Development of Fuel Cell AUV "URASHIMA"

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Urashima, the world's first autonomous underwater vehicle powered by fuel cells, recorded a continuous cruising distance of 220 km off the shore of Suruga basin in June 2004. A closed cycle fuel cell system developed by Mitsubishi Heavy Industries, Ltd. (MHI) is installed in the unmanned underwater vehicle, which incorporates various new ideas and technologies. This latest underwater vehicle features a number of novel functions, including acoustic remote control, weight and trim control system, and investigating and observing functions. At the sea trials, these functions have been confirmed together with a power supplying function by fuel cells, autonomous navigation control, and many other outstanding functions.

1. Introduction

In order to investigate the causes of global warming, it is indispensable to gather and analyze ocean data around the north pole. As an effective means of investigating the Arctic Ocean, access to which is difficult, there has been a demand for development of an autonomous underwater vehicle (AUV) capable of cruising long distances.

Urashima, which is a test vehicle for development of AUV, was delivered to the Japan Marine Science and Technology Center (now Japan Agency for Marine-Earth Science and Technology) in March 2000, and MHI has been promoting ocean cruising tests jointly with the Agency. The vehicle, powered by lithium ion rechargeable batteries, recorded the world's deepest dive for an AUV of 3 500 m in August 2001, and marked a cruising distance of 132.5 km in June 2002. In order to enable it to cruise longer distances, the power source was changed to fuel cells. The new "Urashima" was completed in March 2003 as a cruising vehicle having a maximum range of 300 km.

This paper gives an outline and reports on the seagoing test results of the world's first fuel cell-powered AUV Urashima.

2. Construction and application of Urashima system

Urashima is an AUV, and basically does not require support from a mother ship during navigation, but can be accompanied by a mother ship when carrying out observations. The Urashima system is composed of the vehicle and the on-board facilities.

The on-board facilities include the control container accommodating control and monitor panels, power source container, and fuel cell on-board equipment.

Communication between the vehicle and the mother ship is realized by optical or acoustic means under water, long-distance radio at the surface, and radio wave LAN communication on board.

Urashima has three navigation modes: autonomous navigation mode, acoustic remote control mode, and optical communication control mode by optical fiber cable (called untethered remotely operated vehicle mode or U-ROV mode).

The acoustic remote control mode and U-ROV mode are modes of navigation by remote control command from the mother ship, and the means of command of communication in each case is optical communication by optical fiber of small diameter (1 mm in outside diameter) or acoustic means. For acoustic communication, the vehicle must be located within a conical area of ±30 degrees directly below the acoustic transmitter and receiver of the mother ship. The U-ROV mode is mostly used during the period from start of underwater navigation until acoustic communication with the mother ship has been established. This wide variety of communication monitoring functions is one of the special features of Urashima.

3. Main composition of the vehicle

The principal specifications of the vehicle are given in **Table 1**, and its general arrangement is shown in **Fig. 1**.

(1) Structure

The vehicle consists of pure titanium frames, necessary devices and buoyancy materials, and the outside is covered with FRP fairing covers. The buoyancy materials are syntactic foams of specific gravity of 0.5, and are made of tiny hollow glass microballoons of 40 to 100 μm in diameter solidified with resin.

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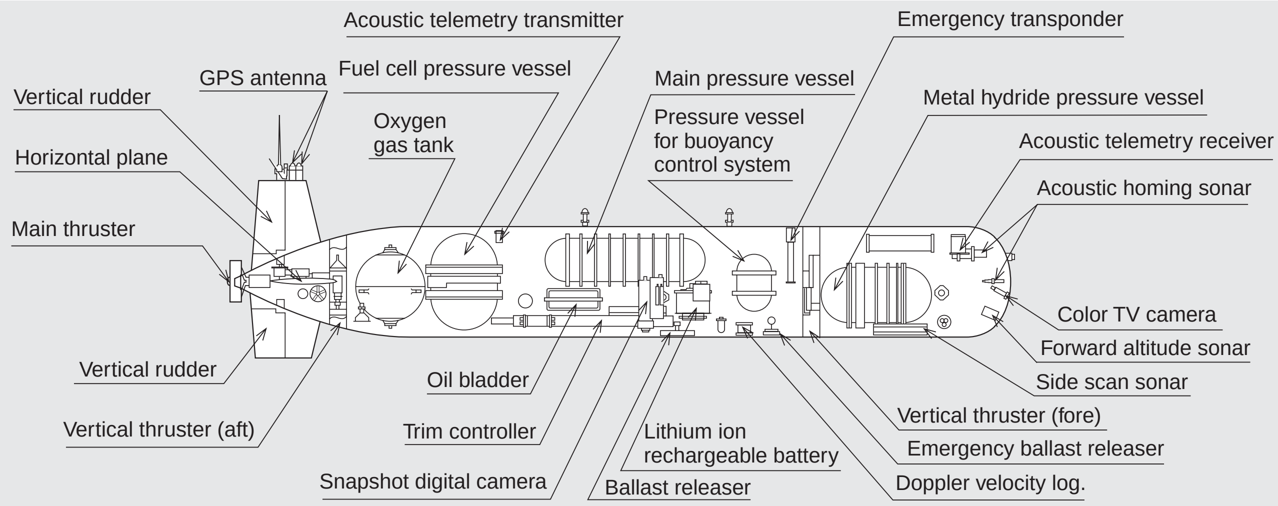

Fig. 1 General arrangement of vehicle
Configuration and layout of the vehicle (side view)

Table 1 Principal specifications of the vehicle

Item	Specification
Type	Autonomous underwater vehicle (AUV)
Overall dimensions (m)	Length x width x height: approx. 10.7 x 1.3 x 1.5
Weight in air (t)	approx. 10
Maximum operating depth (m)	3 500
Maximum cruising range (km)	300
Cruising speed (kt)	approx. 3
Hull system	Trim controller, buoyancy control system, ballast releaser, emergency ballast releaser
Power sources	Fuel cell system - Fuel cell: Polymer electrolyte fuel cell (PEFC), rating 4 kW, 120 V - Oxygen gas tank: internal pressure 14.7 MPa - Metal hydride system Auxiliary power source: lithium ion rechargeable battery for hybrid use
Maneuvering systems	Main thruster 1.8 kW x 1 Vertical thruster 0.6 kW x 2 Horizontal thruster 0.6 kW x 1 Vertical rudder, horizontal plane
Observation systems	TV camera, underwater light, side scan sonar, snapshot digital camera, CTDO, multipoint water sampling device (installed when using lithium ion rechargeable battery as main power source)
Navigation instruments	Inertial navigation system, inclination meter, Doppler sonar, depth meter, altitude sonar, GPS, acoustic homing sonar, forward altitude sonar, acoustic transponder, emergency transponder

(2) Maneuvering systems

Urashima is a cruising vehicle, and is basically designed for straight forward movement. Steering is controlled by the vertical rudder and horizontal plane at the stern. The vertical thruster is used for vertical movement when stopping (hovering).

(3) Weight and trim control system and ballast devices

It is a distinctive feature of Urashima that it has vehicle weight and trim adjusting systems for use during underwater navigation. When Urashima is navigating over long distances, buoyancy balance variation are predicted due to changes in seawater temperature and density. Although the vehicle can be expected to cruise stably even in such conditions by using this system. The fore-aft inclination angle (trim) is adjusted by the trim adjusting device that moves a weight of about 50 kgf by one meter forward or backward. By controlling the oil level contained in the oil bladder, the buoyancy control system can adjust the buoyancy by about 60 kgf. When the mission has been completed for the dive, the vehicle ascend to the surface by dropping the ascent ballasts.

(4) Observation systems

For sea bottom investigations, the vehicle is equipped with a TV camera, a snapshot digital camera, and a side scan sonar. For ocean observation while cruising, various instruments are mounted including a CTDO sensor for continuous measurement of salt concentration, water temperature and dissolved oxygen, and a multipoint water sampling device. The multipoint water sampling device can sample 250 cc of seawater per cell in a total of 200 cells.

4. Fuel cell system

4.1 Fuel cell

The power source used in an underwater vehicle is required to be small in size, light in weight and easy to handle. Urashima uses polymer electrolyte fuel cell (PEFC) system as a power source. As compared with other fuel cells, the PEFC is characterized by a low operating temperature of about 60 to 80°C. Since the temperature is close to normal temperature, it is easy to start and stop, heat insulation measures are possible, and it can be assembled in a small and lightweight system. This fuel cell system and fuel cell stack have been newly developed by MHI to serve as the power source of Urashima. Two stacks are connected in series, and the rated output is 120 V, 4 kW. An outline of the fuel cell system is given in **Fig. 2** and a photograph is shown in **Fig.3**.

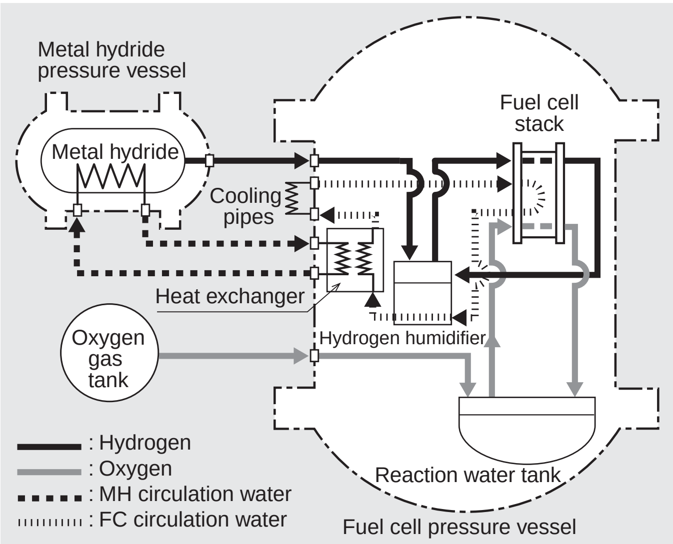

Fig. 2 Block diagram of fuel cell system
Outline and composition of system for gas and circulating water in the fuel cell system of Urashima.

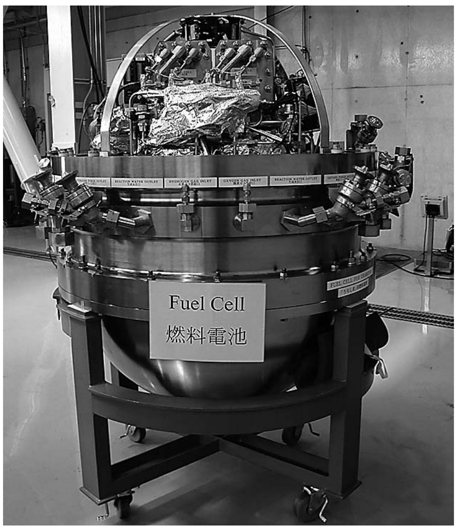

Fig. 3 Fuel cell
Fuel cell system mounted on vehicle's fuel cell pressure vessel

Differing from the land-use system, the fuel cell system mounted on Urashima is a completely closed cycle fuel cell system. Fuel cells are contained in pressure vessels made of titanium alloy, oxygen gas is supplied from a high-pressure (14.7 MPa) oxygen gas tank, and hydrogen gas is supplied as fuel from metal hydride contained in a pressure vessel. Instead of air, pure oxygen is used as the oxidizer, which is also one of the distinctive features of the closed cycle system. The unreacted gas passing through the fuel cell stack is recirculated in the system, and reacted water is collected in a reaction water tank in the fuel cell pressure vessel.

Temperature and humidity control is very important for the PEFC. In the fuel cell stack, circulation water at constant temperature circulates to maintain the operating temperature, and temperature and humidity of the gas line are controlled by heat insulation and heating. In the circulating water line, cooling pipes are provided for releasing heat to the outside of the pressure vessel, and the temperature is kept constant by controlling its flow.

4.2 Metal hydride

To consider safety, hydrogen gas is stored by a storage method using metal hydride. As the metal hydride, AB5 type rare-earth-based alloy is used on account of its excellent absorbing efficiency, and it is capable of absorbing and desorbing in the normal temperature range (20 to 60°C).

Desorbing of hydrogen from the metal hydride is an heat absorbing reaction, and the desportion is controlled by using the waste heat from the fuel cell as the heat source.

Fig. 4 shows an example of gas pressure control of metal hydride in the seawater. As hydrogen gas is consumed, the pressure of the metal hydride drops, but when the pressure drops, the circulating water is passed to raise the temperature of metal hydride, which in turn raises the pressure of the metal hydride. When elevated to the specified pressure, passing of circulating water is stopped. By means of this temperature control, the pressure of the metal hydride is maintained in a range of 0.85 to 0.95 MPaG.

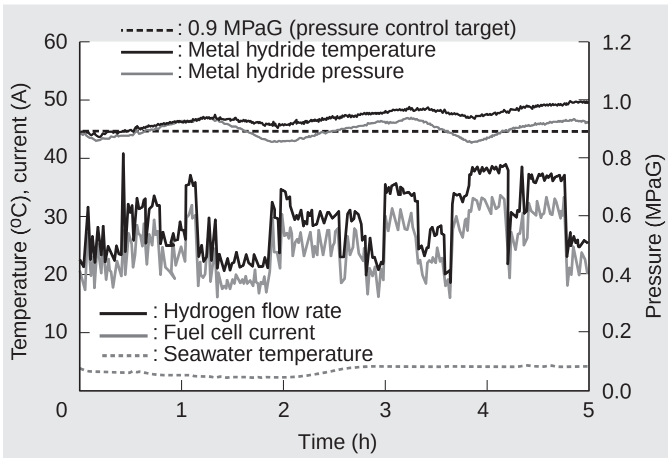

Fig. 4 Pressure control of metal hydride
Gas pressure is kept within a specific range by controlling temperature of metal hydride by means of circulating water.

5. Autonomous control

5.1 System configuration and functions

The configuration of the control system used in autonomous control is shown in **Fig. 5**. The vehicle control system consists of a CPU for calculation and control and a CPU for IO, and is installed in the main pressure vessel. Actuators and sensors of the vehicle are all controlled by the vehicle control system, but the fuel cells and metal hydride are controlled by a dispersal control system having individual control devices in each pressure vessel.

During autonomous navigation, the vehicle is controlled by a predetermined scenario, but optical or acoustic commands from the mother ship can be received whenever necessary. The vehicle is constantly sending data to the mother ship. The vehicle conditions (depth, course, velocity, attitude angle, position, etc.), running conditions of devices and TV image and side scan image can be monitored at all times. At the surface, two-way communication between the vehicle and mother ship is capable by long-distance radio.

5.2 Autonomous navigation function

Autonomous navigation of Urashima is executed according to a predetermined scenario. It is carried out in four hierarchical tasks: (a) supervisory control task, (b) navigation pattern execution task, (c) motion control processing task, and (d) actuator control task.

In the supervisory control task, the execution and progress of the scenario are managed, while in the navigation pattern execution task, execution of the navigation pattern is managed, including change or hold of course, change or hold of depth, etc.

In the motion control processing task, the control command values of the actuators are determined for executing the navigation pattern, and the actuator control task is to drive actuators such as thruster, rudder and trim adjusting devices.

The scenario is written in the sequence of navigation commands, and navigation commands include "Go to specified point," "Correct position by transponder signal," "Cruise at specified depth (altitude), course," "Observe at specified position," and others.

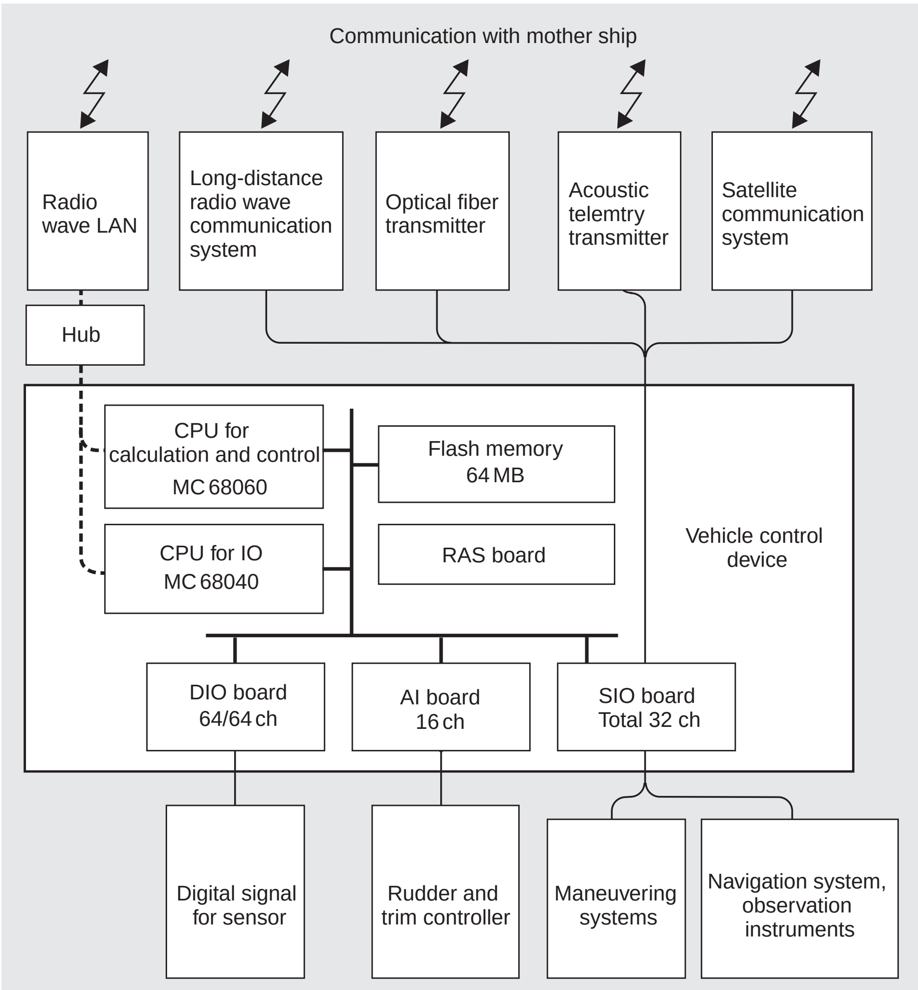

Fig. 5 Control system configuration
Composition and external interface of vehicle control system.

6. Sea trial

A long-distance autonomous cruising test was executed during the period from 9 to 11 June, 2004, to travel back and forth between two points 25 km apart north and south off the shore of Suruga basin. After continuous autonomous navigation of 43 hours at a depth of 800 m and average velocity of about 2.8, the trial was suspended due to an approaching typhoon, but a continuous cruising distance of 220 km was recorded.

During navigation, the fuel cells followed up smoothly to load changes such as variations in vehicle velocity, and operated stably. Supply of hydrogen from the metal hydride was normal, and good overall performance as a fuel cell system was confirmed. **Fig. 6** shows the operation data of fuel cells during the trial.

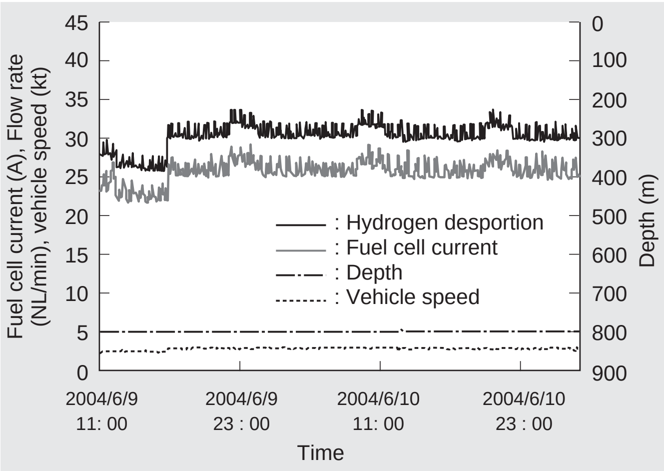

Fig. 6 Operation record of fuel cell
Sea trial data of fuel cell.

In autonomous navigation, two transponders were located in the north and south, and the vehicle traveled back and forth between the two reference points. Usually, a vehicle navigates while ascertaining its position by the inertial navigation system. In case of long-distance cruising under external disturbances of small acceleration components such as tidal currents, the inertial navigation system has dislocation from the actual position by accumulation of errors. To avoid such errors, in Urashima, on the basis of the acoustic transponders preliminarily calculating (calibrating) the location of installation, the position is corrected autonomously by acoustic positioning.

7. Conclusions

We consider it had been sufficiently confirmed that the fuel cells are useful as an underwater power source at the sea trial in June. During continuous navigation for 43 hours, the autonomous control system operated normally, and the vehicle cruised exactly according to the scenario.

In concluding this paper, we express our deep gratitude to the staff members of the Japan Agency for Marine-Earth Science and Technology for their kind support and advice from the initial stage of development of Urashima and fuel cells system for the underwater vehicle.

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