Development of a Human-Sized ROV with Dual-Arm

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Abstract— **In this paper, we describe the development of a human-sized remotely operated vehicle (ROV) with dual-arm. The developed ROV was designed to perform biological researches, geological researches and archaeological explorations in Lake Biwa, the biggest lake in Japan. This ROV has two distinguishing characteristics: one is a dual-manipulator system and the other is an attitude control system. The size of the manipulators is related to the size of a human arm so that the ROV can do work that human divers usually do using the arms. The attitude control system is capable of keeping the vehicle in a horizontal plane, and purposely changing the vehicle attitude angle. Additionally, we developed a new master-slave controller system for this ROV.**

Some fundamental experiments in a diving pool were performed in order to test the capabilities of the developed ROV. After those experiments, a field trial was conducted in Lake Biwa and the ROV carried out some works at a depth of about 10–20 meters.

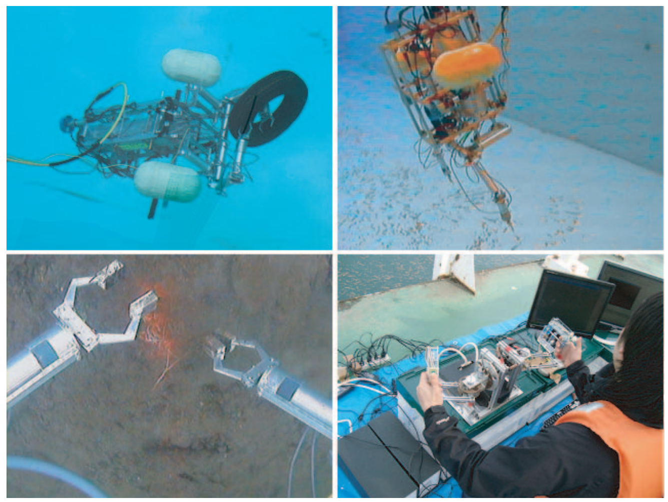

Fig. 1. A human-sized ROV with a dual-manipulator system we have developed. Top left: Removal of an old tire from a diving pool. Top right: ROV is facing downward. Bottom left: Lake bottom (taken by the vehicle camera). Bottom right: A master-slave controller for our ROV.

I. Introduction

Remotely operated vehicles (ROVs) are very important tools for scientific research[1][2] and industry. Large ROVs are capable of having large and multi-degrees of freedom (DOF) manipulators to realize various underwater operations. However, the operations and maintenances of these large ROVs are expensive for a number of laboratories, companies and organizations. Although the power and capabilities of small ROVs are limited, they are cheaper and easy to operate compared to large ROVs. For these reasons, use of a small ROV is required in many situations[3].

Some of small ROVs have a manipulator in order to pick up underwater objects. However, the manipulators of them are generally small and have few DOF. It is often difficult for a user to grasp an object by use of such a manipulator.

This research aims to increase the capability of a small ROV and makes it possible for a small ROV to execute various underwater operations by use of its manipulators. The developed ROV in this paper has two distinguishing characteristics: one is a dual-manipulator system and the other is an attitude control system. The size of the manipulators is related to the size of a human arm and the ROV enables to do work that divers usually do using the manipulators. The developed ROV has also an attitude control system because the motion of these manipulators affects the vehicle attitude. Some attitude control systems have been proposed for underwater vehicles[4]-[6]. In this paper, we propose an attitude control system based on changing of the center of buoyancy with respect to the center of gravity[9]. Additionally, a master-slave controller system was newly developed for our ROV. Using this controller, one operator can control all DOF of the developed ROV.

In this paper, we present the development of a human-sized ROV with a dual-manipulator system as shown in Fig.1. This ROV was designed to perform biological researches, geological researches and archaeological explorations in Lake Biwa, the biggest lake in Japan. In Lake Biwa, an Autonomous Underwater Vehicle (AUV) "TANTAN" has been already utilized for environment monitoring[7],[8] by the Lake Biwa Environmental Research Institute. Unlike monitoring, the main operations of our ROV are sampling operations and contact tasks on underwater objects by use of its manipulators.

The outline of this paper is the following: the hardware design of our ROV is presented in section 2; the details

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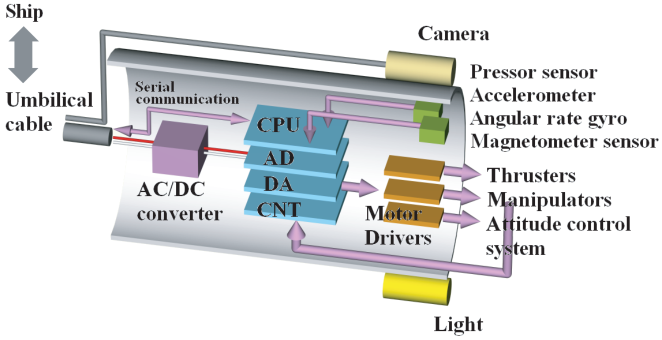

Fig. 2. System configuration

of an attitude control system are described in section 3. A master-slave controller for the developed ROV is explained in section 4. Section 5 presents several experiments in a diving pool to test the capabilities of the ROV. Section 6 shows the result of a field trial that was conducted in February 2010 in Lake Biwa.

II. ROV Design

We have newly designed a ROV to execute various underwater operations. This section describes the hardware design of our ROV.

A. Vehicle

The ROV including a dual-manipulator system and an attitude control system weights about 56 [kg] (in air), and is about 1.4 [m] long, 0.7 [m] wide, and 0.6 [m] tall when the manipulators are located in front of the vehicle. Six 80 [W] thrusters generate the propulsion for the ROV.

Fig. 2 shows the system configuration. A main pressure housing contains a PC/104 CPU module (650[MHz]) running the Linux operating system, D/A converters, encoder counter boards, A/D converters, motor drivers, accelerometer, angular rate gyro, magnetometer, and pressure sensor. The D/A converters and the motor drivers drive the thrusters, the manipulators and the attitude control system. The encoder counter boards read the encoder pulses of the manipulators and the attitude control system. The A/D converters are used for data acquisition of some sensors.

A CCD camera and a LED light are mounted on the front of the ROV. Power and serial communication are provided through an umbilical cable from a ship.

B. Manipulators

This ROV has two manipulators and each manipulator weighs about 5.5 [kg] in air and 3.6 [kg] in water. As shown in Fig. 3, each manipulator has four rotational joints (4 DOF) and a 1 DOF gripper hand. Harmonic drive motors inside waterproof cylindrical links actuate these joints and the grippers and the motor shaft is sealed with O-rings. Each motor has a gear head and an optical encoder for positioning the angle. Tab. I shows the main specifications of the manipulators and motors. The maximum velocity of the end-effector is about 1.0[m/s]. Each manipulator can hold a 1.4 [kg] object underwater.

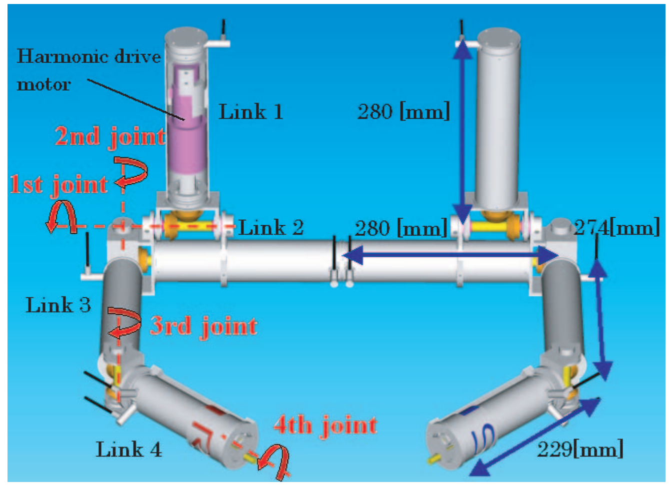

Fig. 3. Human-sized manipulator

TABLE I
Specifications of manipulator and actuators

	Link 1	Link 2	Link 3	Link 4
Link length [m]	0.280	0.280	0.274	229
Link diameter [m]	ϕ 0.055	ϕ 0.055	ϕ 0.050	ϕ 0.050
Link mass [kg]	1.73	1.74	1.12	1.01
Rated output [W]	18.5	18.5	12.3	1.4
Rated torque [N]	5.9	5.9	3.9	0.29
Rated revolution [rpm]	30	30	40	44
Resolution [Pulse/rev]	1000	1000	1000	360
Gear ratio	1:100	1:100	1:100	1:100

As illustrated in Fig. 3, the size of the manipulators is according to the size of human arms. 20 percent of the total weight is attributable to the manipulators. Therefore, it is difficult to maintain static stability and regulate the attitude of the ROV. To overcome such a difficulty, we have developed an attitude control system[9]. The details of the attitude control system are described in next section.

III. Attitude control system

We have proposed the attitude control system[9] based on changing of the center of "Buoyancy" with respect to the center of "Gravity". The proposed system is called a "BG system" in this paper because of the above reason. The changing of the center of buoyancy is accomplished by changing position of movable float blocks. In this section, we explain the availability of a BG system, derive the static model of a ROV with a BG system, explain how to control a vehicle attitude based on the model, and design a BG system for the developed ROV. The BG system plays an important role in keeping and changing the vehicle attitude.

A. Availability of BG System

The BG system[9] is useful not only for attitude maintenance but also for attitude change control of our ROV. This attitude control system makes it possible for the ROV to execute various underwater operations.

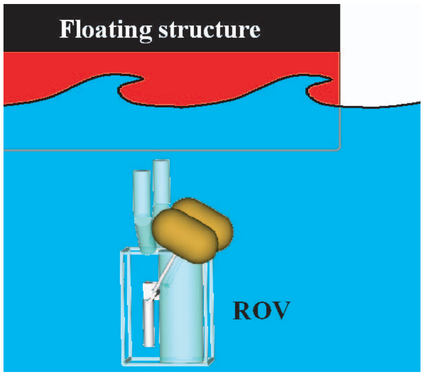

Fig. 4. Application example of BG system (1)

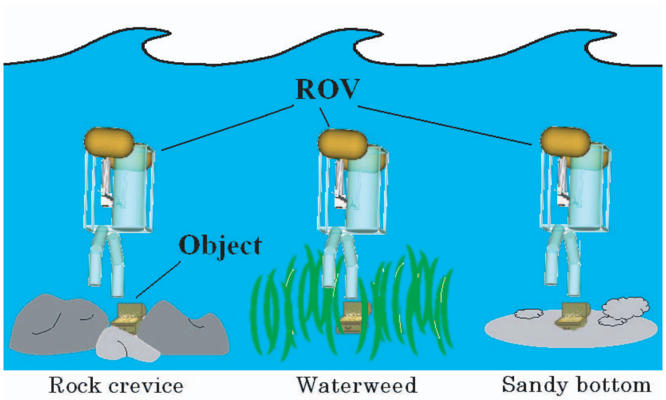

Fig. 5. Application examples of BG system (2)

As depicted in Fig. 1, the developed ROV removes an old tire from a diving pool. Since the vehicle is able to change the pitch angle by using the BG system, it is easy for an operator to control the ROV. Without the BG system, the vehicle would naturally pitch downward and would become unable to move straight ahead. The BG system can be also used for inspection of the bottom of floating structures as shown in Fig. 4.

Besides the above applications, the BG system is important in conducting research on Lake Biwa. Application examples of the system are depicted in Fig. 5. The ROV can reach into a rock crevice and grasp an object while facing downward (Fig. 5 (left)). Fig. 5 (middle) shows that the vehicle keeps its thrusters as far away from waterweed as possible to prevent the propellers from being fouled by waterweed. In the same way, the ROV avoids kicking up sand from the bottom by its thrusters as shown in Fig. 5 (right).

B. Static Model and Control

Here, we derive the static model of a ROV with a BG system, and explain how to control a vehicle attitude based on the model.

Let a body-fixed reference frame be attached to a vehicle, as indicated in Fig. 6. Here, the center of gravity and the center of buoyancy of the vehicle are respectively defined as $\boldsymbol{r}_{Vg}$ and $\boldsymbol{r}_{Vb}$ in the body-fixed frame. Similarly, the center of gravity and the center of buoyancy of the manipulators

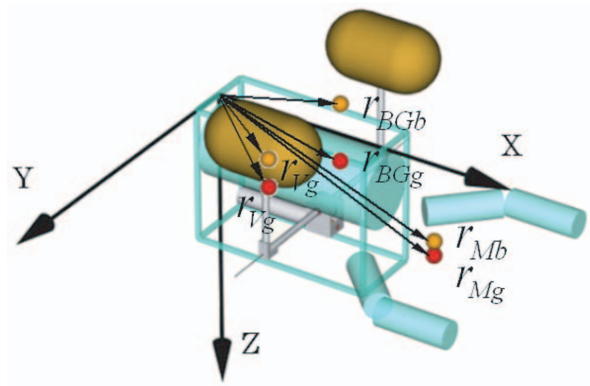

Fig. 6. Body-fixed reference frame

are respectively defined as $\boldsymbol{r}_{Mg}(\boldsymbol{\theta}_M)$ and $\boldsymbol{r}_{Mb}(\boldsymbol{\theta}_M)$ in the body-fixed frame, where $\boldsymbol{\theta}_M$ is the vector of joint variables of the manipulators. Namely, the center of gravity $\boldsymbol{r}_{Mg}$ and buoyancy $\boldsymbol{r}_{Mb}$ are functions of the joint variables of the manipulators.

The center of gravity and buoyancy of the proposed BG system are described, respectively, as $\boldsymbol{r}_{BGg}(\boldsymbol{\theta}_{BG})$ and $\boldsymbol{r}_{BGb}(\boldsymbol{\theta}_{BG})$. The center of gravity $\boldsymbol{r}_{BGg}$ and buoyancy $\boldsymbol{r}_{BGb}$ of the BG system are functions of the independent coordinate vector $\boldsymbol{\theta}_{BG}$ of the BG system.

Based on the definitions given above, the center of gravity $\boldsymbol{r}_g$ and buoyancy $\boldsymbol{r}_b$ of the entire system can be described as

$$\begin{aligned}
&\boldsymbol{r}_g(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M) \\
&\quad = \frac{G_V \boldsymbol{r}_{Vg} + G_{BG} \boldsymbol{r}_{BGg}(\boldsymbol{\theta}_{BG}) + G_M \boldsymbol{r}_{Mg}(\boldsymbol{\theta}_M)}{G_V + G_{BG} + G_M}, \quad (1)\\
&\boldsymbol{r}_b(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M) \\
&\quad = \frac{B_V \boldsymbol{r}_{Vb} + B_{BG} \boldsymbol{r}_{BGb}(\boldsymbol{\theta}_{BG}) + B_M \boldsymbol{r}_{Mb}(\boldsymbol{\theta}_M)}{B_V + B_{BG} + B_M}, \quad (2)
\end{aligned}$$

where the weight and buoyancy force of the vehicle are respectively defined as G_V and B_V, those of the manipulators alone are defined as G_M and B_M, and those of the BG system alone are defined as G_M and B_M.

Consequently, the center of gravity $\boldsymbol{r}_g$ and buoyancy $\boldsymbol{r}_b$ of the entire system are functions of the vectors $\boldsymbol{\theta}_M$ and $\boldsymbol{\theta}_{BG}$.

The above values can be easily estimated from the weights and volumes of the components of a ROV.

If a desired pitch angle of a vehicle is given as an angle θ about the y axis as shown in Fig. 7, then the vector $\boldsymbol{\theta}_{BG}$ can be analytically or numerically calculated to satisfy the following equation.

$$\tan\theta = -\frac{r_{gx}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M) - r_{bx}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M)}{r_{gz}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M) - r_{bz}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M)}, \quad (3)$$

Then a desirable position of the movable float blocks of the BG system is determined.

Similarly, a desirable position of the float blocks can be determined in order to control a roll angle of a vehicle[9].

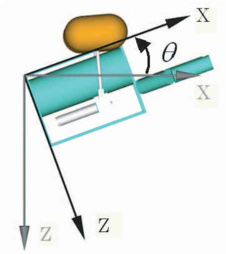

Fig. 7. Pitch angle control

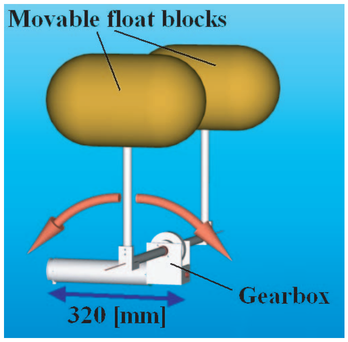

Fig. 8. BG system

TABLE II
SPECIFICATIONS OF BG SYSTEM

Link length [m]	0.280
Link diameter [m]	ϕ 0.055
Link mass [kg]	1.73
Rated output [W]	20.3
Rated torque [N]	3.2
Rated revolution [rpm]	60
Resolution [Pulse/rev]	1000
Gear ratio (Gear head)	1:50
Gear ratio (Gear box)	1:15

C. Design of BG System

The BG system that was developed as a test model comprises a harmonic drive motor (gear ratio 1:50) inside a watertight cylinder, a gearbox (gear ratio 1:15), and movable float blocks as shown in Fig. 8. The specifications of the motor and the gearbox are listed in Tab. II. The angular velocity of the movable float blocks is about 25 [deg/s]. The float blocks are made of a pressure tight co-polymer foam and have 35 percent of its total buoyancy force. This test model provides pitch torque to the vehicle.

IV. MASTER-SLAVE CONTROLLER

It is generally difficult for an operator to control our multi-DOF ROV (this ROV totally has 17 actuators; 6 thrusters, 8 manipulator's joints, 2 grippers and 1 attitude control actuator). We developed a new unilateral master-slave controller system for our ROV. The system comprises a master-slave controller, a monitor and a small PC. The developed controller has a multi-DOF manipulator-like structure because an operator can intuitively control the multi-DOF manipulators of the ROV. This controller has 10 DOF that is equal to the total number of DOF of the manipulators. Moreover, two small joysticks are mounted on the controller to control the vehicle motion as shown in Fig. 9. Each joystick has a push botton to control the pitch angle of the ROV (the BG system).

This controller is about 0.3 [m] long, 0.3 [m] high, 0.6 [m] wide, and weights 5 [kg]. The entire controller system is compact size and is designed to set up and use in any small ships.

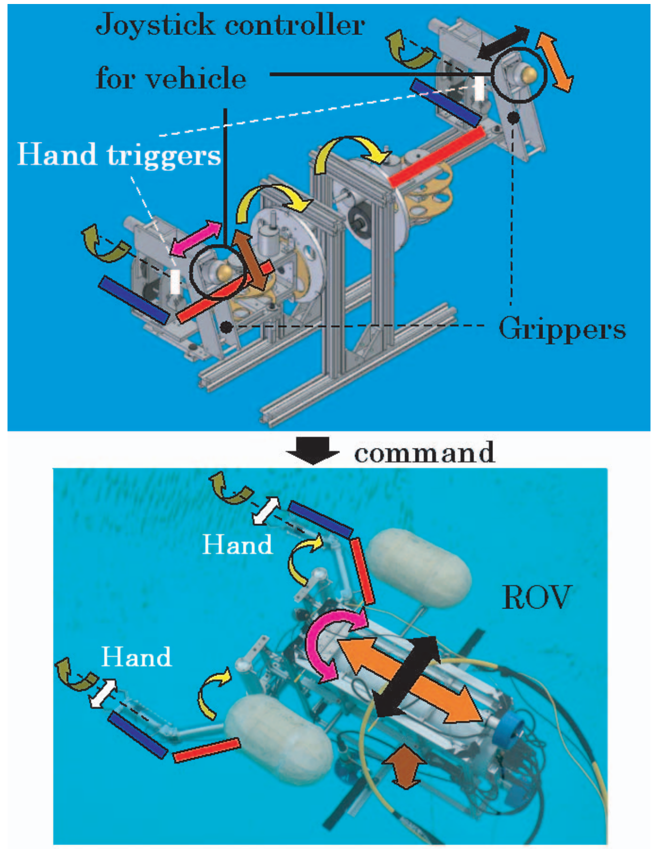

Fig. 9. Unilateral Master-Slave Controller

V. FUNDAMENTAL EXPERIMENTS

In order to test the capabilities of our ROV, several experiments were performed in a diving pool (which is 5 [m] deep).

This ROV has two modes; in the first mode, its manipulators are located on both sides of the vehicle when cruising underwater, as presented in Fig. 10. In the other mode, the manipulators are located in front of the vehicle to support work underwater, as shown in Fig. 11.

One of the tests was a typical operation, where the developed ROV picked up an underwater object. In this test, a metallic cup was chosen as the object so that it was easier for an operator to find it and it was easier for the ROV to grip it. Fig. 12 shows an image captured by a vehicle camera and an image captured by a camera set in the pool.

Another test was that the ROV held a ladder using its two manipulators. As shown in Fig. 13, the vehicle approached the ladder and the left manipulator grasped it first, and the right manipulator subsequently grasped it. This demonstration simulates a docking for a floating structure or a stationary measuring system in Lake Biwa.

Subsequently, we investigated the performance of the developed BG system. Using the BG system, the ROV was able to change the pitch angle between -75 and +105 [deg] as portrayed in Fig. 14. The vehicle was initially facing downward; the vehicle was facing upward in the end.

Fig. 15 depicts a demonstration that the ROV removes an old tire from a diving pool. After the ROV held the tire,

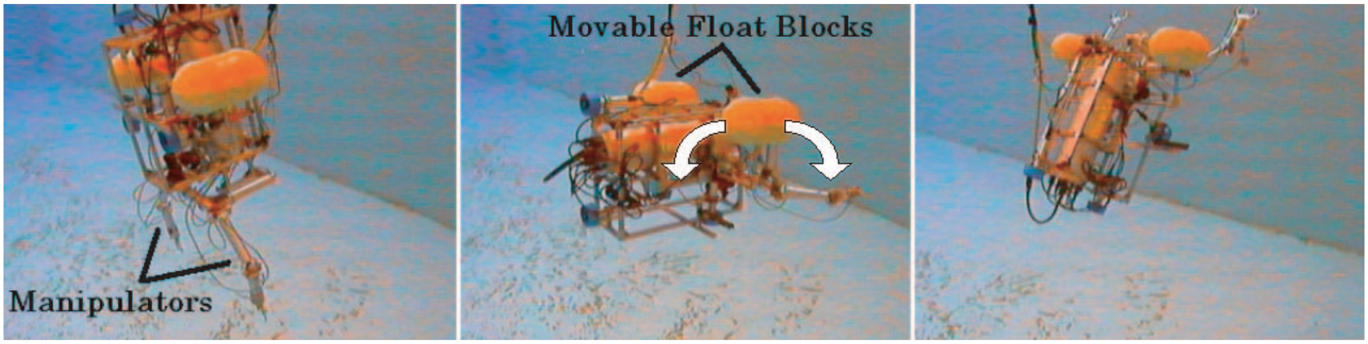

Fig. 14. Attitude Control by the BG system

an operator changed the pitch angle of the ROV using the BG system. For that reason, it was easy for the operator to control the ROV. Without the BG system, the vehicle would naturally pitch downward and would become unable to move straight ahead. In such a case, it might be difficult for the operator to control the vehicle.

As the other demonstration, shown in Fig. 16, the operator inspected the bottom of a boat using the ROV. During the inspection, the ROV was made to face upward. This demonstration simulates an inspection of a floating structure.

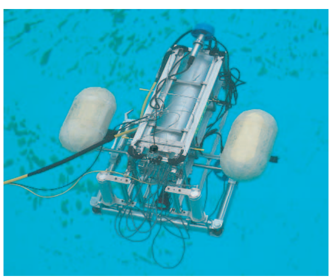

Fig. 10. Move-Mode

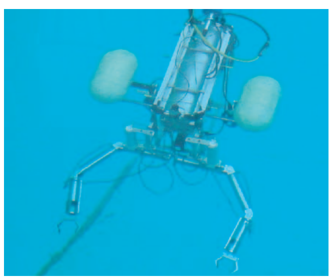

Fig. 11. Arm-Mode

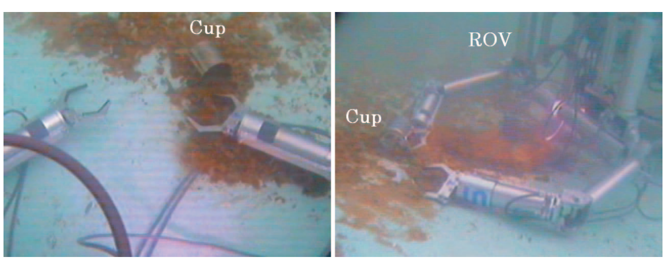

Fig. 12. Picking up a cup

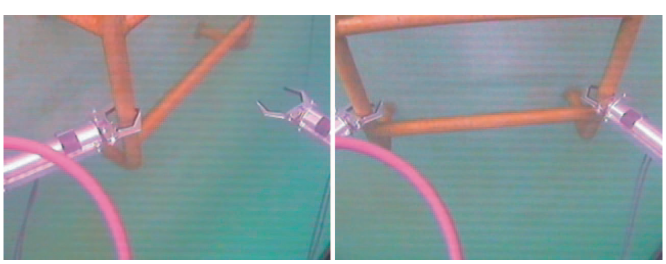

Fig. 13. Grasping a ladder

Fig. 15. Removing an old tire

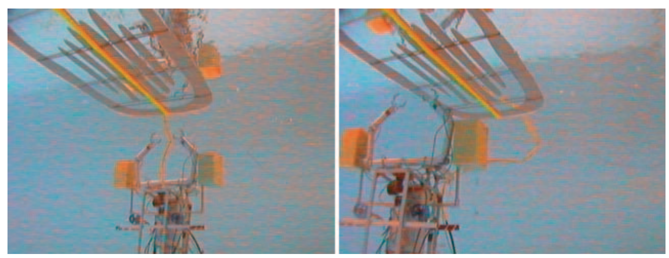

Fig. 16. Inspection of the bottom of a small boat

VI. Field Work

A field trial in Lake Biwa was conducted in February 2010 in order to test the capabilities of the developed ROV. Takeshima island as illustrated in Fig. 17 was chosen for the trial area because the area around the island is surrounded by steep slopes and the depth changes from a few meters to 30 meters.

The ROV was launched from a small boat *YURICAMOME* (Biwako Kisen Steamship Co., Ltd.) as shown in Fig. 18. An operator was controlling the ROV in the boat while watching a monitor screen, which displayed the video image from the vehicle camera.

First, some operating tests of the vehicle, the manipulators and the BG system were carried out near the surface. Then, the ROV dived to depths of around 18 meters and swam across the bottom of the lake. During the diving test, the operator used the manipulators to sample waterweed as shown in Fig. 19

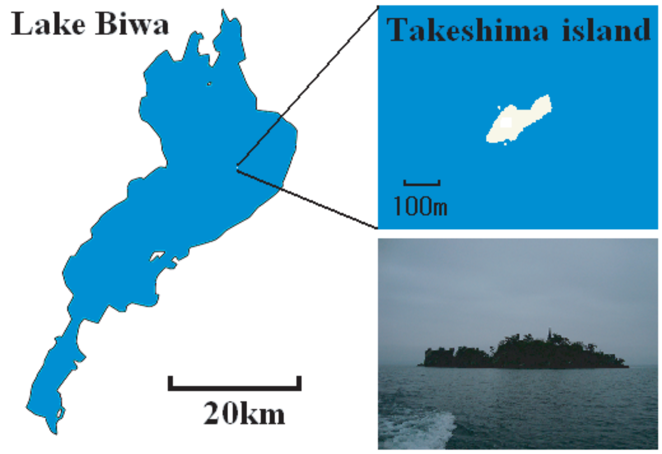

Fig. 17. Lake Biwa and Takeshima island

Fig. 18. Field trial in Lake Biwa

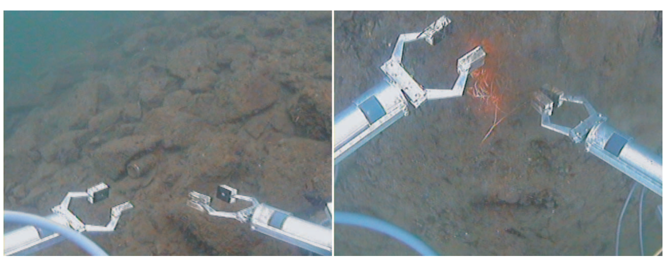

Fig. 19. Bottom of Lake Biwa

VII. Future Work

Our project has only just been started. We continuously increase the capability of the ROV.

One of our interests is to realize sophisticated manipulation and handling with environment recognition sensors. The other interest is to achieve automatic sensory feedback control by using the BG system even if the ROV holds an unspecified object. For the master-slave controller system, we plan to measure and quantitative analyze human characteristics.

Future trials at several locations on Lake Biwa are planned to demonstrate the ROV's capability.

VIII. Conclusion

We developed a Human-sized ROV with a dual-manipulator system in order to be useful for research on Lake Biwa, the biggest lake in Japan. The developed ROV is equipped with two 5-DOF manipulators to achieve various underwater works. The attitude control system mounted on the ROV is capable of keeping the vehicle in a horizontal plane, and changing the vehicle attitude due to a variety of circumstances. Using the developed master-slave controller, one operator can control the ROV including the dual-manipulator system and the attitude control system.

This ROV has been tested with several experiments in a diving pool, and a field trial in Lake Biwa. Results show that the developed ROV is promising for research activities on Lake Biwa. We plan to conduct future trials at several locations on Lake Biwa.

Acknowledgment

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