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REVIEW

Performance of the fuel cell underwater vehicle URASHIMA

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Abstract: The Japan Agency for Marine-Earth Science and Technology acquired an autonomous underwater vehicle, the URASHIMA, in 2000. It has capacity to cruise for 300 km, and to dive up to 3,500 m depth, and it can approach waypoints correctly using inertial or acoustic navigation during autonomous cruising. Autonomous underwater vehicles are expected to explore environmental problems by measuring various oceanic data. Through sea trials, we have been developing key technologies for the vehicle, such as navigation and power sources. This paper describes the vehicle system and sea trial results.

Keywords: AUV, Fuel cell, Homing sonar, Acoustic TV, Acoustic telemetry

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1. INTRODUCTION

To solve various problems on the earth, many research organizations have been widely observing the ocean. Many oceanographic surveys are done mainly by ship, using acoustic devices. The only effective way to sense the seabed remotely is to use acoustic waves, and as such, research on underwater acoustics began before WWI [1]. The tool Sound Navigation and Ranging (SONAR), which calculates distance and images targets by processing echoes, is famous among such devices [2]. But surveying is sometimes inefficient. For example, it is difficult to sample seawater in the Arctic Ocean with ships, because the sea is covered with ice, and it is difficult to even access the research area. Sampling seawater is a very important way to measure carbon isotope content. Precise mapping of seafloor topography is also an important theme to elucidate the varying phenomenon of deep trenches.

Remote observatory vehicles (ROV), which are controlled from a mother ship remotely and can approach the sea bottom unmanned, are useful in such cases. An autonomous underwater vehicle (AUV) in particular, which is a kind of ROV, is the best tool [3]. It can even cruise below icebergs underwater. Besides, it is a stable tool near the sea floor. And in addition to being advantageous for accurate surveying, it also has new sensors, such as synthetic aperture sonar (SAS).

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) launched the AUV URASHIMA in 2000. Figure 1 shows a picture of it, recovered after a cruise. Table 1 shows its specifications. The vehicle is an experimental one aimed at investigating such engineering issues as navigation, telemetry, and energy sources. Homing sonar, consisting of a pinger and an SSBL receiver, is necessary to know its precise underwater position. This is very important. Precise observation cannot be accomplished without precise navigation. An acoustic telemetry system helps us to check the operating AUV, retrieve real-time data from various sensors, and develop it efficiently. The fuel cell — a next-generation power source — permits a cruise range more than double that of conventional power sources.

2. THE AUV SYSTEM

2.1. Outline of the Vehicle

The maximum operation depth of the vehicle is 3,500 m now, but our goal is to make one that can cruise at 6,000 m depth. To approach this goal, a deep diving model was considered from the early development stage. It has the same structure as the manned research submarine

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SHINKAI6500. That is, loading instruments, such as pressure hull electric devices, various sensors, batteries, and thrusters are fixed in a titanium chassis. Buoyancies are put into space among these instruments. Figure 2 shows the URASHIMA's general construction. The chassis is covered with a fairing cover of fiber-reinforced plastic (FRP). Its body is streamlined to reduce drag at high speed. Buoyancy is achieved by a special, high-pressure synthetic foam. It consists of glass micro-balloons for buoyancy and resin as bonding. The foam's specific density is about 0.5. It is manufactured using three-dimensional machining to fit the outline of the chassis and body.

Fig. 1 The AUV URASHIMA, recovered after cruising.

Table 1 Specifications of the URASHIMA.

Dimension	10L × 1.3W × 1.5H m
Weight (in air)	10 ton
Operation depth (max.);	3,500 m
Cruising range	300 km

2.2. Navigation

It is important to know if an AUV is cruising along a planned track. We cannot use a global positioning system (GPS) to determine its underwater position, so we are using an inertial navigation system (INS) to measure the vehicle's position. Since it moves slowly, acquiring accurate acceleration information is difficult. As a result, there is an increased chance of position errors if an AUV relies solely upon INS. The vehicle has a homing sonar at the head of the body, for correcting position errors. Figure 3 shows a picture of the homing sonar. The FRP cover has been removed for this picture. The homing sonar consists of an interrogator and a super short base line (SSBL) receiver. Tables 2 and 3 respectively show the specifications of the SSBL receiver and the interrogator. The interrogator uses 6.6 kHz, and SSBL detects 6.9, 7.2, or 7.5 kHz. It can measure the slant range and bearing angle between the vehicle and a transponder that is within 10 km.

Fig. 3 Interrogator and SSBL receiver in the homing sonar.

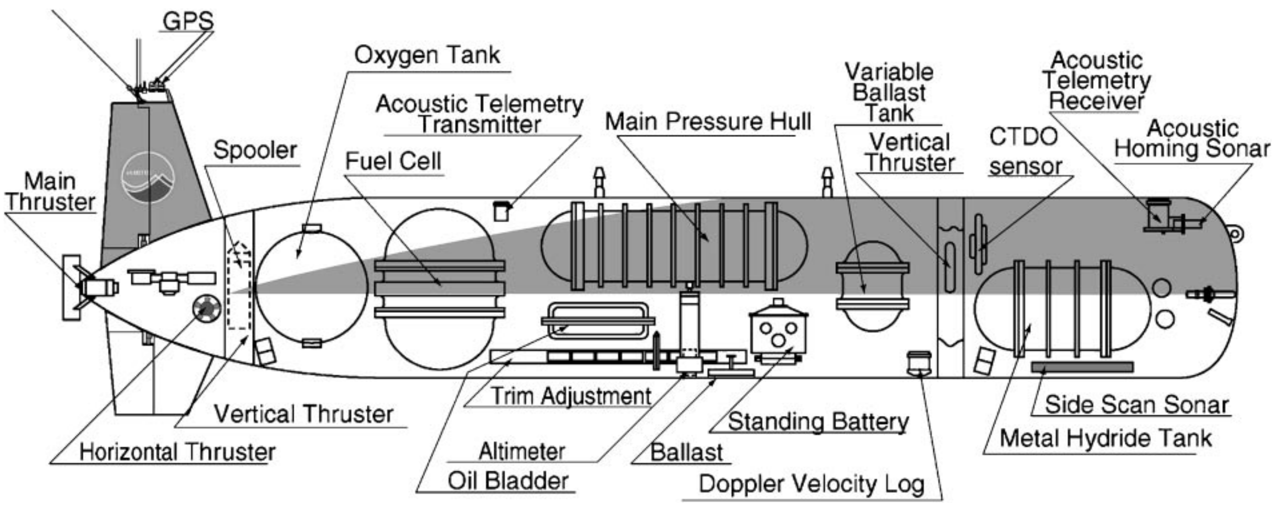

Fig. 2 General arrangement.

Table 2 Specifications of the SSBL receiver in the homing sonar.

Number of elements	3
Frequency	6.9 or 7.2 or 7.5 kHz
Max. detection dist.	10,000 m
Angular accuracy	±2
Range accuracy	5%

Table 3 Specifications of the interogator in the homing sonar.

Transmitting level	190 dB
Pulse width	20 ms
Interrogation freq.	6.6 kHz
Repetition	16 s

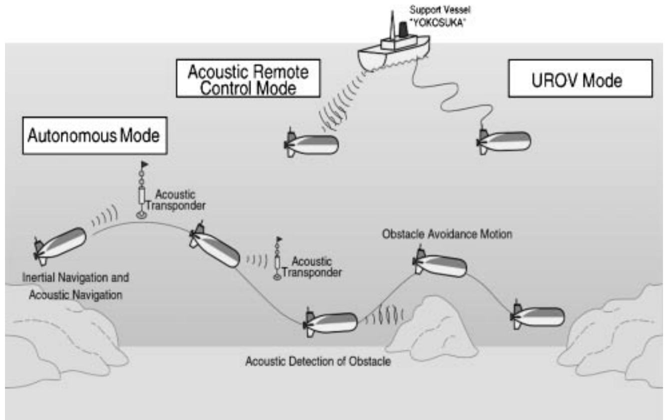

Fig. 5 Three operation modes.

Table 4 Specifications of the acoustic telemetry.

	Up link (AUV to Ship)	Down link (Ship to AUV)
Transmittable Information	SS image TV image Digital still image Sensors data Navigation data Equipment status	Command
Frequency	20 ± 4 kHz	9.5 ± 1 kHz
Modulation	4 or 8DPSK,16QAM	MSK
Bit rate	8 or 16 or 24 or 32 kbps	2 kbps
Max. range	4,100 m	4,100 m
Beam width	80 deg conical	80 deg conical
Pulse width	400 ms	Valuable
Transmitting level	195 dB	190 dB

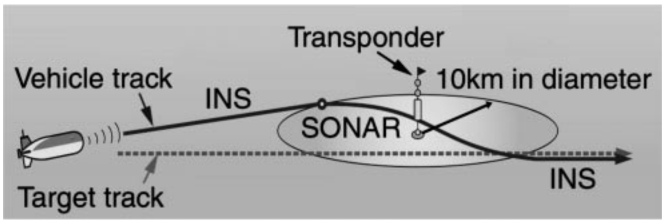

Fig. 4 Inertial navigation and acoustic navigation.

Figure 4 shows navigation near a transponder. We deploy transponders and input those positions into the vehicle in advance, if we forecast a large position error on a planned track. When approaching a transponder, the homing sonar's interrogator pings in a circle, making the transponder ping in response. By receiving a reply with the SSBL receiver array in the homing sonar, SSBL can determine its relative bearings (from phase differences in echoes) and its distance from the transponder (from echo delays), and then the vehicle calculates and updates its position and removes position errors. There is no need for transponders to be on tracks, and the vehicle can attempt to catch a signal many times from different positions on a track if the transponder is in range. For example, only one transponder is needed if we can set a track as the vehicle approaches the transponder once in a period.

2.3. Telemetry

We consider reliable communications between the vehicle and mother ship important in carrying out safe and efficient seagoing trials and developing vehicles. The vehicle operated in three individual modes. Figure 5 shows its vehicle operation. The telemetry system operates in two modes.

In the acoustic remote control mode, we can operate the vehicle remotely and retrieve sensors' data with acoustic telemetry. Table 4 shows acoustic telemetry system specifications. It has an acoustic projector and hydrophone. The projector uses 16–24 kHz, the hydrophone detects 8.5–10.5 kHz, and both directivities are 60 degrees conical. Figures 6 and 7 show a projector and hydrophone on the vehicle, respectively. Uplink means communication to the mother ship from the vehicle, and downlink means from the mother ship to the vehicle.

When the mother ship and the vehicle are aligned within a beam, this telemetry system is available. In the uplink, data measured by all sensors such as current temperature, depth, dissolved oxygen (CTDO), navigation and equipment status are transmitted to the mother ship. Further, a TV image of 512×224 pixels in high-resolution mode and 128×112 pixels in low-resolution mode can be transmitted every eight seconds and one second, respectively, and a one-eighth side scan sonar image can also be transmitted. Table 5 shows specifications of the side-scan sonar. Taking into account sea conditions, the uplink modulation coding is selected from among four or eight differential phase-shift keyings, or 16 quadrature amplitude modulations for reliable communication. It sends commands to control the vehicle. Minimum shift keying (MSK)

Fig. 6 Projector on the vehicle (for uplinks).

Fig. 7 Hydrophone on the vehicle (for downlinks).

Table 5 Specifications of the side scan sonar.

Frequency	190–210 kHz (Chirp modulation)
Beam width	1 deg horizontally 60 deg vertically
Transmitting level	210 dB
Repetition	0.75 s at 500 m 0.15 s at 100 m

is unchangeable modulation coding for downlinks.

The vehicle cruised at 3,518 m depth in 2001, a world record for maximum operating depth for an AUV. We had no trouble communicating with the vehicle on that dive.

Telemetry isn't normally necessary in autonomous mode. Working schedules, which include a planned track and observation procedures, are downloaded into the vehicle before a dive, so we do not have to command and follow it in operation. If desired, however, we can change into acoustic remote control mode anytime by sending an acoustic command.

UROV mode uses optical telemetry through a thin optical cable, 1 mm in diameter and 30,000 m in length. A telemetry system in this mode has the same function as an acoustic one, but its communication speed is very high. The optical cable does not restrict vehicle mobility.

2.4. Acoustic TV

An acoustic TV is mounted under the homing sonar on the vehicle's head. It finds obstacles at 100 m in front of the vehicle and sends acoustic images of obstacles and locations to the vehicle computer. It has a 400 mm diameter acoustic lens and a 2D hydrophone array that consists of 128×128 elements. There are many advantages in this acoustic TV over multi-narrow-beam sonar. First, it does not need a circuit to calculate an image to focus on a target, so it is possible to get a 3D, real-time image, and it becomes compact. The vehicle can find obstacles quickly. Second, an acoustic lens concentrates an echo from one target in one hydrophone on the array, so sensitivity increases by focusing the lens. That is, the vehicle can find further objects. Figure 8 shows a frontal picture of the acoustic TV. It has three projectors that have different transmitting frequencies from each other: 400 kHz, 500 kHz, and 600 kHz. We can use not only one frequency according to the situation, we can also use all frequencies, in rotation. Figure 9 and Table 6 show a block diagram and specification, respectively.

Figure 10 is a picture of the target used in a test on a barge. The target is a sheet-like cushion for baggage twisted around a framework shaped like a letter A. The distance between the target and the acoustic TV is about 3 m. Figure 11 is an acoustic image captured by this TV. We can distinguish the shape of the letter A easily.

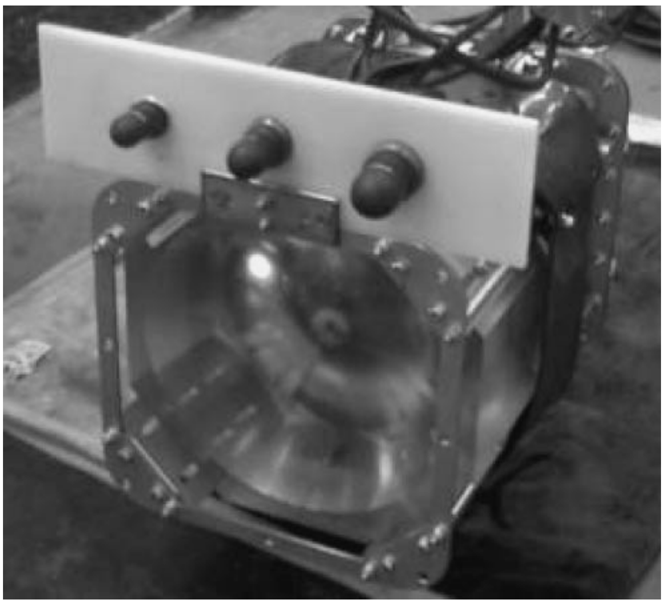

Fig. 8 Acoustic TV.

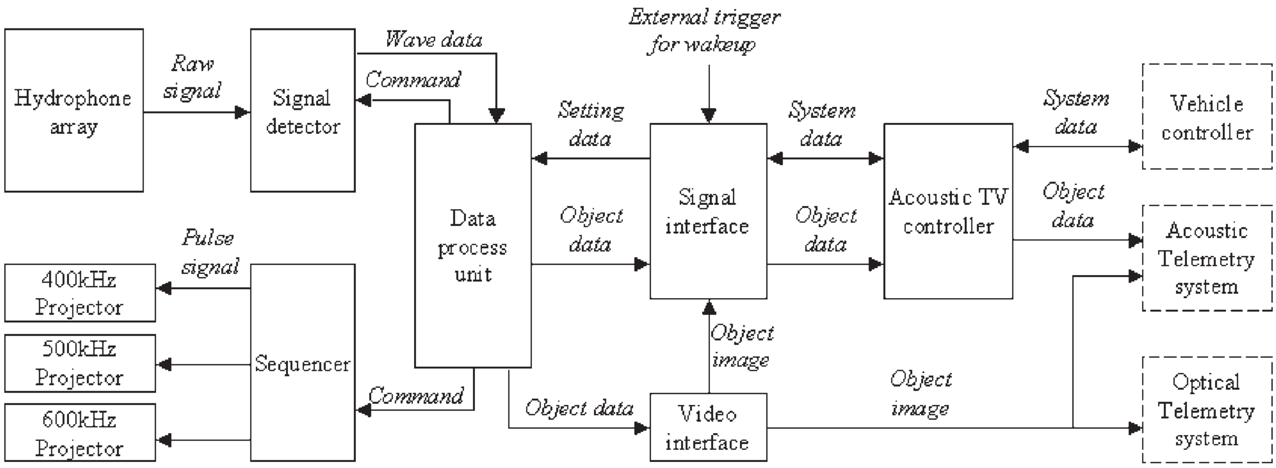

Fig. 9 Block diagram of the acoustic TV.

Table 6 Specifications of the Acoustic TV.

Transmitters	
Frequency	400, 500, 600 kHz
Beam width	60 deg conical
Pulse width	2.5 ms
Ping interval	Min. 200 ms
2D array receiver	
View angle	60 deg conical
Number of elements	128 × 128
Type of elements	Diced piezoelectric ceramics
Acoustic lens	
Material	Acryl resin
Focal length	250 mm
Aperture	400 mm
Angular resolution	1 deg (on axis)
Convergence gain	30 dB (on axis)

Fig. 10 Target letter A.

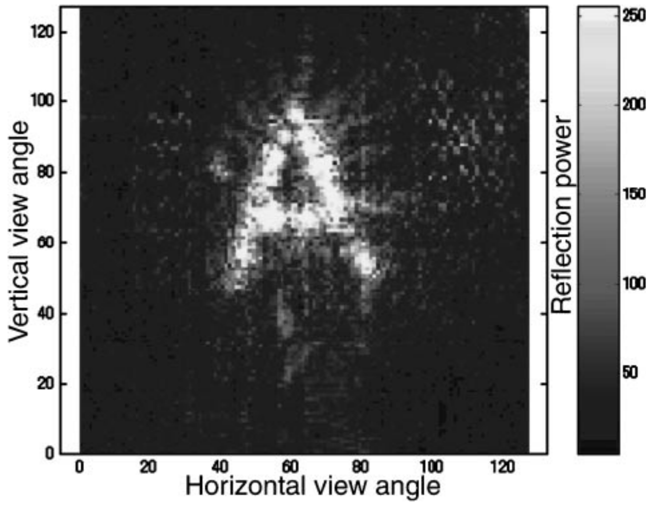

Fig. 11 An image of the target letter A captured by the obstacle avoidance sonar.

3. POWER SOURCE

3.1. Fuel Cell

The vehicle's power source is a fuel cell for long-range cruising [4]. We have used lead acid and silver zinc batteries as conventional power sources for underwater vehicles. As electric capacity increases, however, battery volume and weight also increase, causing underwater vehicles to be large and heavy. Our goal is development of an underwater vehicle that can cruise over 1000 km, so these conventional batteries were of insufficient capacity for cruising such distances. In addition, compact power sources are also convenient to handle. Unmanned vehicles often use acoustic sensors, so it is better for these vehicles to have suppressed acoustic noise as much as possible.

For these reasons, we sought a new kind of power source with high energy density and efficiency, and that generated low acoustic noise. We felt the fuel cell was the

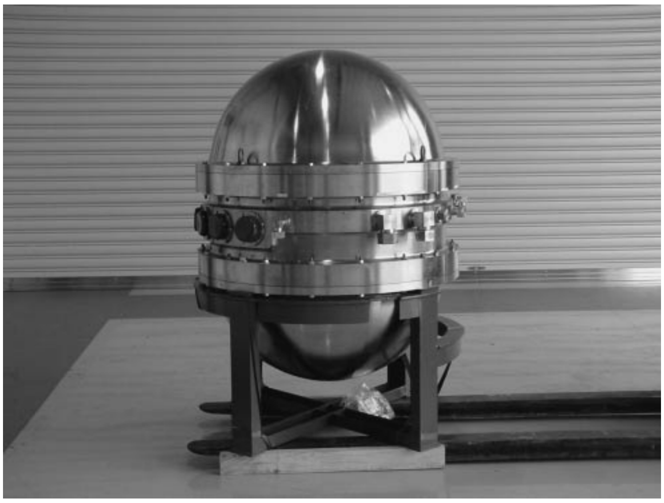

Fig. 12 Titanium alloy canister storing fuel cell stacks and equipment.

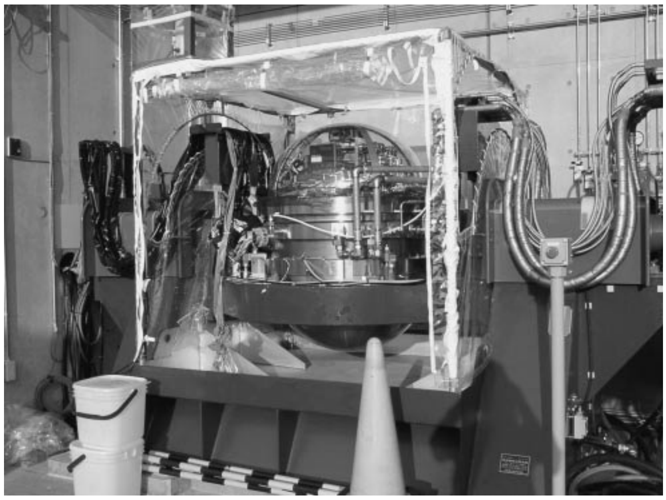

Fig. 13 PEFC on a swing test machine.

best answer. A fuel cell generates electricity with oxygen and hydrogen. Both are light materials, so the energy density relative to weight is high. Moreover, it generates electricity needing only supply of hydrogen and oxygen to a power generation stack. As a result, it is a silent reaction.

The vehicle powered by a Li-ion battery had a 100 km cruising range. After upgrading the power source to a fuel cell, the cruising range increased to 300 km, while allowing the vehicle body to remain slender. Figure 12 shows a picture of the fuel cell.

3.2. Development of a Closed Cycle Fuel Cell for an Underwater Vehicle

JAMSTEC began to develop fuel cells in 1991, and had developed a prototype of a closed cycle fuel cell using a solid polymer electrolyte (PEFC). It developed 1.5 kW capacity in 1993, and 4 kW capacity in 1998. After fundamental testing, vibration frequency testing during power generation had been conducted with an exclusive test device created for this trial. Many load problems occurred, but these were finally cleared in the autumn of 2002. Figure 13 shows the scene of vibration testing. This fuel cell stores generated water in a container.

3.3. Gas Storage

Hydrogen is normally stored in a high-pressure gas tank, but a high-pressure gas tank in a high-pressure environment is undesirable for safety reasons. We had researched several ways to safely store gas underwater, and paid particular attention to storage using metal hydride. Metal hydride is a kind of alloy that can store hydrogen. AB5-type metal hydride absorbs hydrogen under 0°C, stores it at about 25°C, and discharges it at temperatures of over 50°C, in atmospheric pressure. This characteristic makes handling metal hydride at operation temperature simple. Figure 14 shows a picture of metal hydride and its vessel. Figure 15 shows a pressure-composition-isotherms (PCT) curve.

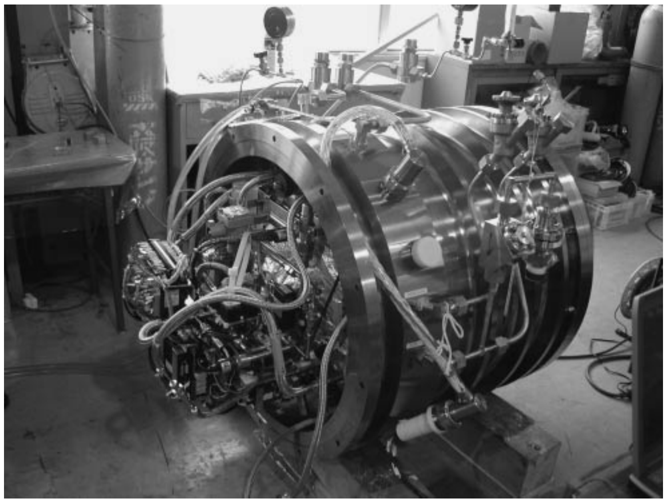

Fig. 14 Titanium Alloy Canister for MH Storage (without the top cover).

In Fig. 15, the temperature at which AB5 type metal hydride discharges hydrogen is higher than the temperature in the general deep sea. This means there is a need for AB5 to be heated in the deep sea. On the other hand, this fuel cell dissipates about 50% of its energy as heat. To solve these problems, the vehicle has a heat-exchange system which uses water as a heat carrier to the metal hydride from the fuel cell. The water is heated by surplus heat from the fuel cell, and the temperature of metal hydride is increased by it.

4. URASHIMA SEAGOING TRIAL

In Suruga Bay, in September 2003, we carried out a seagoing trial and achieved the first autonomous cruise powered by a fuel cell. The vehicle cruised for six hours,

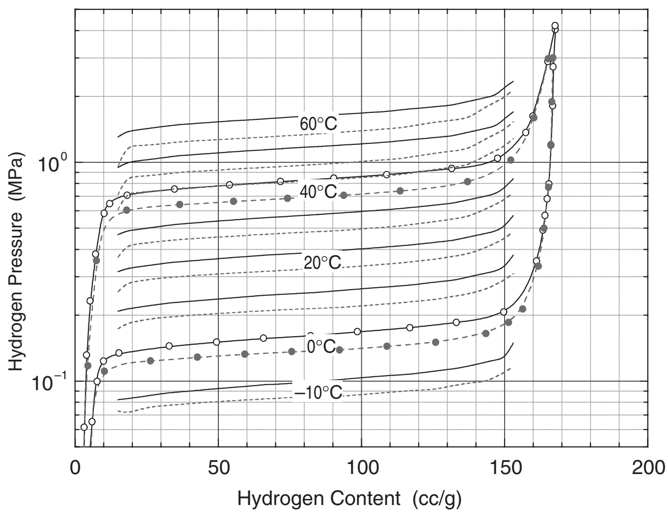

Fig. 15 Metal Hydride AB5-type PCT curve.

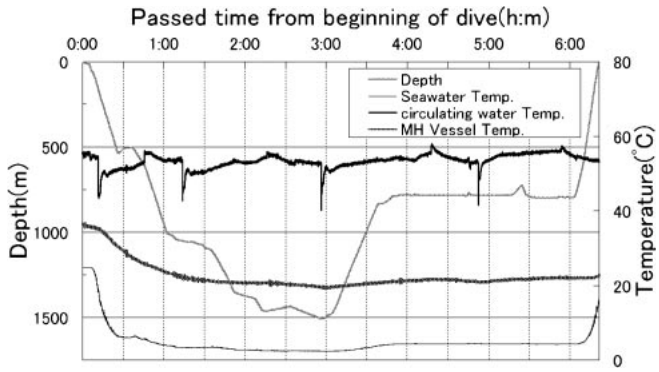

Fig. 16 Depth, temperature of surrounding water, circulated water and metal hydride.

covering 21 km in total. The amount of hydrogen consumption in this trial was 10.9 Nm^3, or about 10% of capacity. The metal hydride was kept at the proper temperature throughout the trial. Figure 16 shows currents at specific depths, temperature of the surrounding waters, circulating water and metal hydride over the trial.

We analyzed depth and a trace of the vehicle at point A in Fig. 17. Figure 18 shows roll, pitch, and heading for 120 seconds around point A, when the heading control system was active. Target heading was set at 270 degrees at the point. We see that the vehicle maintained heading errors under one degree, nor was the vehicle shaking more than one degree in roll and pitch. Figure 19 shows a tracing of the vehicle at point A. The maximum gap in yaw from the regressive line of its tracing is 0.039 m for a 50 m cruise, and 0.145 m for 200 m. These prove the vehicle is quite stable.

We set a simple scenario for autonomous cruising, in which the vehicle would approach point B in Fig. 17 and turn 180 degrees. The vehicle did it safely.

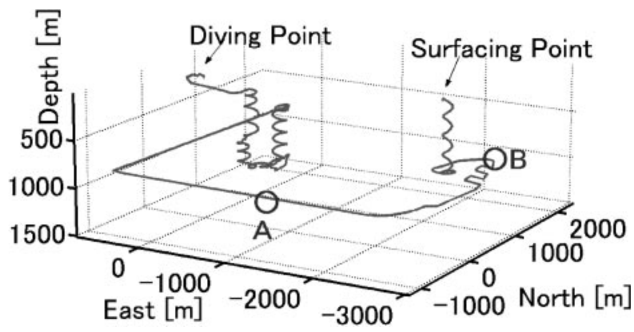

Fig. 17 A tracing of the vehicle in the sea trial.

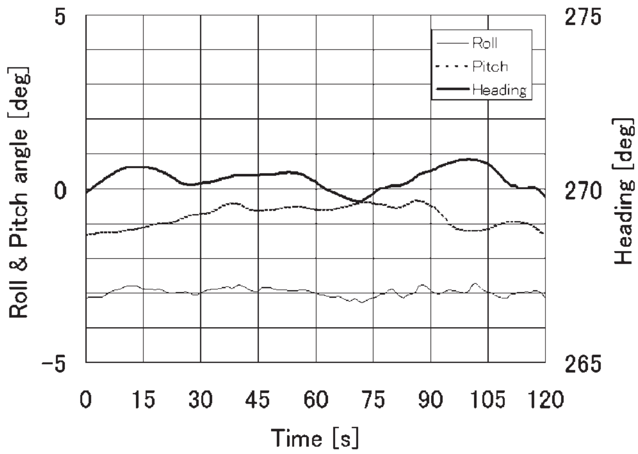

Fig. 18 Depth of the vehicle at point B.

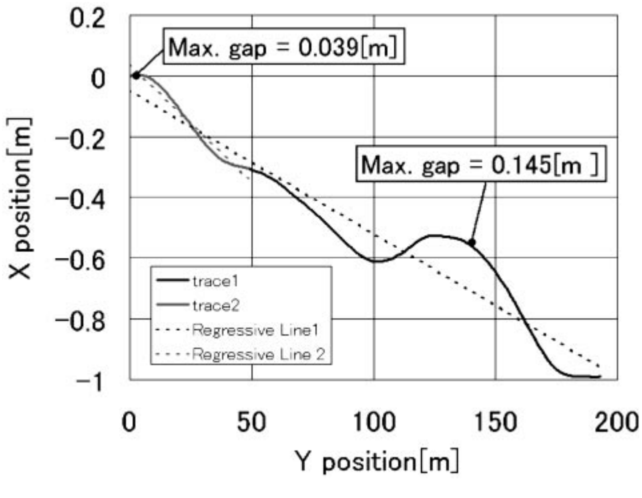

Fig. 19 Route gap of the vehicle at point B.

5. CONCLUSION

The AUV "URASHIMA" was able to reach a target point several hours from the start of its dive. If the vehicle had had no special acoustic devices such as homing sonar and an acoustic telemetry system, its position would be lost and we could not determine its critical conditions. We did not have an opportunity to use the Acoustic TV in this sea trial, but we think it will help the vehicle be successful in mountainous oceans.

We have proved fuel cells are available, instead of conventional batteries such as a Li-ion secondary batteries, for underwater vehicles. We are planning a seagoing trial this year, for an autonomous cruise of over 300 km. If we succeed, it will become another world record — a goal of this project. We will change the project's goal into an investigation and survey after that success, and we will also transform the vehicle into one that is useful and easy for researchers. Through these changes, we will obtain the know-how to build URASHIMA 2.

The distinguished stability of the vehicle will probably open new survey methods. It is confirmed that SAS can get very fine images of targets, such as a small ball 4 cm in diameter, and objects on the bottom of an acoustic tank [5]. SAS needs a highly stable platform to display its performance. According to analysis of the vehicle's route gap, it satisfies SAS stability needs. We will be examining vehicle stability in detail from now on.

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