CONTINUOUS DEVELOPMENT OF AUTONOMOUS UNDERWATER VEHICLES
-A LONG WAY TO MID-OCEAN RIDGE SYSTEMS-

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Abstract
The first period of AUV development in the world started in the 1970s, and some ocean going AUVs were constructed in order to demonstrate the new technology and the potential of AUVs. It was encouraging, that “Epaulard” of CNEXO (IFREMER) was capable of deep sea floor exploration at such an early stage of AUV development.

Some years later in 1984, a program of AUV R&D was initiated at the University of Tokyo in which to date, more than ten kinds of AUV have been constructed. The final goal of the program is to frequently survey mid-ocean ridge systems using many AUVs. Our first project was the "PTEROA Project", in which the AUV "PTEROA 150" was constructed as our first ocean going AUV. Following the "PTEROA Project", we started the "R-One Project" in 1990, and the "R-Two Project" in 2001. The newest AUV "r2D4" was completed in July 2003 as part of the project, and carried out dives to fault lines in the Sea of Japan (in 2003, a maximum dive depth of 502m), Kuroshima Knoll (2003, 663m), NW Rota 1 Underwater Volcano (2004, 1,400m), and Myojin-sho Caldera (2005, 1,057m). Although these places are very attractive for scientists and engineers, they are, unfortunately, not mid-ocean ridge systems.

In December, 2006, 22 years after starting our R&D of AUVs, we succeeded in operating "r2D4" along the rift valley of the Central Indian Mid-Ocean Ridge System. The AUV "r2D4" surveyed the Roger Plateau (2,701m) and the Great Dodo Lava Plain (2,701m), took beautiful high resolution images of the sea bottom using its side scanning Sonar and interferometry Sonar, and found a significant anomaly in Mn concentration and turbidity at the Beak Rocks.

In order to identify small features in subsequent visits, we named some specific rocks, mounds, peaks and valleys. We hope that these names attract the attention of engineers and scientists.

In this paper, the long journey to the ridge system and mile stones to our final goal are presented.

Introduction
The first UUST (Unmanned Untethered Submersible Technology) symposium was held in May, 1980 at New Hampshire organized by Marine Systems Engineering Laboratory of University of New Hampshire [1]. In the proceedings, there are only a small number of underwater vehicles: i.e. Epaulard of CNEXO (IFREMER at present, France) and SPURV I & II of University of Washington (U.S.A.) were operational, and Angus Rover of Heriot-Watt University (U.K.), Eave-East of Univ. of New Hampshire (U.S.A.), Eave-West of NOSC (U.S.A.) and UFSS of Naval Research Lab. (U.S.A.) were going to be tested. It was encouraging that "Epaulard" of CNEXO successfully carried out deep sea floor exploration at such an early stage of AUV development. In the summary of the proceedings, Dr. Robert W. Corell of the University of New Hamphire addressed:

“The vehicle’s development and its mission are inseparable. The several programs reviewed at the symposium differ widely in mission, and are substantially different, therefore in design and appearance.”

His remark is outstanding. Since there are many types of missions AUVs should carry out in the ocean, it is necessary to develop many kinds of AUVs; i.e. AUV-Diversity should be a key word for underwater roboticians [2].

About five years later from this big initiative, we started a program of R&D of AUVs in the Institute of Industrial Science of the University of Tokyo in 1984, recognizing that the AUV could be an innovative platform for ocean research and exploration. The final goal of the program is to frequently survey mid-ocean ridge systems using many AUVs. Our first project was the "PTEROA Project", in which the AUV "PTEROA 150" shown in Fig. 1 was constructed in 1988 as our first ocean going AUV [3].
Based on experiences of design, construction and operation, we recognized that in order to enhance AUV R&D, it is necessary to develop many types of AUV, such as cruising, glider (Albac [4]), hovering (Tri-Dog1 [5]) and testbed (Twin-burger [6], IKURA [7]) and not limit ourselves to only the construction of full-scale ocean going models such as “R-One Robot” and “r2D4”.

Thus, we started the second program which provide students with versatile testbed AUVs for research on AUV intelligence. However, the R&D of full-scale ocean going models that can demonstrate to scientists their sophisticated performance in mid-ocean ridge systems is the key project of our institute.

Following the "PTEROA Project", we started the "R-One Project" in 1990, and the "R-Two Project" in 2001. The AUV “R-One Robot” shown in Fig. 2 was constructed in 1995, and has a length of 8.2 m and a mass of 4,000 kg.

One of special features of this robot was the newly developed closed-cycle Diesel engine system for electric power supply. The “R-One Project” was concluded by the successful dives of “R-One Robot” to Teisi Knoll in 2000 [8], which provided us with high-resolution side scanning images of Teisi Knoll taken from various directions as shown in Fig. 3.

About ten years had passed from the starting date of the project, mainly because of funding and debugging of software. However, the next “R-Two Project” progressed smoothly. By introducing the highly reliable software of R-One Robot, we designed a compact AUV “r2D4” whose configuration is similar, and control system identical to its predecessor as shown in Figs. 4 and 5. The newest AUV “r2D4”, which is 4.4 m in length, 1,510 kg in mass and can dive up to 4,000 m in depth, was completed in July 2003.
It carried out dives to fault lines in the Sea of Japan (in 2003, maximum dive depth of 502m), Kuroshima Knoll (2003, 663m), NW Rota 1 Underwater Volcano (2004, 1,400m) and Myojin-sho Caldera (2005, 1,057m). Though the difficulty of the dives increased progressively, the AUV “r2D4” was capable of clearing these difficulties. Although these places are very attractive for scientists and engineers, they are, unfortunately, not mid-ocean ridge systems.

In December, 2006, 22 years after starting our R&D of AUVs, we succeeded in operating “r2D4” along the rift valley of the Central Indian Mid-Ocean Ridge System. The AUV “r2D4” surveyed the Roger Plateau (2,701m) and the Great Dodo Lava Plain (2,701m), and took beautiful high resolution images of the sea bottom using its side scanning Sonar and interferometry Sonar.

In order to identify small features in subsequent visits, we named some specific rocks, mounds, peaks and valleys. We hope that these names attract the attention of engineers and scientists.

Kuroshima Knoll Dives

Kuroshima Knoll, whose peak has a depth of about 640 m, is located at 24.08N, 124.10E, south of Ishigaki Island. In this location, spouting of cold water with methane had been discovered previously using ROVs and HOVs. The configuration of the top of the knoll taken by the multi-narrow beam bathymetry Sonar from a surface ship is shown in Fig. 6. In December 2003, the AUV “r2D4” cruised near the bottom (20-30 m in altitude) 4 times and took interferometry data as shown in Fig. 7, which shows in detail, the complicated topography of the knoll [9]. The high resolution map shown in Fig. 7 demonstrates a quality of data that can only be obtained through the stable motion of the AUV.

NW Rota 1 Underwater Volcano Dives

In spring of 2004, NOAA reported that Northwest Rota 1 Underwater Volcano at 14.36N, 144.46.5E, whose configuration is similar to Mt. Fuji, was very active (http://oceanexplorer.noaa.gov/explorations/04fire/logs/aprill01/april01.html). The survey of active volcanoes is an attractive mission for AUVs as they can operate far from the support vessel, whose safety should be guaranteed, and the AUV “r2D4” was deployed around the top of the volcano [10].

Figure 8 shows the dive plan of #16 dive which was carried out on May 31, 2004. In the first sage, the AUV cruises over the top of volcano changing its depth, which is called the Progressive Ascent and Descent Operation (Prog-AD, which is similar to Tow-Yo operation of towed vehicles) from 400 – 510 m in depth. Then, it performed 5 bungee jumps from the top to the bottom of the south wall. In the third stage after the jumps, the AUV surveyed the small hill at a 1,400 m depth.

In-situ Mn measurement device GAMOS found high anomalies in Mn concentration during the dive. Video
images showed us that the AUV penetrated highly-turbid plumes many times during the mission. Although the AUV kept about 100m in altitude from the surface of the volcano, we can estimate two locations where these plumes come from.

Myojin-sho Caldera Dives

Myojin-sho Caldera is located about 800km south of Tokyo, and has a diameter of 8km. There is an active underwater volcano called Myojin-sho in the northeastern part of the outer rim of the caldera, which erupted repeatedly in 1952. Tragically, the research vessel Kaiyo-maru No.5 was involved in an eruption and sank instantaneously resulting in the loss of 31 people. The Kuroshio current usually runs over the caldera, and so this region has fast currents sometimes exceeding 3 knots. The caldera is surrounded by steep walls, with the height of the west wall 1,100m. It can be said that the operation of human occupied and remotely operated vehicles into the caldera is very dangerous due to the hostile environment. Therefore, this was the target of r2D4’s next dive [11].

Figure 9 shows the trajectory of r2D4 in the horizontal plane, and Fig. 10 shows the vertical profile where the horizontal axis indicates time. In Fig. 10 the depth of bottom measured by the vehicle, altitude of the vehicle and the time when the vehicle passed through each waypoint are presented to show the behavior and timing of events the vehicle performed in the caldera.

The vehicle started diving in the north of the Beyonese Rocks to get DVL data and high accuracy of positioning of its inertial navigation system. Unfortunately initialization time on the surface using GPS was insufficient, and so the positioning error increased as shown in the figure. We sent position update commands to the vehicle three times during the mission to maintain accurate tracking of the planned track lines. At waypoint 24, r2D4 succeeded in a vertical descent and ascent maneuver between a 210 m depth range, and then moved northward descending to the bottom of caldera. During this descent, the vehicle captured the topography of the surface of central cone taken by the interferometry Sonar as shown in Fig. 11. Because of accumulated position error after waypoint 27, the vehicle came close to the north cliff and touched the bottom. The vehicle understood the situation by herself and terminated the mission, surfacing using two vertical thrusters.
Central Indian Mid-Ocean Ridge System Dives

In December 2006, we succeeded in operating the AUV “r2D4” along the axis of the Central Indian Mid-Ocean Ridge System, and in taking clear side scan images of the floor of the rift valley in Segment 16 [12].

Segments 15 and 16 are part of the Central Indian Mid-Ocean Ridge System that extend approximately 280 km from 18_00S to 20_20S as shown in Fig. 12. The R/V Hakuho-maru that belongs to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), left Port Louis in Mauritius on December 7, 2006 for the NH06-4 Leg 3 cruise, stayed around the rift valley until 21st of December, and returned to Port Louis on the 23rd. The team organized to explore Segments 15 and 16, whose chief scientist was Prof. Kensaku Tamaki, consisted of four sub-groups; i.e. AUV, chemistry, bathymetry, and rock sub-groups. The aim of the AUV “r2D4” was to survey the rift valley using its side scanning Sonar, which is associated with an interferometry receiver Sonar, referring the bathymetry data measured by the R/V Hakuho-maru (20 kHz), and GAMOS which was introduced in the previous section to finds of anomalies in the Mn concentration.

Table 1 Dives of r2D4 along Segments 15 and 16

The AUV performed three separate dives as shown in Fig. 13, and found some anomalies in the concentration of manganese, but unfortunately we could not identify the location of the source of these anomalies.

Fig. 13 Three trajectories of “r2D4” around “Roger Plateau”

The second area is a narrow gorge in the middle of segment 16. Fig. 14 shows the dive plan for the #32 dive denoted by waypoints and tracklines, which were designed in order to take side scan images of the axis of the rift valley covering almost all the flat area. It was planned taking into consideration a maximum 300 m error in position estimation and the maximum operation time of 10 hours. Along the center of the gorge, three track-lines can cover the wide width (about 3 km) of the bottom. The lowest height from the bed between waypoints was determined as 60 m to get clear side scan images.

Fig. 14 Course plan of #32 dive to “the Great Dodo Lava Plain”

Fig. 12 Segments 15 and 16 of Central Mid-Ocean Ridge System

The AUV “r2D4” performed 5 fives during the cruise as shown in Table 1. The first dive (#28) was carried out to test the complete system. The AUV surveyed around “Roger Plateau (tentative name)” at 19_34S, 65_51E in the middle of Segment 15 three times. Then, the last dive (#32) was a long-term survey of the “the Great Dodo Lava Plain (tentative name)” at the center of Segment 16.
The AUV “r2D4” descended to the east peak of the rift valley, at a depth of 2,400 m, near the center of the gorge. After calibrating the magnetism sensor by turning “8-figure”, the AUV jumped off the cliff to the bottom of 2,700 m deep gorge, cruised over the bottom for about 6 hours at 3.3 knots as shown in Fig. 15, and took side scan images of the bottom surface covering 25 km².

Considering the configuration of the bottom, it is estimated that the bottom of the lava plain has a relative profile depth of 300 m. Consequently, the volume of lava is estimated at 16 km³.

Figure 17 is a close up view of the central part of the gorge. There are some cracks on the surface caused by the expansion, which is estimated 3.8 cm per year.

Conclusions and Acknowledgements

AUVs should dive to areas of which we know very little. In order to accomplish safe and challenging diving, it is necessary to establish a reliable system based on many sea trials. Excellent team-work is essential for this accomplishment, and also encouragement by colleagues, friends, and senior people is substantial. I would like to express my great thanks to Prof. Richard Blidberg for his initiative in the AUV community and advice to our projects. Attending UUST symposia and eating lobster in New Hampshire are the most comfortable events in these decades.

References