during experiments in the water basin and seafloor are introduced fragmentarily.

CR200 has two manipulators (Figure 26). In turbid water, operators have to control the manipulators when they cannot see them using the optical camera but see using the acoustic camera only. In the acoustic images, we could not recognize the shape of the manipulators easily and directly because the manipulators were too close to the camera. We could presume, however, positions of the gripper using shadows. Open state and closed state could be discriminated. The left image of Figure 27 shows the gripper is open while the right image of shows the gripper is closed. Figure 28 is another image showing the manipulator, its shadow and toolsled. The left is at zero roll angle whereas the right is at 90o roll angle. As intensity of the acoustic beam which was reflected by the metallic manipulator was too strong, its detailed shape could not be imaged.

CR200 is able to walking on the floor, and then it can take acoustic pictures from place to place. The object of interest, steel drum (Figure 25) could be inspected from place to place (Figure 29).

Figure 30 shows the images showing features of sea floor. There were slander rods and abandoned bundle of fishnet. Features of the seafloor could be also recognized. Role of the acoustic camera as a method to image forward was well conducted.
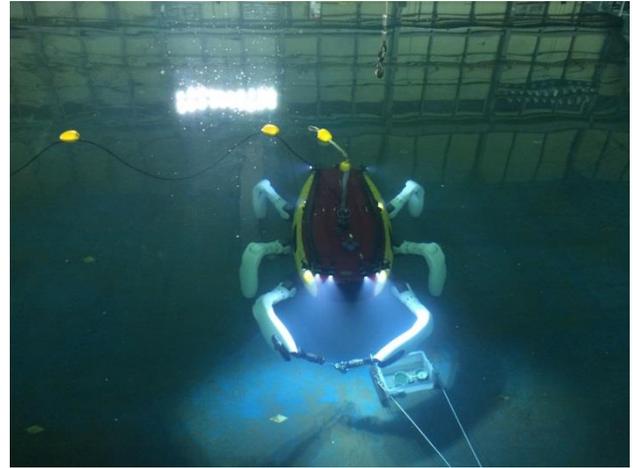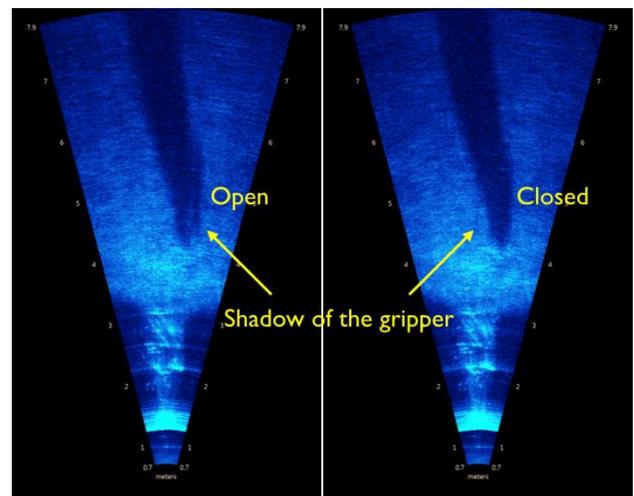

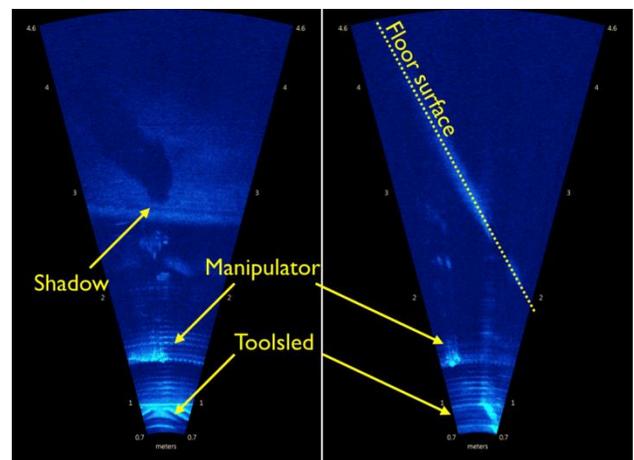**Figure 27** Acoustic Shadow images of the gripper

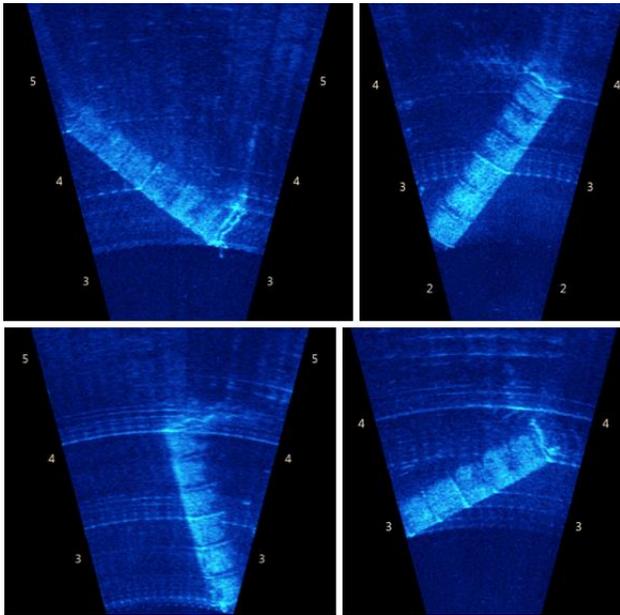**Figure 28** Gripper and toolsled: Roll at 0o (Left) and Roll at 90o (Right)

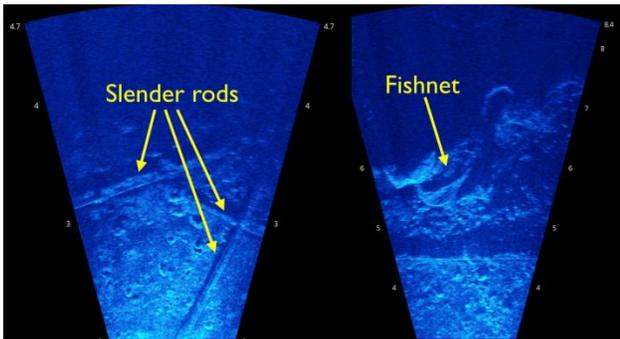**Figure 29** Images of the object taken from place to place

Figure 30 Acoustic images: Slender rods (Left) and fishnet (Right)

5.0 CONCLUSION

In this paper, we discussed operations and applications of the acoustic camera and a new type of ROV; CR200. Using this camera, the CR200 could inspect the object of interest from place and place with various side view angle. Application researches were also conducted. Especially, we placed more emphasize on effects of the acoustic camera's motions on the images. Figure 31 shows block diagram showing relationships among motions and applications. In the roll motions for generating stereoscopic images, relationship between parallax and roll angle of the camera will be modelled mathematically. For 3-D reconstruction, we will investigate how to discriminate duplicated points through multiple images to get more realistic reconstruction results.

By experiments and tests in the water basin and seafloor, we could verify performance of the acoustic camera as a forward looking device for the CR200. At that same time, feasibility of performance of the CR200 platform as an actively adaptable

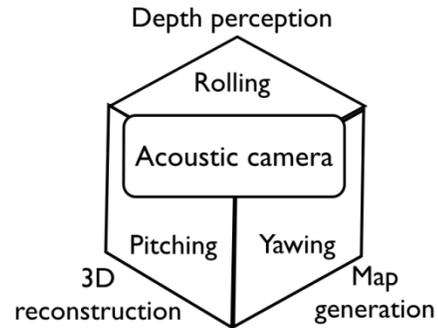underwater mobile observant platform has been verified.

Figure 31 Applications of the acoustic camera depending on its three kinds of motions

References

[1]   Belcher, E., Fox, W.L.J., Hanot, W. 2002, Dual-Frequency Acoustic Camera: A Candidate for an Obstacle Avoidance, Gap-Filler, and Identification Sensor for Untethered Underwater Vehicles. *Proceedings of OCEANS'02 MTS/IEEE*. 2124-2128
[2]   Jun, B. H., Shim, H., Kim, B., Park, J. Y., Baek, H., Yoo, S. and Lee, P. M. 2013. Development of Seabed Walking Robot CR200. *Proceedings of OCEANS'13 MTS/IEEE Bergen*. 1-5.
[3]   Shim, H., Jun, B. H., Kang, H., Yoo, S., Lee, G. M., Lee, P. M. 2013. Development of Underwater Robotic Arm and Leg for Seabed Robot, CRABSTER200. *Proceedings of OCEANS'13 MTS/IEEE Bergen*. 1-5.
[4]   Sound Metrics Corp. [Online] www.soundmetrics.com.
[5]   Park, J. Y., Baek, H., Lee, P. M., Jun, B. H. 2013. Generation of Anaglyph using High Resolution Acoustic Images. *Proceedings of OCEANS'13 MTS/IEEE San Diego*. 1-4.
[6]   Park, J. Y., Baek, H., Lee, P. M., Jun, B. H. 2013. High-resolution Acoustic Camera on CR200 and Post-Processing. *Proceedings of Int'l Symposium on Unmanned Untethered Submersible Technology (UUST 2013)*.
[7]   Park, J. Y., Baek, H., Shim, H., Jun, B.H., Lee, P.M., 2014. Field Operation of a High-resolution Acoustic Camera on CR200 and Mosaicking. *Proceedings of Int'l Conf. on Underwater System Technology: Theory and Applications (USYS,14)*. 169-174.
[8]   Hurtós, N., Cufí, X., Salvi, J. 2013. A Novel Blending Technique for Two-dimensional Forward-looking Sonar Mosaicking. *Proceedings of OCEANS'13 MTS/IEEE San Diego*.1-7.
[9]   Jun, B. H., Shim, H., Kim, B., Park, J. Y., Baek, H., Yoo, S., Kang, H., Lee, G. M. and Lee, P. M. 2013. First Field-Test of Seabed Walking Robot CR200. *Proceedings of OCEANS'13 MTS/IEEE San Diego*.1-6.
[10] Belcher, E., Hanot, W., Burch, J. 2002. Dual-Frequency Identification Sonar (DIDSON). *Proceedings of the 2002 International Symposium on Underwater Technology*. 187-192.

[11] Kim. B., Shim, H., Yoo, S. Y., Jun, B. H., Park, S.W., Lee, P. M. 2013. Operating Software for a Multi-legged Subsea Robot CR200. *Proceedings of OCEANS'13 MTS/IEEE Bergen*. 1-5.
[12] Seto, Mae L. 2013. *Marine Robot Autonomy*. Springer
[13] Li. S., Ma, L. Ngan, K.N., 2013, Anaglyph Image Generation by Matching Color Appearance Attributes. *Signal Processing: Image Communication*. 28(6): 597-607.

[14] Park, J. Y., Jun, B. H, Lee, P. M., Oh, J. 2009. Experiments on Vision Guided Docking of an Autonomous Underwater Vehicle Using One Camera. *Ocean Engineering*. 36(1): 48-61.