Experimental Results of an Autonomous Underwater Vehicle "Urashima"

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***Abstract*-Japan Marine Science and Technology Center (JAMSTEC) has advanced the development of an ocean going Autonomous Underwater Vehicle (AUV). Technical problem on an AUV is to develop instruments for digital telemetry, highly accurate positioning in the sea and an efficient power source. The AUV in JAMSTEC has digital telemetry, accurate positioning system and high energy density battery. Sea test started in 2000, results were fed back to instruments to improve AUV performances. The quality of the communication has improved by the noise reduction. The positional error of the AUV was evaluated with a track given by an acoustic positioning system and DGPS on board a support vessel. The examination was planned and expanded based on previous results step by step. As the result, the AUV cruised more than 130km along the pre-programmed route while having submerged. This paper summarized the result of the sea area examination executed from 2000 to 2002.**

I. INTRODUCTION

In a lot of oceanographic surveys by surface vessels, however it was done at the observation of the point and its efficiency is not high in some cases. For instance, it is difficult for us to sample seawater in the Arctic Ocean by a vessel because the sea is covered with ice. However, it is necessary to sample for the ocean circulation from the content of the isotope of the carbon in seawater. Precise investigation of seafloor topography is important theme for the sliding phenomenon elucidation of the earth's crust. But acoustic instruments of sea floor detailed mapping onboard a ship is not enough for accuracy. Those cases as above, observations by an AUV which is approached near seafloor or cruised under ice are expected in the future.

Marine Science and Technology Center (JAMSTEC) completed an oceangoing autonomous underwater vehicle "Urashima"(hereafter called AUV) in 2000. This AUV is an experimental one for investigating engineering issues such as precise navigation, acoustic noise, avoidance and energy source for a long-range cruising. The AUV equipped a multiple water sampler, a conductivity temperature dissolved oxygen (CTDO) sensor, a side scan sonar and a digital camera for scientific investigation.

The principal particulars of AUV are shown in Table1. The maximum cruising range was planned at 100km by the lithium ion secondary battery and is aimed at 300km by the fuel cell. It is scheduled that the hydrogen gas and the oxygen gas are supplied to the fuel cell stored in the pressure hull to supply electricity to each component. The maximum submergence depth is 3,500m. This paper describes about the summary and topics of sea tests of the AUV.

Photo 1 AUV recovered at sea by a support vessel.

Table 1 Principal particulars of AUV "Urashima"

Dimensions	Length 10 m Width 1.3 m Height 1.5 m Weight 7.5 / 10 tons
Maximum Range	300 km (Fuel Cell) 100 km (Lithium ion battery)
Maximum Depth	3,500 m
Cruising Speed	3 kn. (Maximum 4 kn.)
Positioning	Inertial Navigation System Doppler Sonar Homing Sonar
Operation Mode	Autonomous Remote (Acoustic, Optical)
Sensors	Multiple Water Sampler Side Scan Sonar Snap Shot Digital Camera Forward Looking Sonar CTDO

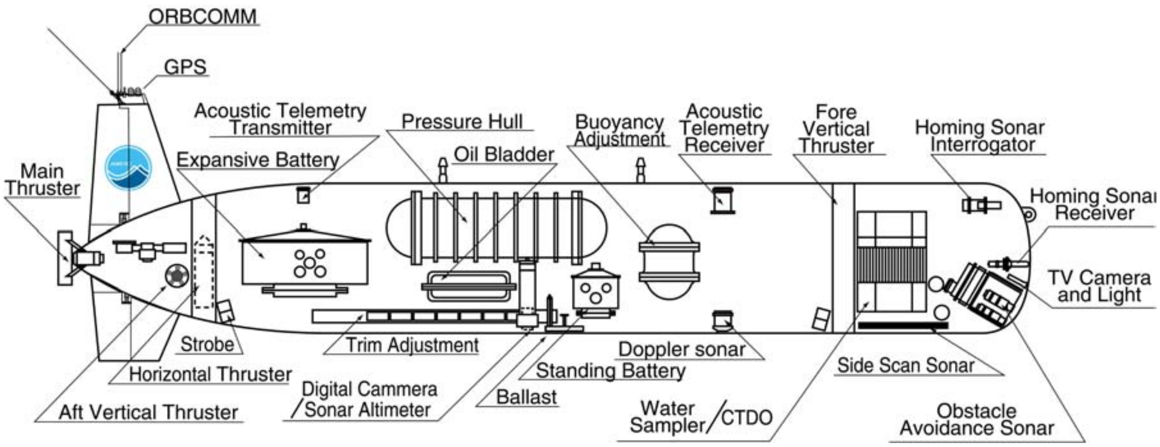

Fig.1 General arrangement of the ocean-going autonomous underwater vehicle “Urashima”.

II. AUV System Configuration

A. The Vehicle

Fig.1 shows the general arrangement of AUV equipped with the lithium-ion battery. A primary battery container at midship and an expanded battery container at aft side are installed. Capacity of batteries is totally 40kWh. The AUV is propelled by a main propeller driven by an electric motor in the back of the body. Yaw motion is controlled by vertical rudders. Pitch angle is controlled by a pair of horizontal rudders and a 100kg mass which moves longitudinal direction of body. Heave and yaw is controlled by two vertical thrusters and a horizontal thruster at slow speed. Sway and roll cannot be controlled from its thruster arrangement. The density of seawater increases as depth becomes deep as well known as the state equation of seawater in UNESCO. The buoyancy of the vehicle is to be changed by the density variation of seawater if AUV moves to the vertical direction. As a result, the AUV can keep depth like as it will prevent increasing of the resistance at advance speed and the sea-floor investigation by sidescan sonar or cameras mounted on its body at drifting. For this purpose, VBT (VBT: Variable Ballast Tank) was installed to regulate the buoyancy constant. Internal oil is injected or is exhausted to a bladder from VBT, and the buoyancy is decreased or increased. Electronics for control, positioning and communication are stored in the pressure container at the center of its body.

B. Effective Sea Test

In sea tests, we equip an AUV console system in two 10ft-containers onboard the support vessel “Yokosuka” (4,439GT: hereafter, called “support vessel”). The console is composed computers, three kinds of telemetry system (acoustic, optical and radio communication) and power sources. Fig.2 shows the appearance of the sea test in underwater. The communication is possible in full duplex through acoustic or optical link between the AUV and the support vessel.

Informations including speed, heading, INS, consumed electric energy and sensor data etc. of the AUV are up-linked to the support vessel through digital acoustic telemetry and they are watched on displays in the console during

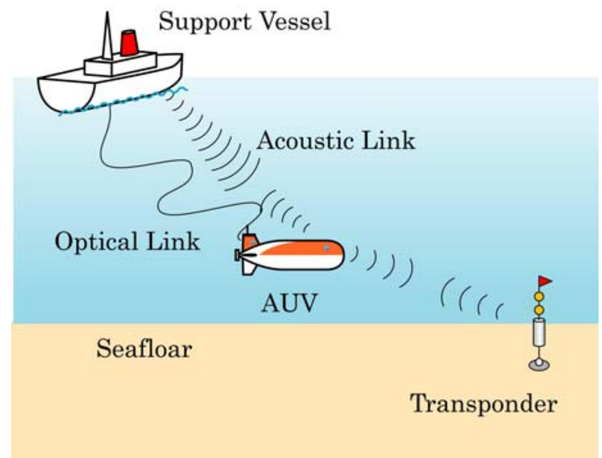

Fig.2 Image of sea test and telemetry between AUV and a surface vessel.

autonomous cruise. The AUV will cruise alone, but these real time data in test phases is precious not only to improve the system, but also to avoid some unexpected motion of the AUV. In some cases, the vehicle can also be controlled manually to give commands from the console. TV image are also received on board the support vessel through uplink for scientific observation.

C. Navigation and Positioning

The AUV is programmed to refer an information file called “scenario”. It works as a navigator which is composed from cruising and observation schedule. Cruising information is including passthrough points (way-points), depth, speed in underwater, acoustic transponder locations and their reply frequencies. A scenario is made up on the AUV console system in every time and download to computers based on VxWorks in the AUV before launching.
The precise navigation in underwater is based on an inertial navigation system (INS). It measures motion of body in 6 degree of freedom and calculates position in every moment. Its motion sensors in the INS are composed of the high accuracy ring-laser gyros and acceleration sensors in triaxis strapped-down method. To improve position accuracy, the system is added another sensors.

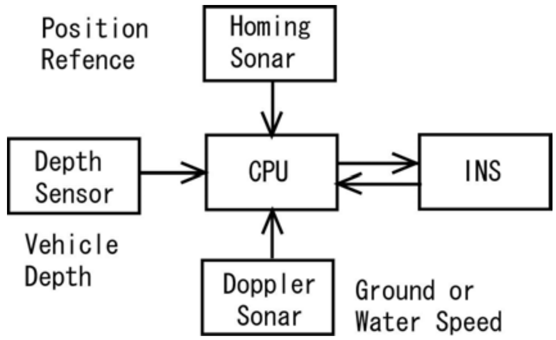

Fig.3 A precise positioning instruments in the AUV.

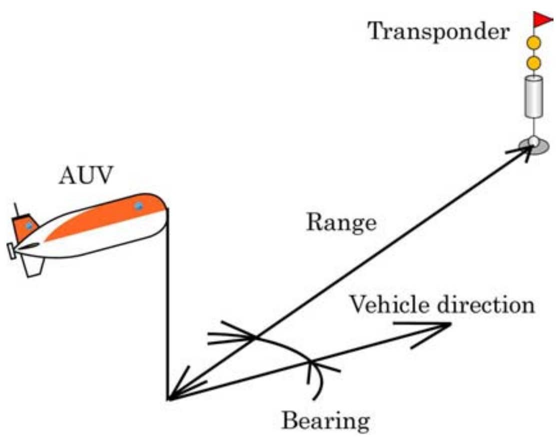

Fig.4 Concept of homing sonar.

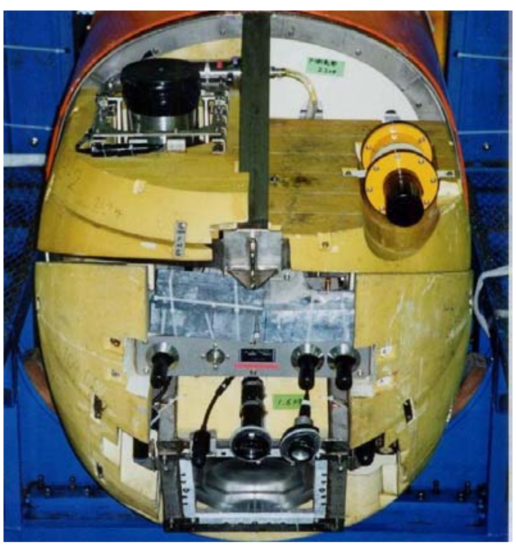

Photo 2 AUV front view without cover. Three receivers are mounted on a metal plate at vehicle center. There are two acoustic transducers on its top, Interrogator (PORT) and an acoustic telemetry receiver (STBD).

A doppler sonar in the body bottom directly measures its velocity to decrease errors in speed caused by INS and the depth of AUV is measured directly by depth sensors. As a result, a positional calculation with high accuracy can be expected more than the cases to use INS alone. However, it is an insurmountable difficulty to ignore the accumulated position error in long time operation by enviomental disturbances. Therefore, it is not enough to enhance underwater time of the AUV, because of its position uncertainty. It is a conventional method to surface and receives GPS, to correct position error for an AUV cruises shallow water. However the AUV cruises deep water, energy and time will be wasted to surface and another method have to be considered. Fig.4 shows the concept of the homing sonar. The acoustic wave propagates longer, the transmission loss increasing, and the received sound pressure should be recognized at minimum detection threshed level by the homing sonar. A distance between two transponders is decided by position error rate of the AUV and the detection range of the homing sonar. It measures a slant range and a bearing angle to an acoustic transponder deployed at a known location and has a capability of 10km detection range, as same as a super short base line acoustic positioning system. Photo.2 shows the front view of AUV removed its fairing cover.

Three receivers are mounted at accurate space in line to make different phase signals. The pair of closed receivers roughly measures the bearing angle to transponder in the phase difference of each hydrophone. The pair of separated receivers accurately measures phase difference to decide the bearing angle even low received signal level. The slant range between AUV and the transponder is calculated by the round trip time and the sound speed.

D. Noise Reduction of Propulsion System

The noise level at AUV receiver increased greater than the planned value when a fore vertical thruster was operated, and the quality of down-link was decreased in sea tests. It was found that the reduction gear of fore vertical thruster influenced the receiver.

To improve the acoustic communication range, a low noise reduction gear for propulsion system was designed. A propulsion system of the AUV is composed of a motor, reduction gears, and a propeller, and they are stored in a case. It is operated not only in sea water but also under the high pressure in deep sea, then small size and lightness are also demanded. Then, a motor and a reduction gear are installed into a case and oil is filled to keep equilibrium the internal and environmental pressure. This structure prevents to be infiltrated seawater to inside easily. But, the sound insulation is difficult to prevent noises generated by the movement. It was necessary to decrease the noise of the reduction gear.

Contact ratio means the number of contact teeth at the same time. It is known contact ratio relates to the key factor of the noise generated by a pair of gears. As the increase of the contact ratio, then the noise in operation decreases. The contact ratio of the helical gear is greater than spur gear because it is sum of transverse contact ratio same as spur gear and overlap contact ratio only helical gear. In a case of the this propulsion system, 2.656 contact ratio was obtained by helical gear, is greater than 1.377 of spur gears.

Because the size of the reduction gear was not revokable,

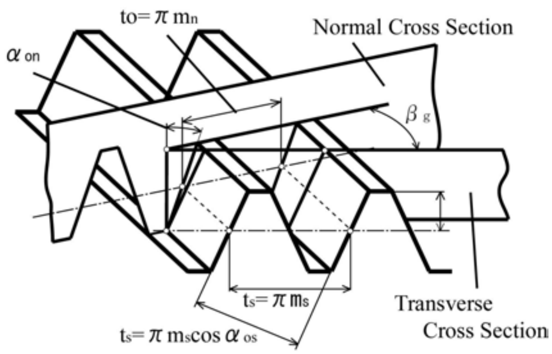

Fig.5 Tooth form of helical gear.

Photo 3 Spur gear (left) and helical gear (right) for propulsion system.

Table 2 Summary of sea test topics from 2000 to 2002.

Year		2000	2001	2002
Engineering Cruises	[times]	4	4	2
Maximum Depth	[m]	1,753	3,518	1,560
Maximum Range	[km]	7	60	133
Underwater Time	[hr.]	4	12	30

the helix angle Bg in Fig.5 of thread was adjusted with the module and the best tooth form was obtained for same pitch circle. Results of the new helical reduction gears, its noise level was decreased 16dB compared with spur gear in an acoustic tank.

III. Summarized Results in the Sea

Table 2 shows summarized topics of sea tests from June 2000 to August 2002. The range and underwater time increased every year, and the stable examination became possible. In 2000, as it is the first year of AUV sea test, engineering characteristics and properties of the vehicle was obtained through four engineering cruises. Telemetry, maneuverability and autonomous controllability of the system were improved. Handing on the support vessel including launch and recovery method was decided in this year too.

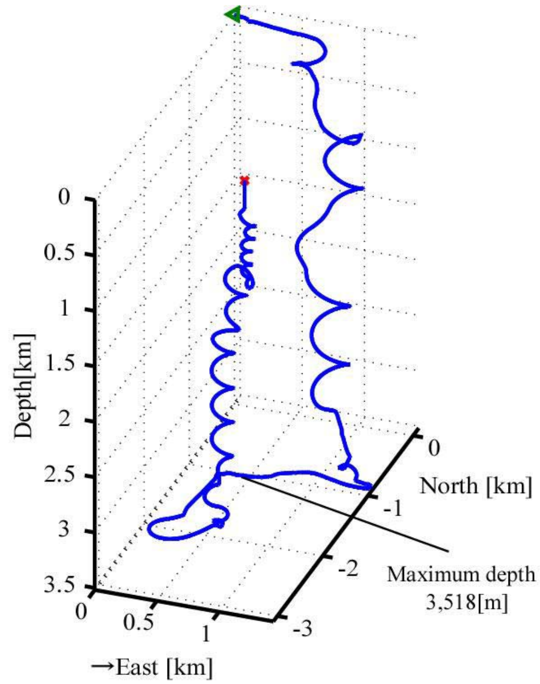

Fig.6 AUV track submerged to the maximum operation depth in Naze Basin.

In 2001, the purpose of sea test was aimed to submerge to the maximum operation depth 3,500m. The accuracy of the positioning system inside based on the INS was estimated.

In 2002, results till 2001 was concentrated for the long time autonomous cruise test for estimating battery capacity. Typical test results are described as follows.

A. Submerging to Maximum Depth

The maximum depth submergence test was executed in the sea area of 3,520m in depth (Naze basin) in the Amami Oshima east in August, 2001. As sea condition was a quite calm, the quality of communication can be estimated SN ratio, excepted the doppler shift caused by a ship motion.

Fig.6 shows the track of AUV. The optical telemetry is possible high speed communication and profitable to send the acoustic signal received by the vehicle receiver to the support vessel in real time. The optical fiber is spooled in the reel called "spooler" and is pulled out from spoolers by both of the AUV and the support vessel motion. To save fiber, the support vessel was stopping, because it was shown consumed fiber length in each spooler is proportional to moved distance of the AUV or the vessel. AUV had descended to the maximum depth while turning like the spiral with maximum down pitch angle controlled by horizontal rudders at 3kn of advance speed. The fiber was spent 7.6km in a spooler on AUV and 0.6 km on the support vessel respectively.

The procedure of experiments in the sea, both of the received signal level and noise level were analyzed and it was confirmed that the vehicle is responded correctly by the acoustic command from the support vessel in different depth. Table 3 shows a comparison of acoustic down link possibility in different gears. In Case 3, the vehicle was responded successfully at the probability of 83% when it was 831m in the slant range (vehicle depth is 800m). After the

Table 3 Communication Range and Error of Acoustic Telemetry Downlink.

	Type	Range [m]	Transmitt [times]	Success [times]	Probability [%]
Case1	Helical	2,107	8	6	75
Case2	Helical	1,122	10	10	100
Case3	Spur	831	12	10	83

Table 4 Results of Vehicle Noise Level in Different Thruster Condition.

Thruster	Depth [m]	Noise Level [dB]	Sound Noise Ratio [dB]
Stop	3,020	53.3	28.0
Slow	3,200	63.1	20.0
Half	3,150	72.8	10.0
Full	3,500	75.5	6.0

Table 5 Receiving Directivity of a Homing Sonar

Distance From Transponder [km]	Valid Bearing Angle [deg]		Max. Detection Angle [deg]
	PORT	STBD	
7	45°	39°	45°
4	40°	70°	70°
2	56°	70°	70°

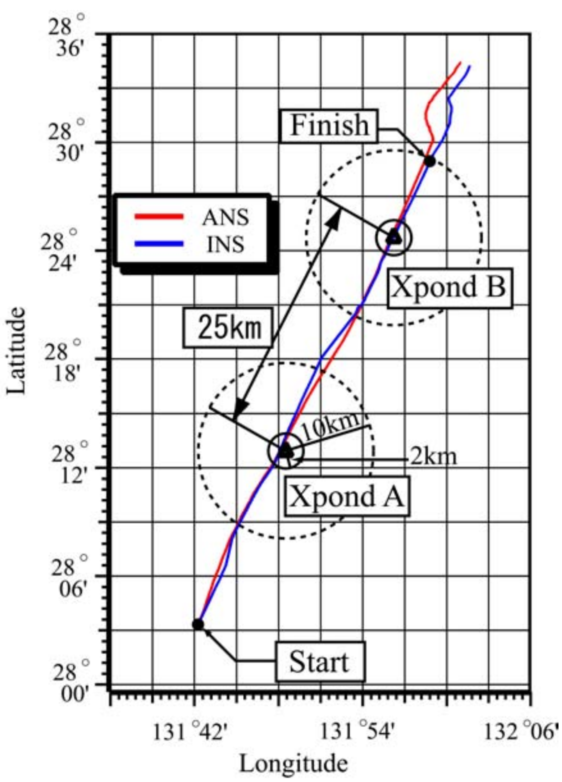

Fig. 7 Two tracks to estimate positioning system of AUV in Naze Basin.

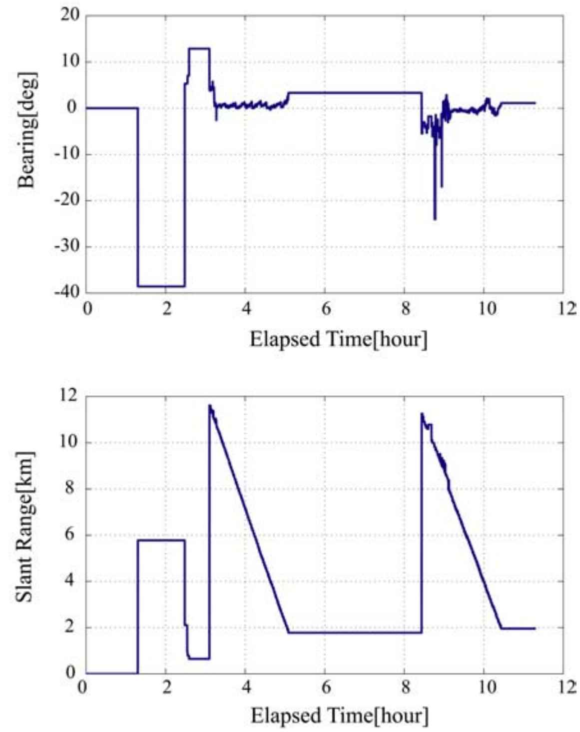

Fig.8 Time history of slant range and bearing angle measured by the homing sonar at Naze Basin.

improvement, the vehicle received commands successfully at the probability of 75% when it was 2,107m in the slant range (vehicle depth is 2,010m). It is considered that probabilities of Case 1 and Case 3 are mostly equal, the transmission distance increases by a factor of 2.5. Case3 shows a result before the improvement, spur reduction gears were installed. This value of 2.5 times corresponds to decrease 8.0dB of noise level, which is half value of the test in the acoustic tank. However, there is a possibility that its noise will increase because the thruster was installed in the vehicle. From Case2, AUV accepts commands through acoustic telemetry in any operational condition till vehicle depth of 1,100m, and it is desirable for the reliability of telemetry to have margin.

Table 4 shows the results of noise level measured over 3,000m range. The noise level of AUV is 53.3dB when all thrusters were stopped. The AUV was controlled successfully by acoustic down-link when a front vertical thruster was operated at slow speed. The contact ratio in the spur gears and helical gears for AUV are 1.377 and 2.656 respectively mentioned in the previous section. The thruster was operated at slow speed at slow speed, though the noise level increases to 63.1dB, the signal to noise ratio was 20dB which is lower than designed value (15dB). However, it is operated over half speed, possibility of down link decreases by increasing thruster noise.

B. Estimating of AUV Positioning System Accuracy

The AUV measures its position by its precise positioning system inside shown in Fig.3.

The maximum detection range of 12km at acoustic axis of the homing sonar receiver obtained in sea test. Table 5 summarized its directivity. It shows 70deg within 4km distance from a transponder.

It is difficult to estimate positional error of AUV without reference. To analyze positional accuracy of AUV, we obtained another AUV track measured by the ANS (ANS : Acoustic Positioning System) with a differential GPS receiver on board the support vessel. We compared two AUV tracks measured by different method and the ANS track is assumed the truth, it is possible to estimate the INS positioning error. To obtain data concerning with positional error, we prepared a sea test. The start point where AUV changed to autonomous mode was about 20km far away from the first transponder. A scenario was programmed as follows.

1) AUV approaches to the way-point at A transponder and the homing sonar starts detection from 10km away. (The transponder labeled A is not the target.)
2) The position truth of AUV is calculated by the homing sonar and update INS position.
3) The AUV approaches to A transponder within 2km.
4) AUV is changed the target of way-point at transponder B and cruising is continued. (B transponder is not the target.)
5) AUV detects B transponder from 10km away by the homing sonar.
6) The position truth of AUV is calculated by the homing sonar and update INS position similarly to 2) above.
7) The AUV approaches to B transponder within 2km similar to 3).
8) AUV continues sailing with the heading angle kept.

Fig.8 shows the result, as two AUV tracks and the transponder locations. An track shown ANS in explanatory notes assumes truth as above, the position error of INS is considered within 2km by the distance of two tracks during 25km between A and B transponder. Positional error is considered under 10% of moved distance.

It is found that the ANS overlapped INS track within 10km distance from a transponder indicated dashed circle. It means that INS position had been updated by the homing sonar and position error of the AUV is cancelled. It was proved for AUV to cruise successfully according to the program above. The total distance of and the underwater time were 70km (60km in autonomous) and 11 hours 20 minuets respectively.

C. Estimating Maximum Range

As a compilation of a past examination, this test was scheduled. To improve the reliability of the communication, the depth of 800m was decided from a result of telemetry in section A. It does not receive the influence of the Kuroshio Current. Distance of transponders is decided both of positioning accuracy of AUV and the homing sonar detection capability. As test results, distance of two transponders is able to expand to 80km in section B. However one purpose of this test, we obtained result, different frequency transponders were detected sequentially according to the scenario and positional error was cancelled.

Fig.9 shows the result, AUV was cruised autonomy 133km along four way points, same points at where acoustic transponders deployed every 30km along Nankai Trough and Suruga Trough in 2002. The AUV cruised 800m depth, over the range (100km) in design, supplied electric power by lithium-ion batteries.

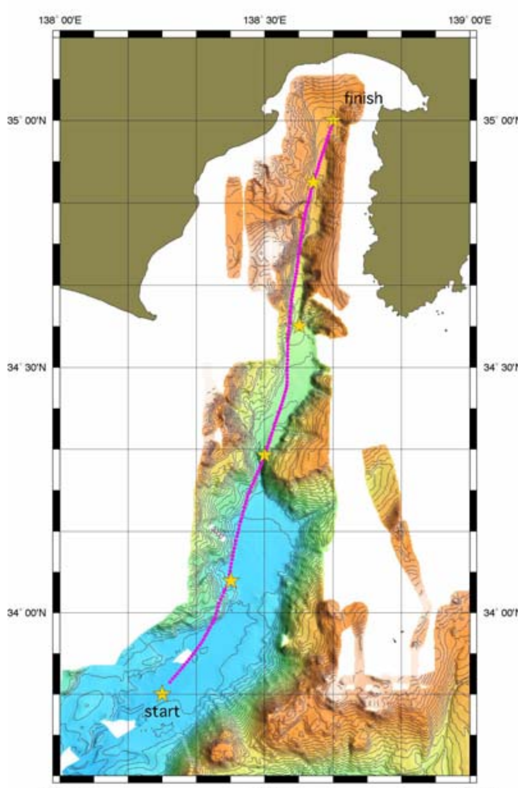

Fig.9 AUV track along Nankai Trough and Suruga Trough.

IV. Conclusions

Sea test results is concentrated, the AUV was cruised successfully over 130km range in 2002. The AUV equips a fuel cell after construction during 6 months from Oct. 2002. JAMSTEC started sea test for the FC autonomous underwater vehicle from 2003. The oceanographic survey technique using AUV will be established in near future.

Acknowledgments

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