Introduction to an AUV "r2D4" and its Kuroshima Knoll Survey Mission

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Abstract - **In this paper, a newly developed AUV "r2D4" is introduced and its mission of surveying Kuroshima Knoll is addressed. As the successor of the AUV "R-One Robot", r2D4 was designed by IIS, the University of Tokyo, and constructed by MES, with the primary missions being the investigation of deep sea bottom and AUV intelligence. r2D4 is a highly reliable AUV with its length of 4.4 (m), demonstrating sufficient compactness as well as multifunctional capabilities and large maximum operating depth of 4000 (m). The first sea trial of r2D4 was carried out at Suruga Bay, July 2003. After the exploration off Sado Island in the Sea of Japan, r2D4 was deployed for the investigation of Kuroshima Knoll in December 2003. During Kuroshima mission, high quality acoustic images of seabed using interferometry sonar were obtained through the operation of r2D4, which could only be achieved by accurate and robust attitude control. The method of on-site position error correction was developed and testified during the Kuroshima Knoll mission. In this correction, based on the optimal estimation of SSBL position, regressions of actual vehicle trajectories are carried out to estimate the deviation between reference and actually formed way points. On the basis of the success in Kuroshima Knoll survey mission, r2D4 will be deployed in Mariana back-arc basin, toward the discovery of newly activated hydrothermal vents.**

I. INTRODUCTION

On the physical, chemical and biological oceanographic research, survey of hydrothermal vents has important scientific meanings. It is the slightly open window through which we can peep into the global magma activity, over the 80(%) of which are said to occur underneath the ocean floor. By way of the biological and chemical analyses of sea water near those vents, it is expected to grasp meaningful clues concerning the evolution of species on the earth.

In order to present a more effective and robust platform for the investigation of undersea hydrothermal vents, r2D4 (Fig.1) was launched in July 2003, merely 1.5(years) after the start of development project. r2D4 shares many of hardware / software elements with "R-One Robot" (Fig.2), the predecessor of r2D4.

Since the first field operation at Suruga Bay in July 2003, r2D4 has completed total 19 dives at several sites of sea region. In December 2003, r2D4 was deployed at the site of Kuroshima Knoll, off the coast of Ishigakijima, located at the far west end of Ryukyu Islands. Site of Kuroshima Knoll is the place known to have enormous sedimentation of methane hydrates, accompanying the cold seep activities.

In addition to physical and chemical measurements of sea water properties, r2D4 made detailed acoustic images of seabottom, using interferometry sonar system.

Though the position accuracy obtained by INS(Inertial Navigation System) installed in r2D4 is sufficiently high, authority of it is lost when the aid from DVL (Doppler Velocity Log) becomes unavailable. When the vehicle is subjected to carry out a bottom tracking below the altitude of 200(m), it is the interval until reaching that altitude during which significantly large position error accumulates owing to the lost DVL aid. During the Kuroshima Knoll survey, vehicle position was corrected by getting rid of this accumulated position error in INS. In this correction, true position obtained from SSBL estimation is used to evaluate current position error, followed by the transmission of it to AUV to update the INS.

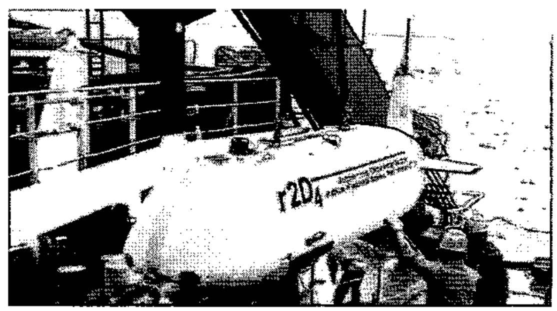

Fig.1 AUV "r2D4" during Kuroshima Knoll Survey Mission

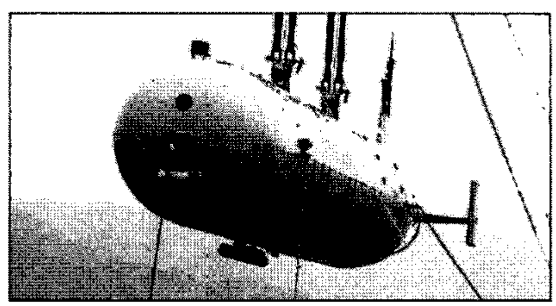

Fig.2 AUV "R-One Robot" during Teisi Knoll Survey Mission

II. VEHICLE DESCRIPTION

A. *Specifications and Features of r2D4*

r2D4is a mid-small size AUV designed to conduct survey of underwater hydrothermal vents. As is analogized from its name, maximum depth of operation is 4000(m). Due to the length and weight which are decreased to 1/2 and 1/3 of those of R-One respectively, r2D4 requires much simpler and lighter furnishes to handle it. In pursuit of the sufficient data acquisition during the mission, r2D4 is equipped with various sensors for instrumentation and observation with redundancy. Except for the default items shown in Table1, r2D4 is able to extend the necessary equipments in response to the requirements from the individual missions.

Table1 Principal Dimensions and Equipments of r2D4

Length Overall (m)	4.4
Breadth (m)	1.08
Height (m)	0.81
Weight (kg)	1506 (w/o payload)
	1630 (w payload)
Max. Oper Depth (m)	4000
Cruising Range (km)	60
Max. Speed (m/s)	1.544
Energy	15.2(kWh) Li-ion Battery
Main CPU	Power PC 233MHZ
OS	VxWorks
Navigation Device	INS(FOG) + DVL
Actuators	Main Thruster (Deflectable)
	Vertical Thrusters (×2)
	Elevators (×2)
Sensors	Side Scan Sonar
	Interferometry Sonar
	Video Camera (×2)
	3-Axes Magnetometer
	Oxidization-Reduction Voltage Meter
	Mn Ion Densitometer
	pH Sensor
	Turbidimeter
	Thermal Flow Meter
	CTDO

Among the intrinsic features of r2D4, self-completeness in system configuration is one of the most outstanding one. Since it aims at the operation in deep sea region, highly reliable autonomy without human control is extremely important. While it conducts minimum deviation tracking of reference trajectory and optimum attitude control under the normal state, fail-safe action of wide and duplicated guard protects the vehicle when it detects an occurrence of fatal abnormality in vehicle state or environmental condition.

B. Design Support by CAE Application

Some of design parameters related to the features on dynamics and control of the vehicle were determined based on the simulation results from CAE application.

In order to make drag improvement, nose shape of r2D4 was designed to be a streamlined body, while that of R-One was a blunt one. Total drag on the body was estimated via CFD analysis, which is obtained as the integration of hydrodynamic pressure and tangential stress by friction over the entire body surface. Fig.3 shows the grid system for the analyses, and Fig.4 the pressure distribution on the body as the result of an analysis.

Not only drag, dynamic model describing 6-d.o.f. motion responses of the vehicle was completed based on the results from CFD analyses. Repeated CFD analyses over the range of kinematic variables such as u(surge vel.), v(sway vel.), w(heave vel.), etc. derive the so called 'stability derivatives' , which constitutes the equations of motion. Eq.1 and Eq.2 are the equations of motion which describe longitudinal (surge, heave and pitch) and lateral (sway, roll and yaw) motion responses of r2D4, respectively.

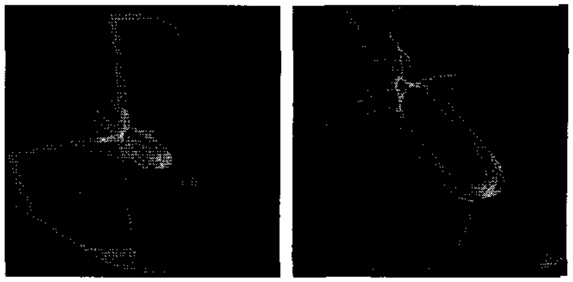

Fig.3 Grid System of r2D4 for CFD Analyses

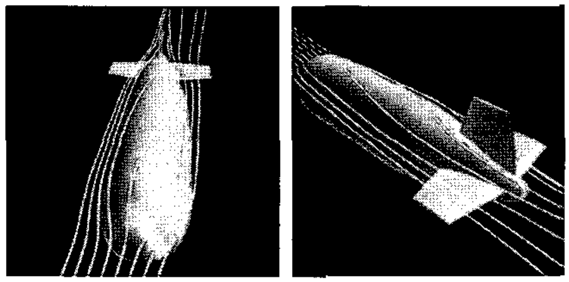

Fig.4 Pressure Distribution on the Body Surface of r2D4

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.1465 & 0.0263 & 0.0 & -0.0006 \\ 0.0683 & -1.3658 & 3.8905 & 0.1900 \\ -0.0062 & -0.0132 & -1.2340 & -0.0832 \\ 0.0 & 0.0 & 1.0 & 0.0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0.0491 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0112 & 0.0006 & 0.0679 & 0.0679 \\ 0.0 & -0.0029 & 0.0018 & -0.0979 & -0.0979 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix} \begin{bmatrix} n_m \\ n_{vf} \\ n_{vr} \\ \delta_{el} \\ \delta_{er} \end{bmatrix} \quad (2.1)$$

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -0.5266 & -0.0024 & -0.8046 & -0.0052 \\ -3.5308 & -4.7897 & 8.0281 & -10.5544 \\ -0.1472 & -0.0332 & -0.4068 & -0.0722 \\ 0.0 & 1.0 & 0.0 & 0.0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} -0.0335 & -0.0011 & 0.0011 \\ 0.0244 & -2.1704 & 2.1704 \\ 0.0486 & -0.0149 & 0.0149 \\ 0.0 & 0.0 & 0.0 \end{bmatrix} \begin{bmatrix} \delta_{pr} \\ \delta_{er} \\ \delta_{el} \end{bmatrix} \quad (2.2)$$

In Eqs.(2.1)~(2.2), u(m/s), v(m/s), w(m/s) are surge, sway and heave velocities. Similarly, p(rad/s), q(rad/s), r(rad/s) denote angular velocities of roll, pitch and yaw motions. n_m(rps), n_{vf}(rps), n_{vr}(rps) are no. of revolutions of main, fore-vertical and rear-vertical thrusters. δ_{pr}(rad), δ_{er}(rad), δ_{el}(rad) denote deflection angles of main thruster axis, right and left elevators, respectively. ϕ(rad) and θ(rad) are roll and pitch displacements.

Depth (Altitude) and heading controls are the means to change the dynamic state of r2D4. According to a current reference state in vehicle dynamics, necessary actuator input is calculated by the controller, consisting of PID compensations. Optimum values for PID gains are derived via the simulations of vehicle motion based on the closed-loop vehicle dynamics. Figs.5~6 show the results of depth and heading control by the actions of designed controllers.

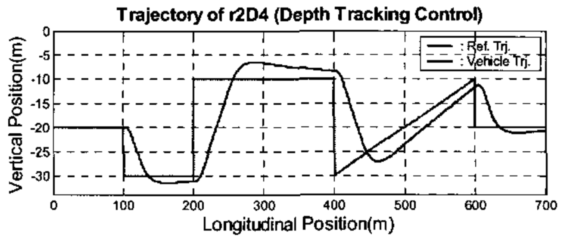

Fig.5 Vehicle Trajectory from Depth Tracking Control

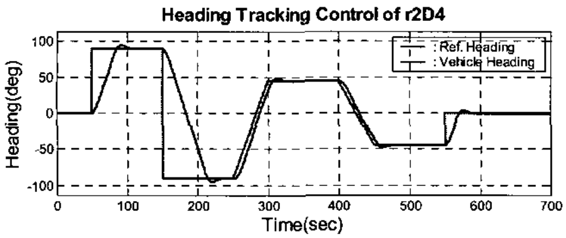

Fig.6 Heading Series by Tracking Control

III. DEPLOYMENT OF r2D4 IN SEA AREA

A. Sea Trial of r2D4 in Suruga Bay

Right after its completion, r2D4 was deployed at the northern part of Suruga Bay, 150(km) southwestward from Tokyo (Fig.7).

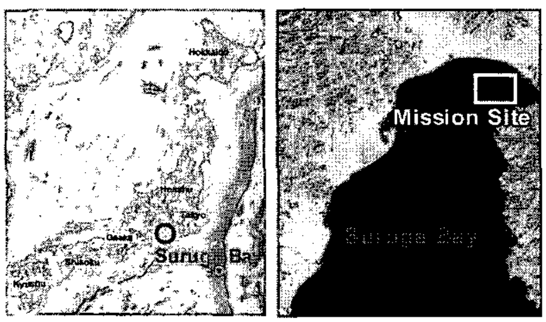

Fig.7 Location of the Mission Site (Suruga Bay)

The objective of Suruga Bay mission was to perform engineering tests on the overall hardware / software systems of r2D4, in order to detect any initial defect not found yet. In this respect, r2D4 testified most of sensors and control systems during the Suruga Bay mission, whether they operate properly.

Along a reference trajectory composed of appropriately distributed way points, r2D4 made seabottom tracking with the constant altitude of 30(m). By completing this tracking mission successfully, it was convinced that control system of r2D4 operates properly and accurately, in cooperation with the altitude and depth sensors.

Bathymetry and bottom profile of the sea area were also obtained via the constant altitude flight of r2D4.

B. Deployment of r2D4 in Sado offing

Followed on the Suruga Bay mission, r2D4 was deployed at the offing of Sado island, located in the sea of Japan, 40(km) off Niigata (Fig.8). During the Sado mission, r2D4 performed acoustic surveys of seabed underneath the area of Ryotsu Bay, resulting in the fine 3-dimensional image of the seabed (Fig.9).

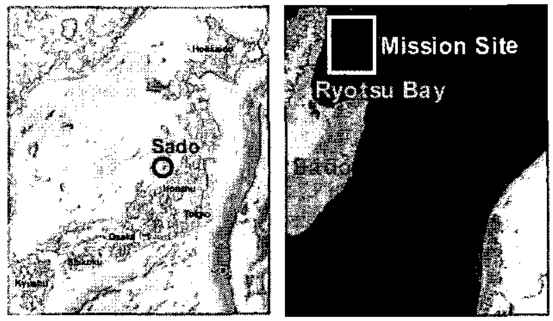

Fig.8 Location of the Mission Site (Sado Offing)

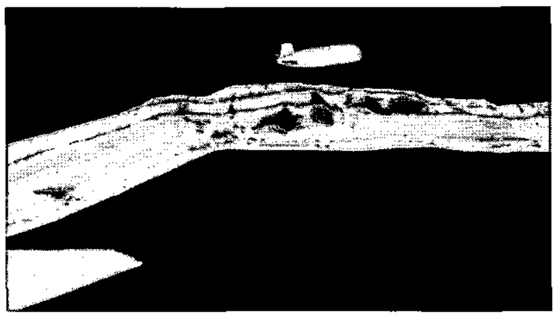

Fig.9 3-D Seabed Image of Sado Offing taken by r2D4

Fig.10 depicts the 3-D trajectory of r2D4 in Sado offing, formed by the completion of Sado mission. In Fig.10, within the interval of red-colored trajectory, vehicle kept the constant depth while it made seabottom tracking with the constant altitude control within the blue one.

In addition to the acoustic survey of the seabed, r2D4 made CTDO instrumentation during Sado mission.

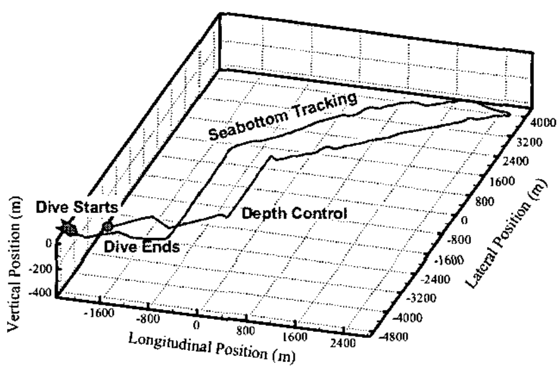

Fig.10 3-D Vehicle Trajectory during Sado Mission

C. Kuroshima Knoll Survey Mission

In December of 2003, r2D4 was deployed at the site in the Offing of Ishigakijima, Okinawa prefecture, located at the far west end of Ryukyu Islands (Fig.11). Kuroshima Knoll is the place known to have enormous sedimentation of methane hydrate, accompanying the cold seep activities. To detect and observe cold seep activities was one of the main objectives of Kuroshima mission. Another objective was to perform several tests on each system element of r2D4, in preparation for the mission of Mariana back-arc basin survey toward the discovery and observation of hydrothermal vents around it.

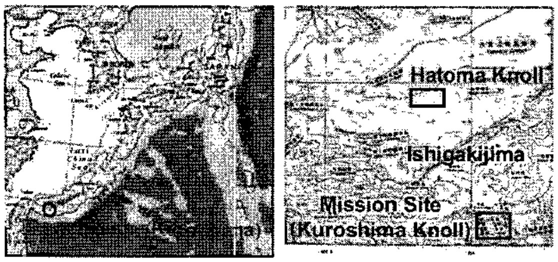

Fig.11 Location of the Mission Site (Kuroshima Knoll)

r2D4 project, supported by Japan Society for the Promotion of Science (JSPS), has been in progress by the collaboration of many researchers and engineers from diverse fields. Researchers and engineers for underwater robotics are from IIS (Institute of Industrial Science), the University of Tokyo and MES (Mitsui Engineering and Shipbuilding). Other researchers from the field of ocean science are the experts in oceanographic researches in Japan. Followings are the research groups participated in the Kuroshima Knoll survey mission.

- IIS, the University of Tokyo
- MES
- ORI (Ocean Research Institute), the University of Tokyo
- MES
- National Institute of Advanced Industrial Science and Technology (AIST)
- Kyoto University
- Tohoku University
- Central Research Institute of Electric Power Industry (CRIEPI)

1) On-Site Localization of r2D4 based on SSBL Estimation

Accurate localization is an important task for an AUV to accomplish the imposed underwater mission successfully. If it fails, any precious discovery or survey looses the availability. As mentioned previously, PHINS is a highly accurate INS system installed within r2D4. But the highly accurate localization by this INS is able to be assured provided it operates with the aid of DVL action against the seabottom. When the vehicle is subjected to carry out bottom tracking, until reaching a threshold altitude of DVL return from the bottom (200(m), for the DVL of r2D4), significant amount of position error accumulates due to the unavailability of bottom DVL. During the Kuroshima Knoll survey, a method of updating vehicle position in INS developed by the authors was testified. In this method, true position of the vehicle is determined by the estimation of SSBL tracing. To evaluate the error between true position and the one being recorded in INS, a lattice consisting of test intervals with waypoints (Fig.12) are prepared at the entrance of the survey trajectory. Position error is determined as the deviation between 'true' and 'reference' vehicle positions, evaluated at waypoints in the lattice. Refer to Ura and Kim [1] to see the details of the localization method introduced here.

In Fig.12, two kinds of trajectories during Kuroshima mission (Dive #08, Dec. 18th, 2003) are shown. Red one is the trajectory recorded in INS, while the blue one is corrected trajectory using proposed method. As shown in this figure, when the depth of operation exceeds hundreds of meters, accumulated position error is hard to ignore.

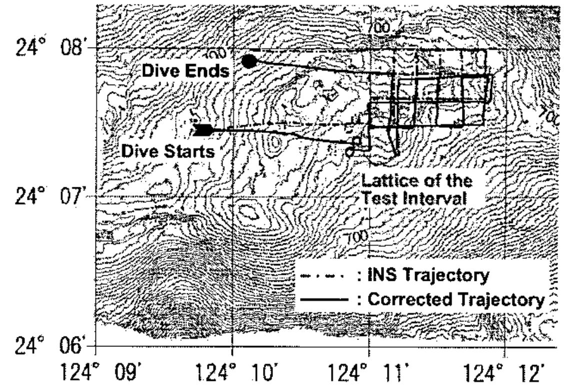

Fig.12 Planar Trajectories of r2D4 during Dive #08, Kuroshima Mission (INS Record / Corrected)

2) Summary of Kuroshima Knoll Survey Mission

Tables2a~d summarize the four dives conducted by r2D4 during Kuroshima mission. As shown in the Tables, r2D4 made survey activities by either constant depth (Dive #8) or bottom tracking (Dive #9~#11). Figs.13a~d depicts 3-D corrected vehicle trajectories of each dive. In these figures, longitudinal and lateral positions are the relative displacements with respect to the origin, which is taken as the midpoint of planar coordinates (latitudes / longitudes). Vertical position represents the depth of vehicle with the negative sign.

During the Kuroshima mission, r2D4 made survey activities utilizing several sensors installed. Examples are the IFS (Interferometry Sonar) for topographical survey of the seabed and CTDO (Conductivity, Temperature, Depth and Oxygen) measurements.

- *Summary of Dive #08*

Table2a Description of Dive #08 in Kuroshima Mission

Date	Dec. 18th, 2003
Duration	3(hr) 01(min)
Navigation	Const. Depth
Survey	SSS, IFS, CTDO
Notes	Mission Completed

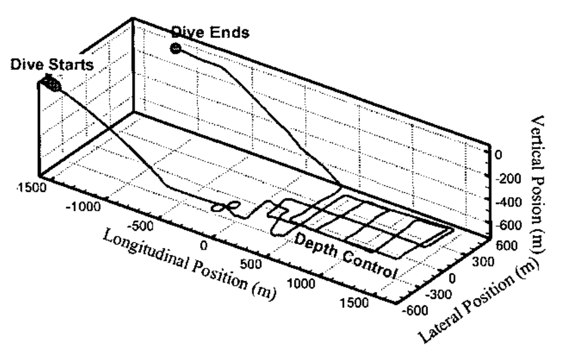

Fig.13a Trajectory of Dive #08, Kuroshima Mission

• Summary of Dive #09

Table2b Description of Dive #09 in Kuroshima Mission

Date	Dec. 20th, 2003
Duration	1(hr) 14(min)
Navigation	Const. Altitude
Survey	SSS, IFS, CTDO
Notes	Emergent Mission Interruption due to INS Error

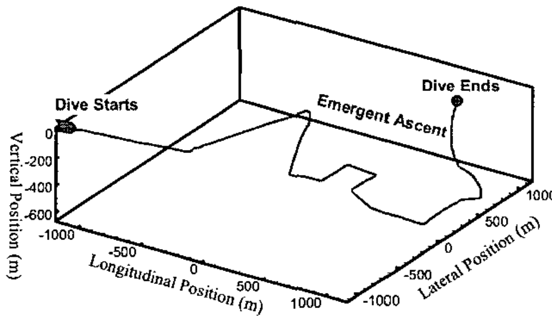

Fig.13b Trajectory of Dive #09 in Kuroshima Mission

• Summary of Dive #10

Table2c Description of Dive #10 in Kuroshima Mission

Date	Dec. 21st, 2003
Duration	29(min)
Navigation	Const. Altitude
Survey	SSS, IFS, CTDO
Notes	Emergent Mission Interruption to avoid Bottom Collision

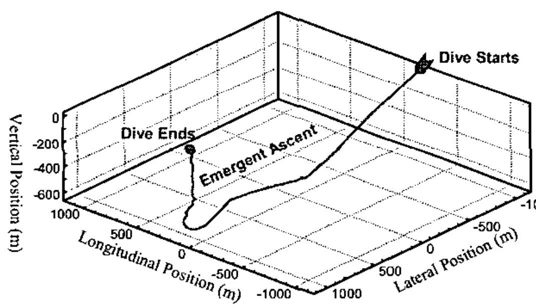

Fig.13c Trajectory of Dive #10 in Kuroshima Mission

• Summary of Dive #11

Table2d Description of Dive #11 in Kuroshima Mission

Date	Dec. 21st, 2003
Duration	2(hr) 50(min)
Navigation	Const. Altitude
Survey	SSS, IFS, CTDO
Notes	Mission Completed

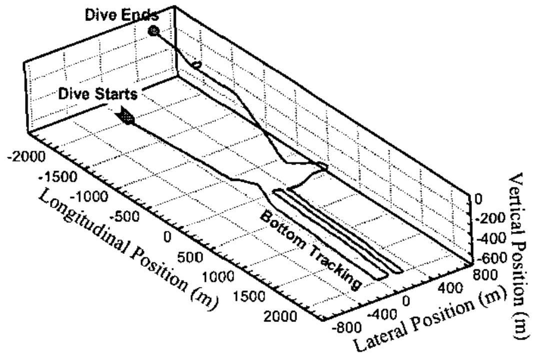

Fig.13d Trajectory of Dive #11 in Kuroshima Mission

IV. ACOUSTIC SURVEY OF KUROSHIMA KNOLL

Since the AUV can approach the seabottom being merely several meters apart, it has large advantage on the survey of detailed bottom topography, enabling the generation of seabottom images of high resolution. As a tool for acoustic survey, r2D4 is equipped with Side Scan Sonar (SSS). But it is known that interferometry sonar system is more appropriate to obtain bathymetry mapping of high resolution, as well as the backscatter imaging [4]. In advance of the Kuroshima Knoll survey, interferometry sonar system was installed in r2D4, by combining additional three hydrophones with SSS.

In order to improve the bathymetry measurement, synthetic aperture technique was applied to the interferometry analysis. Thought the standard synthetic aperture technique uses a small length transducer and wide azimuth focusing, standard SSS transducers are utilized for the interferometry system in r2D4.

While the deep sea multibeam echo sounder provides sea bottom bathymetry data with the resolution of tens of meters, interferometry sonar system of r2D4 presents far more detailed bathymetry information utilizing synthetic aperture. Fig.14 shows the contour of seabottom near the top of Kuroshima Knoll. Contours are discriminated by the level of 0.5(m), showing the achievement of very high resolution in bathymetry measurements.

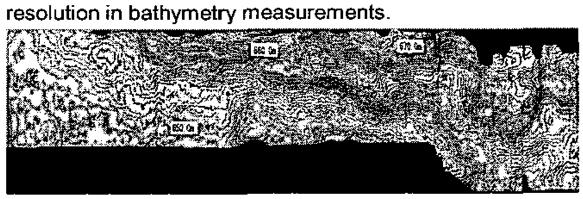

Fig.14 Depth Contour near the Top of Kuroshima Knoll

V. CONCLUSIONS

In this paper, an AUV r2D4 and its deployment results are introduced. r2D4 was launched in July 2003, after 1.5 (years) of the development period. Through the consecutive two missions conducted at Suruga Bay and Sado Offing, tests on hardware and software systems are done, to be fed back in fixing the revealed defects and improving the vehicle system. Kuroshima Knoll survey was the first practical mission of r2D4, deployed as an autonomous undersea platform for oceanographic survey. Experiences and know-hows obtained through the completion of Kuroshima mission will be utilized in building more reliable system environments of r2D4 toward the mission in Mariana back-arc basin, the place of deep sea hydrothermal activities.

Acknowledgments

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