Exploration of Underwater Volcano by Autonomous Underwater Vehicle

Tamaki Ura
Institute of Industrial Science, the University of Tokyo
ura@iis.u-tokyo.ac.jp, 4-6-1, Komaba, Meguro, Tokyo 153-8505 Japan

ABSTRACT
This paper outlines the exploration of Teisi Knoll by the autonomous underwater vehicle the R-One Robot, as carried out October 19-22, 2000, and presents images taken by the sidescan SONAR fitted to the bottom of the vehicle. The R-One Robot was launched from the R/V Kaiyo, started diving near the support ship, followed pre-determined tracklines which were defined by waypoints, and finally came back to the destination where it was recovered by the support vessel. In order to minimize positioning error, which is determined by the inertial navigation system and Doppler SONAR, the robot ascended to the surface several times to ascertain its precise position using the global positioning system, the antenna of which is fitted on the vertical fin. Taking advantage of this positioning system, the robot followed the pre-determined tracklines with an error of less than 40 meters in 30 minutes of continuous submerging. Disturbance to the robot is small enough compared to towed vehicles that its movement can be regarded as stable. This stability resulted in clear side scanning images of the knoll and surrounding sea floor. The robot stopped at the center of the knoll, and descended vertically into the crater. When the vehicle was in the crater, anomalous manganese ion concentrations were detected by the in situ trace metal micro-analyzer GAMOS, which was loaded in the payload bay at the front of the robot.

1. Introduction
As has been shown by the extensive use of remotely operated heavy machines and equipment in disaster recovery at such disaster sites as the Mt. Fugen in Nagasaki Prefecture and Mt. Usu in Hokkaido, the use of unmanned machines in danger areas such as near active volcanoes seems an obvious next step given the technological progress being made in this area.

The observation of shallow sea floor volcanoes always entails risk. The difficulty of observing underwater volcanoes where visibility is poor, is far greater than that involved in surveying aboveground volcanoes. Examples such as the Kaiyo Maru V which sank at the Myojin-sho underwater volcano in 1952, and the hydrography vessel Takuyo which narrowly escaped disaster in the Teisi Knoll in 1989, demonstrate the danger and difficulties involved in such undertakings.

A vehicle that is expected to be able to perform the observations that the above two vehicles are not capable of is the autonomous underwater vehicle (AUV) which has been under intensive development. A great deal of research and development on AUVs began in Japan in the 1990s, and AUVs have been shown to be able to achieve results that other submersible equipment cannot [1]. The five major advantages to AUVs are:

1. They offer stable mobility because they are untethered.
2. Because they are built to travel automatically, they do not place an excessive burden on operators by requiring them to operate the controls continuously for long hours.
3. They can be submerged safely if care is taken when they are launched from the support vessel and recovered in the same way.
4. Since there is no cable handling, operations can be performed minimal deck equipment and work.
5. If surveys are being conducted near shore, it can be deployed from shore or a port which does not involve a heavily equipped support vessel.

This paper shows the potential and superiority of cruising AUVs for underwater volcano observation by discussing deployments and the
results of a fully automated observation study conducted using the AUV "R-One Robot" (Fig. 1) at Teisi Knoll (Fig. 2) October 19-22, 2000.

2. R-One Robot

In 1990, the Institute of Industrial Science (IIS) at the University of Tokyo and the Mitsui Engineering & Shipbuilding Co., Ltd., jointly launched a research and development project on AUVs that are capable of diving for long-range dives. In 1995, a prototype robot was completed, the R-One Robot [2]. Electricity is generated by a closed cycle Diesel engine (CCDE) system. The R-One Robot is a large robot measuring about 8 m in length and weighing 4 tons in air. It can travel underwater for about 16 hours at a speed of 3 knots. Its maximum diving depth is 400 m, and 0.6 m³ at the front of the robot can be used as a wet payload bay. The robot moves forward under power from an electric main thruster. It is fitted with two vertical thrusters that enable it to hover and to perform vertical descents and ascents.

![Figure 1 R-One Robot Going to Dive](image)

On July 17, 1996 the first autonomous diving session was performed off the coast of Tamano City. On August 21 it successfully completed a 4-hour test of approximately 20 km continuous autonomous diving off the coast of Tanabe City in Wakayama Prefecture. In 1998, the robot dived for 12-continuous hours in the same area.

Improvements during 1999 have made it possible for the robot to communicate using low-orbit satellites when it surfaces, making it possible for operators on the support vessel or those on shore-based to know its surfacing location. It is also equipped with a sidescan SONAR which is a Klein Model 2000 modified for AUV use. For three months starting in July 1999 tests and surveys were performed off the coast of Monbetsu City in Hokkaido. Based on the data obtained, software was improved, enabling diverse diving patterns to be attempted and increasing the reliability of autonomous operation.

The robot's position is determined by inputting the ground speed from the Doppler SONAR into an inertial navigation system based on ring laser gyros. GPS data retrieved when the vehicle surfaces is also used to make position information adjustments. When the ground speed cannot be measured due to the distance of the vehicle from the sea floor, position information adjustments can be made based on water speed. Consequently, the estimation of water current speed and direction is the key to accuracy. On long range dives, the accuracy of this technique is better than that of the pure inertial navigation mode which uses only acceleration and angular velocity. As the maximum depth on dives at the Teisi Knoll was an approximately 100 m, the speed can be referred to the sea floor from the start of the dive. As such, the position accuracy was quite good throughout the mission. On dives conducted before 1998, position adjustments were made only by using information sent to the robot through an acoustic command link from the support vessel, as the robot's software was not able to ascend the robot to the surface to make automatic position information adjustments.

3. Teisi Knoll

According to sea floor hydrographic chart no. 6362 dated March 12, 1992 entitled Sagami Bay Northwest (Fig. 2), the Teisi Knoll is located at 34:59.4N, and at 139:08.0E (Tokyo datum), and has a crater of approximately 200 m in diameter on otherwise fairly flat open floor at a depth of 95 m. The crater edge rises to a depth of 81 m, and the maximum depth of the crater bottom is recorded as 122 m.

It should be noted that there was no transponder nor other homing device on the sea floor in the target area. The support vessel Kaiyo (belonging to the Japan Marine Science and
Technology Center) was only used to launch and recover the vehicle, and to carry out adjustments and maintenance after recovery. No commands were sent to the robot from the operators during its dive, nor were the internal conditions of the robot monitored. However, in order to verify the position accuracy of the robot, a super-short baseline acoustic positioning system (SSBL) installed on the support vessel was used to regularly monitor the robot's position.

![Figure 2 Location of Teisi Knoll](image)

**4. Dive Description**

Three dives were completed as shown in Table 1. Once a dive plan was made, it was checked by the robot action simulator, which is based on the multi-vehicle simulator "MVS" [3]. The simulation was executed to consider the effects of water currents and other factors.

The first dive was a preparatory dive. The vehicle descended to a fixed depth of 10 m, or about 80 m from the sea floor, and moved along a line through the center of Teisi Knoll (34:59.4N) from the west (139:07.8E) to the east (139:08.2E). The robot traveled at 2.4 knots and surveyed the entire underwater crater using its sidescan SONAR. It simultaneously verified the accuracy of its position.

On the #42 and #43 dives, the robot, as illustrated in Fig. 3, obtained images of the sea floor using its sidescan SONAR, and traveled at a specified depth or a specified altitude from the sea floor. It performed vertical descents and ascents as necessary near the crater. This series of activities was performed according to a preprogrammed mission script installed in the robot, i.e. the robot performed all required actions without external input.

![Figure 3 Artist's Image of Autonomous Dive around Teisi Knoll](image)

<table>
<thead>
<tr>
<th>Table 1 Data of Dives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dive No.</td>
</tr>
<tr>
<td>#40</td>
</tr>
<tr>
<td>#42</td>
</tr>
<tr>
<td>#43</td>
</tr>
</tbody>
</table>

4-1. #42 Dive
4-1-1. Trackline Plan

Figure 4 shows the plan for the #42 dive. The points shown on the map are the waypoints. The program defines each waypoint and describes the activities between waypoints (WPs) as follows:

1) The robot is launched from the support vessel near the first waypoint (WP1).
2) It travels for two minutes on the surface, and once it has reached a certain forward speed, lowers its elevators (a pair of moveable fins attached to the horizontal tailplanes at the rear of the robot) and descends.
3) It stops for a moment at a depth of 20 m, hovers using only its vertical thrusters, and verifies the difference between the robot's weight and buoyancy.
4) It travels to WP1.
5) It passes WP1 and heads toward WP2,
maintaining a depth of 50 m. The WP is set with a latitude, longitude, depth, and a certain allowable error. In this case, it is set at a range of 30 m from the waypoint with an allowable depth error of 1 m.

6) After passing WP2, the robot calibrates the gravitometer, which is used to measure the gravity field and which is carried as payload, by setting the main thruster, the output of the vertical thrusters, the elevator angle, and the rudder angle (the direction of the main thruster) so as to minimize fluctuations in the robot's movement. This is called uncontrolled cruising mode. Because the robot may get into a dangerous situation during uncontrolled cruising, limits are set on allowable changes in depth and direction before this mode is terminated.

7) It cruises at a fixed depth of 50 m from WP3 to WP4.
8) When it reaches WP4, it holds that position, raises its elevator, and ascends to a depth of 10 m at its maximum pitch angle. Next, it stops its main thruster and surfaces using only its vertical thrusters.
9) It uses its GPS to determine its position, adjusts its position data in the inertial navigation system, restarts its main thruster, lowers its elevator, and descends toward WP5.
10) When it arrives at WP5 at a depth of 50 m, it heads toward WP6, and dives at a fixed altitude of 15 m.
11) At WP6, as at WP4, it surfaces, adjusts its position using the GPS, dives again, and heads toward WP7.
12) When it arrives at WP8 at a fixed depth of 50 m, the robot once stops its main thruster, and then controls its main thruster such that it is moves at a ground speed of 0-0.1 m/s while descending to a depth of 85 m using its vertical thrusters. It should be noted that the robot does not reverse its main thruster for its own safety. Next, it ascends to its original depth of 50 m. If there is a response within the specified range of its forward looking SONAR before it reaches its target depth, it will not descend any further and will ascend to a depth of 50 m or perform predetermined evasive maneuvers.
13) Maintaining a depth of 50 m, it proceeds to WP9 near the center of the crater and performs the same vertical descent and ascent as was performed at WP8. This time its target depth is 110 m.
14) Next it travels to WP10, performs the same maneuvers as at WP4, and dives toward WP11.
15) It proceeds to WP12 at an altitude of 15 m, performs the same maneuvers as at WP4, and proceeds to WP14 and WP15 at a fixed depth of 50 m.
16) It surfaces once again at WP15, proceeds to WP16, WP17, and WP18 at a fixed depth of 50 m, and surfaces at WP18.

![Figure 4 Plan of the #42 Dive](image_url1)

![Figure 5 Trajectory of R-One Robot in the #42 Dive](image_url2)

17) The surfaced robot adjusts its position information using the GPS while at the same time communicating its position to the support vessel via a communication satellite. As it may take several minutes to obtain a link to the satellite for this communication depending on the location of the satellite, the robot tries this task only once during this mission. It dives...
again, returns to WP18, and dives to WP19 at a fixed depth of 50 m.

18) At WP19 and WP20 it performs the vertical descent and ascent that it performed at WP8 and WP9.

19) It travels to WP21 at a fixed depth of 50 m, and performs the same uncontrolled cruising from WP21 that it performed at WP2.

20) It travels to WP22 at a fixed depth of 50 m, raises its elevator, and ascends in a northerly direction to a depth of 10 m. Next, it stops its main thruster, surfaces using only its vertical thrusters, adjusts its position information using the GPS, and notifies the support vessel of its position via a communication satellite. This completes this series of missions.

To minimize tracking errors, the robot surfaced to adjust its position information using the GPS about once every 30 minutes. When traveling to the next WP, the robot would determine the direction it would have to take to get from its position to the target WP. It measured the water current speed from its ground speed and water speed, used this information to perform rudder control so as to avoid lateral drift from the trackline, and proceeded toward the next WP along a straight path via the route of shortest distance.

4-1-2. Tracking and Movement

The robot determined its position, as discussed in section 2, using the output of the inertial navigation system and the GPS when surfaced. The support vessel Kaiyo used to transport, launch, and recover the robot is equipped with a SSBL device that can fix the robot's position. Figure 5 shows the robot's position using both monitoring methods. It shows that the robot faithfully carried out the actions instructed in Fig. 4.

It should be noted that when the robot came near the surface, the SSBL data is less accurate. Also, errors increase as the Kaiyo changes heading and moves. Considering these factors, it can be seen that the accumulated error up to the point that the robot surfaced and reset its position based on the GPS data was less than 50 m. The total errors calculated by the GPS position adjustments were 190 m over the course of a 249-minute dive. This indicates that the robot passes the tracklines with an average position error of 47 m/hour.

Based on the Doppler SONAR data, it is observed that the water current at a depth of 50 m was flowing at an average of about 0.08 m/s toward 100 deg. At 15 m above the sea floor, it was flowing at an average of about 0.24 m/sec toward 140 deg.

Since the robot could not control its direction when performing uncontrolled cruising maneuvers at WP2 and WP21, it strayed significantly off its planned tracklines. When it strayed more than 2 m from the target depth during both maneuvers, uncontrolled cruising was terminated, and the robot continued on to WP3 and WP22.

When it surfaced after passing WP4, it can be seen in the figure that there is a sudden position change, which is the result of GPS position adjustments as shown in Fig. 5. These discontinuous position changes occurred every time the robot surfaced.

When the robot stopped its main thruster at WP8, 9, 19, and 20 and performed vertical descents and ascents, the robot's lateral motion was not being controlled. It may have drifted horizontally due to current. The robot descended until it reached its altitude limit.

4-2. #43 Dive
4-2-1. Trackline Plan

The #43 dive was dedicated to a constant-depth dive (65m), and descents and ascents inside the crater. The robot followed tracklines as shown in Fig. 6, the spacing of which is 0.5', i.e. about 90 m in longitude and 75m in latitude. It was only scheduled to surface once during the voyage for a GPS position adjustment. The sidescan SONAR range was set at 200 m.

The mission process was the same as in the #42 dive, but this time it traveled at a fixed depth of 65 m for the entire trackline. It performed descent and ascent maneuvers at WP2, 3, 17, and 18.

4-2-2. Tracking and Movement
Figure 7 shows the trajectory. The robot was launched near WP1 and moved nearly 300 m to the south during its 2-minute pre-dive approach, then proceeding to WP1 underwater. As it was only scheduled to surface once at WP14, it also sent its position data to the support vessel via satellite link at this time which took about 7 minutes. This series of maneuvers for surfacing involved having the robot raise its elevator and surface at a pitch angle of 20 deg, so it moved about 250 m west of WP14 before getting to the surface. It also drifted south on the surface while communicating with the satellite. In the time it took to dive, it had moved about 300 m to the east. For the surfacing maneuver at WP24, the WP depth was set at 10 m, and from there the robot performed a vertical ascent. Consequently, the surfacing point was almost directly above WP24. Water current at a depth of 65 m was flowing at an average of about 0.07 m/s to 200 deg.

This dive indicates that in spite of the extensive length of the dive, the error was still less than 50 m. Also the total error derived from the GPS position adjustment and the final surfacing position adjustment was 54 m over the course of a 200-minute dive. It can be said that the position accuracy is less than 16 m/h which is much better than that of the #42 dive.

Figure 6 Plan of the #43 Dive

Figure 8 shows the shape of the sea floor calculated from the robot's altitude data and the robot's course when it passed near the crater heading north-south. It shows that the robot descended from its fixed depth into the crater. At WP13 the robot descended about 20 m down from the crater edge. As its ground speed was negative during the descent, it activated its main thruster and accelerated until its ground speed was 0.1 m/s. As a wall of the crater was then detected within 100 m in front of the robot at that point, it stopped its descent, and started to ascend.

5. Crater Images from Sidescan Sonar

During its #42 and #43 dives, the robot reached a position six and seven times, respectively, at which it could obtain images of the crater of Teisi Knoll within the set range of its sidescan SONAR. Taking advantages of this SONAR systems ability to measure at both 100 kHz and 500 kHz
simultaneously, it was able to obtain a total of 26 pages of images of the crater. Three images, as examples, are shown in Fig. 9 (#42 dive 100kHz, from WP5 to WP6), and Figs. 10, and 11 (#43 dive 100kHz and 500kHz, from WP7 to WP8). They are taken when the robot passed the north edge of the crater from east to west, and the opposite direction, respectively.

When the robot travels at a fixed depth or a fixed altitude, it moves forward in a fairly straight line. However, because the rudder control cancels out water current effects, the direction of the robot facing is not always equal to that of its motion, i.e. side slip is not negligible. For this reason, it should be noted that the scan direction is not perpendicular to the robot's trackline. It can be seen that it is possible to obtain very vivid images of the crater by stabilizing the robot's position and movement.

Figure 9 Side Scan SONAR Image (100kHz) Taken during #42 Dive. The Vehicle went from East to West at 15m Altitude.

Since the vehicle cruised at constant altitude at 15m from WP5 to WP6 during #42 dive, the image of the bottom of the crater could not be captured. On the contrary, altitude during #43 dive was almost twice as high as the previous one, the images in Figs. 10 and 11 show detailed configuration in side the crater.

As the 500 kHz data in Fig. 10 was taken from the same location as the 100 kHz data, the general shape is the same, but the resolution is significantly better than in the 100 kHz image. However, in addition to the narrow range of the area scanned, the Doppler SONAR (frequency 300 kHz) also has an effect on these images. Although it is possible to remove this noise from the image, this has not been done for the images shown here in order to show original images.

Lines of latitude and longitude calculated from the position verified by the robot have been added to each image. These correspond to the latitude and longitude lines shown in Figs. 4 and 8, divided into 0.1’ increments. Plus (+) signs have been added at 34:59.4N, and at 139:08.0E.

6. Anomalous Manganese Concentrations

For this experiment, a geochemical anomaly monitoring system [4] was fitted in the payload bay at the front of the robot. This device
continuously analyzes manganese ion concentrations. It detected manganese ion concentrations that were abnormally high compared to the surrounding areas at two locations during the #42 dive and one location during the #43 dive. High values during the #42 dive were recorded when the robot was traveling at an altitude of 15 m along the northeast side of the crater, and descending into the center of the crater, respectively, as indicated by the blue circles in Fig. 5. The anomaly detected during the #43 dive is likewise indicated in Fig. 7, and was found during the robot's descent into the center of the crater.

These data suggest that underground water with high levels of manganese is emanating from the sea floor to the center and outer edges of the crater.

7. Future Developments

This experiment demonstrated that the AUV can contribute to understanding oceanic and underwater lithospheric features as a stable underwater observation platform. The robot can certainly be put to good use in ocean research based on that the software currently installed is significantly well designed.

The observations presented here were made by carrying the robot on a support vessel to the experimentation site, however it is also possible to deploy the robot from the Port of Ito near the experimentation site and have it travel on its own to the site from there for 5 km. This is made possible by the robot's large energy capacity. In this case, a small craft such as pleasure or fishing boat could be used to support the robot. This procedure would make it extremely easy to deploy the robot for observation.

At this point in time, the robot is unable to recognize the crater based on sidescan SONAR images and automatically make advanced judgments such as deciding to approach it. However, as developments are made in computer and image processing technologies, adding such advanced search functions will eventually be possible. It would also be easy to reconfigure the software such that the robot would automatically perform a more thorough examination of any locations where it detected anomalous values of manganese concentrations or temperatures.

During each of the dives of this study, the sidescan SONAR range was set at the same setting from the beginning to the end of the dive. For this reason, the range turned out to be too great during the robot's low-altitude travel during the #42 dive. The software is currently being reconfigured to allow it to be set differently at each trackline. In this way, the potential uses of AUVs in underwater observation will increase, and further investigations will have to be conducted on plans to use AUVs for observing sea floor volcanic activity.

Based on this successful exploration at Teisi knoll [5], the second stage project "R-Two Project" following the "R-One Project" started from July of 2001. By the end of 2003, the authors group will construct a new practical vehicle for detailed and intelligent survey of hydro-thermal ventic areas along mid-ocean ridge systems.

Acknowledgement

Exploration of Teisi Knoll was carried out as a joint project between IIS, JAMSTEC (Japan Marine Science and Technology Center) and MES (Mitsui Engineering and Shipbuilding Co., Ltd.)

References