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An Attitude Control System for Underwater Vehicle-Manipulator Systems

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Abstract— **As described in this paper, we propose an attitude control system for underwater vehicle/manipulator systems (UVMSs) based on control of the position of the center of buoyancy with respect to the center of gravity. Control of the center of buoyancy is accomplished using movable float blocks. The attitude control system is useful to control the pitch angle of UVMSs to enhance their performance and to improve their efficiency of underwater operations.**

A UVMS that has two 5-degree-of-freedom (DOF) manipulators was developed to verify the effectiveness of the proposed attitude control system. This paper presents a numerical study and some experimental results obtained using the UVMS with the attitude control system. We experimentally confirmed that the proposed system can change the pitch angle of the vehicle between -120 and $+105$ deg. In another experiment, attitude-maintenance control was conducted. Results show that the proposed system can maintain the vehicle's horizontal attitude during motion of the manipulators.

I. INTRODUCTION

The advantages of using small UVMSs include their low cost, efficiency, safety, and wide range of application. Some major applications of small UVMSs include inspection of underwater structures, environmental monitoring, studies of marine biology, and archaeological exploration.

However, using small UVMSs presents some disadvantages. For example, the attitude of small UVMSs easily becomes unstable because of their low static stability arising from the short distance between their centers of gravity and buoyancy[1]. Their static stability is even further reduced when a manipulator moves or when a manipulator holds a payload. For these reasons, conservative hardware design has been used such that the weight of manipulators is small with respect to the weight of vehicles. Such design is intended, to the greatest degree possible, to prevent the centers of gravity and buoyancy from destabilizing or moving the vehicle.

This problem persists as a challenging topic in the development of small UVMSs. In this paper, to increase the static stability of small UVMSs, we propose an attitude control system based on position control of the center of buoyancy with respect to the center of gravity.

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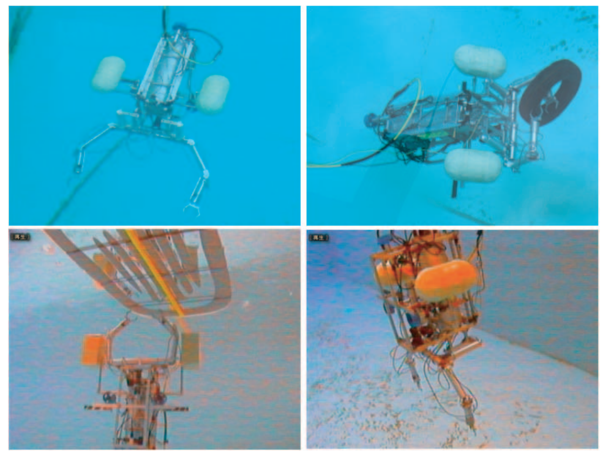

Fig. 1. Top left: A small UVMS ”CoCo dexterity” with an attitude control system we developed. Top right: Removal of an old tire from a diving pool (demonstration). Bottom left: inspection of the bottom of a boat while the UVMS is facing upward (demonstration). Bottom right: UVMS is facing downward.

Several researchers have developed underwater gliders that are steered by changing the position of the center of gravity with respect to the center of buoyancy[2]–[4]. The mechanism to achieve this change is achieved by weight(s) inside the gliders; it is used as a propulsion device. Other researchers have applied this mechanism to underwater vehicles[5]. Some researchers[7] have proposed an attitude adjusting device inside an ROV based on the changing the position of the center of gravity. Using computer simulations, they investigated a sliding mode controller for the device to maintain the vehicle's attitude.

In other approaches, Remotely operated Television Vehicles (RTVs) such as N-100EXY[6] have coinciding centers of gravity and buoyancy. Such a coincidence makes it possible to change the RTV attitude easily using thrust forces. However, when the manipulator holds a payload, such RTVs lose static stability and become difficult to control; it is difficult even to maintain the vehicle attitude. Another study[1] specifically examines estimation of physical-hydrodynamic parameters of a manipulator. Feedforward control based on the parameters is experimentally executed to maintain the vehicle attitude using thrust forces during the motion of the manipulator.

An attitude control system we propose in this paper is useful not only for attitude maintenance but also for

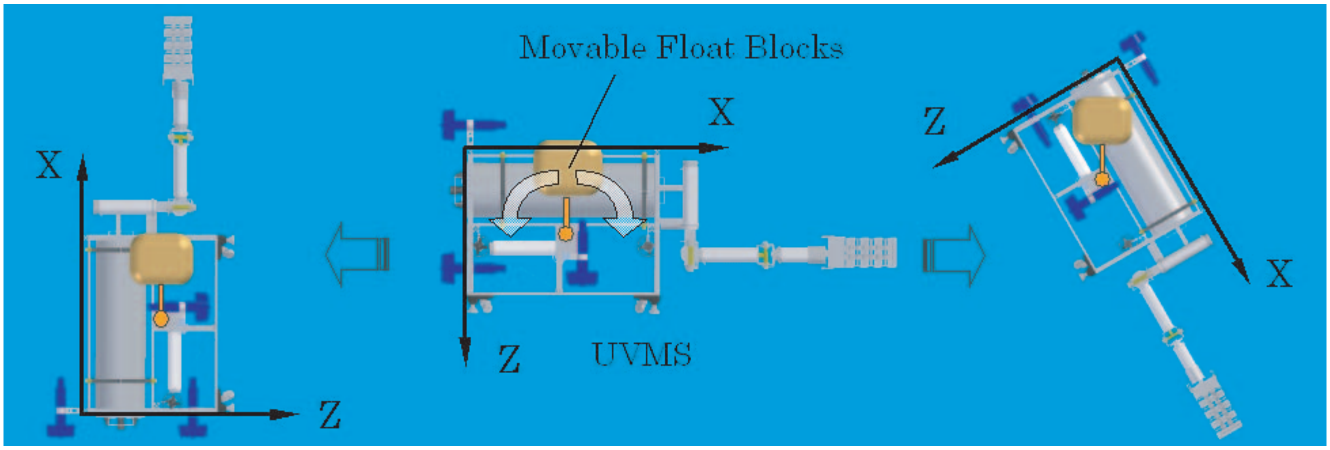

Fig. 2. Attitude Control System (BG system)

attitude change control even if the weight of manipulators is large with respect to the vehicle weight. For this study, we developed a UVMS that weighs about 56 [kg] (in air) including 11.2 [kg] (in air) of two manipulators. In fact, 20 percent of its total weight is attributable to the manipulators. Therefore, it is difficult to maintain static stability and regulate the attitude of the UVMS during underwater operations using the hardware design approaches described above. The proposed system for UVMSs is based on position control of the center of buoyancy. Control of the center of buoyancy is accomplished using movable float blocks. To verify the effectiveness of the proposed attitude control system, we developed an UVMS that has two 5-DOF manipulators, as depicted in Fig. 1. The UVMS with the proposed system installed can change the pitch angle between -120 and $+105$ deg, as described in the experiments of section 5.

Figure 1 shows that the proposed attitude control system makes it possible for UVMSs to execute widely various underwater operations. The proposed system presented in this paper is called a "BG system" because the system controls the center of "Buoyancy" with respect to the center of "Gravity".

The outline of this paper is the following: development of the UVMS with the attitude control system (BG system) is presented in Section 2; and the capabilities of the BG system are discussed theoretically in Section 3. Based on the discussion presented in Section 3, a numerical simulation was conducted to test the performance of the proposed system. It is described in Section 4. Section 5 presents several experiments that were done in a diving pool using the UVMS to test the effectiveness of the proposed system. The results show that the proposed system is promising for use in attitude control of UVMSs.

II. UVMS WITH BG SYSTEM

The UVMS we developed has two 5-DOF manipulators and an attitude control system, as portrayed in Fig. 1 to execute widely various underwater operations.

The weight of the UVMS including the manipulators and the BG system is about 56 [kg] and the size 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. Each manipulator weighs about 5.5 [kg] (in air) and has four rotational joints (4 DOF) and a 1-DOF gripper. Harmonic drive motors inside waterproof cylindrical links actuate these joints and the gripper. Each motor has an optical encoder for positioning the angle. The size of the manipulators is related to the size of a human arm to enable the UVMS to do work that divers usually do. Actually, 20 percent of the total weight is attributable to the manipulators. Therefore, the BG system plays an important role in attitude control.

The BG system that was developed as a test model in this research comprises a harmonic drive motor (30[W], gear ratio 100:1) inside a watertight cylinder, along with two movable float blocks. The float blocks are driven by the harmonic drive motor through a reduction gearbox (40:1). As a result, the angular velocity of the float blocks is about 3 [deg/s]. Figure 2 shows that control of the center of buoyancy is accomplished by the movable float blocks. The movable float blocks have 35 percent of its total buoyancy force. The BG system provides pitch torque to the vehicle; six thrusters provide propulsion to the vehicle.

A main pressure housing contains a PC/104 CPU board (650[MHz]) running the Linux operating system, D/A boards, A/D boards, CNT boards, motor drivers and a full 360 degree range clinometer. Power and serial communication are provided through an umbilical cable from the surface. A CCD camera and LED light are mounted on the front of the UVMS. These components make it possible for an operator to control the UVMS (6 thrusters, 10 motors inside the manipulators, and 1 motor inside the BG system).

III. STATIC MODEL OF UVMS WITH BG SYSTEM

In this section, we derive the static model of UVMSs with a BG system, and explain how to control the vehicle attitude based on the model. Additionally, we present a numerical study of the relation between a rotational angle of movable float blocks and an attitude angle of a vehicle.

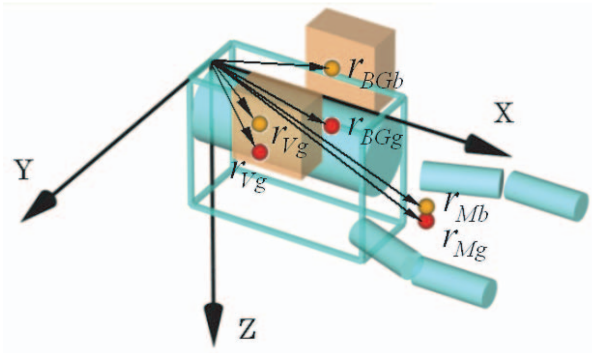

Fig. 3. Body-fixed reference frame

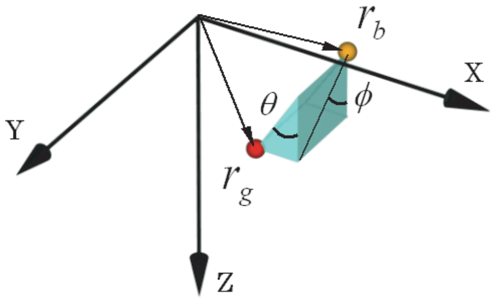

Fig. 5. Position vectors $\boldsymbol{r}_g$ and $\boldsymbol{r}_b$ used for attitude control

A. CENTER OF BUOYANCY AND CENTER OF GRAVITY OF UVMS

Let a body-fixed reference frame be attached to a vehicle, as presented in Fig. 3. 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 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 whole system can be described as

$$\boldsymbol{r}_g = \frac{G_V \boldsymbol{r}_{Vg} + G_{BG}\boldsymbol{r}_{BGg}(\boldsymbol{\theta}_{BG}) + G_M \boldsymbol{r}_{Mg}(\boldsymbol{\theta}_M)}{G_V + G_{BG} + G_M} \tag{1}$$

$$\boldsymbol{r}_b = \frac{B_V \boldsymbol{r}_{Vb} + B_{BG}\boldsymbol{r}_{BGb}(\boldsymbol{\theta}_{BG}) + B_M \boldsymbol{r}_{Mb}(\boldsymbol{\theta}_M)}{B_V + B_{BG} + B_M} \tag{2}$$

where the weight and buoyancy force of only 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.

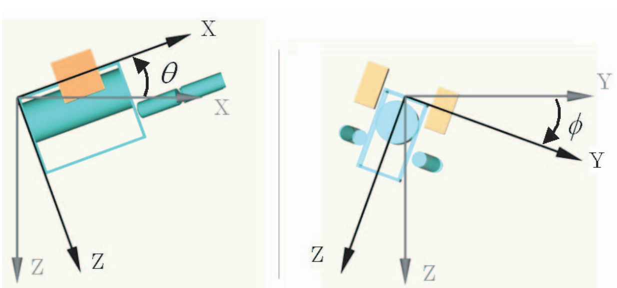

Fig. 4. Pitch and roll control

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 $\boldsymbol{\theta}_{BG}$.

B. VEHICLE ATTITUDE CONTROL BASED ON THE BG SYSTEM

The following are assumed: weights G_V, G_M and G_{BG}, buoyancy forces B_V, B_M and B_{BG}, centers of gravity $\boldsymbol{r}_{Vg}$, $\boldsymbol{r}_{Mg}(\boldsymbol{\theta}_M)$ and $\boldsymbol{r}_{BGg}(\boldsymbol{\theta}_{BG})$, and centers of buoyancy $\boldsymbol{r}_{Vb}$, $\boldsymbol{r}_{Mb}(\boldsymbol{\theta}_M)$ and $\boldsymbol{r}_{BGb}(\boldsymbol{\theta}_{BG})$. In fact, these values can be estimated easily from the weights and volumes of the components of an UVMS.

If a desired pitch angle of a vehicle is given as an angle θ about the y axis, as shown on the left-hand-side of Fig. 4, then the vector $\boldsymbol{\theta}_{BG}$ can be analytically or numerically calculated to satisfy the following equation.

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

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

Similarly, if a desired roll angle of a vehicle is given as an angle ϕ about the x axis, as shown on the right-hand-side of Fig. 4, then the position of the movable float blocks is controlled to satisfy the following equation.

$$\tan\phi = \frac{r_{gy}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M) - r_{by}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M)}{r_{gz}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M) - r_{bz}(\boldsymbol{\theta}_{BG}, \boldsymbol{\theta}_M)} \tag{4}$$

The BG system adjusts the float blocks to satisfy both Eq. (3) and Eq. (4) if a pitch angle θ and a roll angle ϕ are given simultaneously. Figure 5 shows that the center of gravity $\boldsymbol{r}_g$ and buoyancy $\boldsymbol{r}_b$ of the whole system in the body-fixed frame are expressed.

The distance between the center of gravity and the center of buoyancy is an index of the UVMS' static stability. We can also control the strength of the static stability if a BG system has sufficient degrees of freedom.

A vehicle cannot be rotated to a yaw angle about the z axis by the static movement of a BG system.

C. NUMERICAL STUDY OF THE 1-DOF BG SYSTEM

In previous subsections, we discussed general considerations for the three-dimensionally-controlled center of gravity $\boldsymbol{r}_g$ and buoyancy $\boldsymbol{r}_b$ using a BG system. In this subsection,

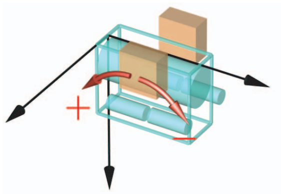

Fig. 6. Move-Mode

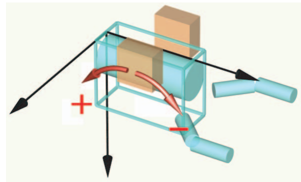

Fig. 7. Arm-Mode

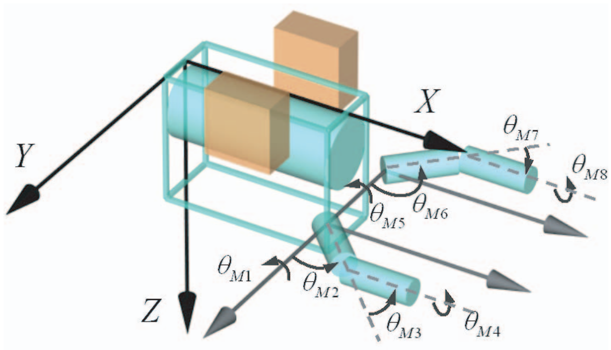

Fig. 8. Joint variables of manipulators

TABLE I
PARAMETERS: MOVE-MODE

Vehicle	G_V[kgf]	40.93
	$\boldsymbol{r}_{Vg}$[m]	$(0.322, 0, 0.226)$
	B_V[kgf]	31.68
	$\boldsymbol{r}_{Vb}$[m]	$(0.303, 0, 0.196)$
Manipulator	G_M[kgf]	11.2
	$\boldsymbol{r}_{Mg}$[m]	$(0.713, 0, 0.343)$
	B_M[kgf]	4.0
	$\boldsymbol{r}_{Mb}$[m]	$(0.713, 0, 0.343)$
BG system	G_{BG}[kgf]	4.0
	$\boldsymbol{r}_{BGg}$[m]	$(0.530 - 0.342S_\theta, 0, 0.320 - 0.358C_\theta)$
	B_{BG}[kgf]	20.45
	$\boldsymbol{r}_{BGb}$[m]	$(0.530 - 0.342S_\theta, 0, 0.320 - 0.358C_\theta)$

$S_\theta = \sin\theta_{BG}, C_\theta = \cos\theta_{BG}$.

TABLE II
PARAMETERS: ARM-MODE

Manipulator	G_M[kgf]	11.2
	$\boldsymbol{r}_{Mg}$[m]	$(0.930, 0, 0.410)$
	B_M[kgf]	4.0
	$\boldsymbol{r}_{Mb}$[m]	$(0.931, 0, 0.410)$

we present a numerical example of the performance of a 1-DOF BG system mounted on the vehicle we developed.

The BG system that was developed as a test model has a rotary motor and two movable float blocks. The float blocks are driven by the rotary motor through a reduction gearbox. Therefore, the rotational angle of the motor shaft determines the position of the float blocks. In other words, the rotational angle of the motor uniquely determines the center of gravity $\boldsymbol{r}_{BGg}$ and buoyancy $\boldsymbol{r}_{BGb}$ of the BG system.

However, the center of gravity $\boldsymbol{r}_g$ and buoyancy $\boldsymbol{r}_b$ of the whole system cannot be determined uniquely even if the center of gravity $\boldsymbol{r}_{BGg}$ and buoyancy $\boldsymbol{r}_{BGb}$ of the BG system are determined. The reason is that the center of gravity $\boldsymbol{r}_g$ and buoyancy $\boldsymbol{r}_b$ of the entire system depend not only on the center of gravity and buoyancy of the BG system; they also depend on those of the manipulators.

For that reason, we consider two cases; in the first case, the manipulators are located on both sides of the vehicle when cruising underwater, as presented in Fig. 6. In the other case, the manipulators are located in front of the vehicle to support work underwater, as shown in Fig. 7. The joint variables of the manipulators are defined as portrayed in Fig. 8, and the joint variables in the move-mode are given as

$$\begin{aligned}\boldsymbol{\theta}_M &= (\theta_{M1}, \theta_{M2}, \cdots, \theta_{M8})^T \\ &= (0, -90, 0, 0, 0, 270, 0, 0)^T, \end{aligned} \tag{5}$$

and the joint variables in the arm-mode are given as

$$\begin{aligned}\boldsymbol{\theta}_M &= (\theta_{M1}, \theta_{M2}, \cdots, \theta_{M8})^T \\ &= (0, 45, 45, 0, 0, 135, -45, 0)^T. \end{aligned} \tag{6}$$

We numerically investigate the relation between the rotational angle θ_{BG} of the movable float blocks of the BG system and the pitch angle θ of the vehicle corresponding to the move-mode and arm-mode. In each case, the vector $\boldsymbol{\theta}_M$ of the joint variables of the manipulators is constant (Eq. (5) and Eq. (6)). Therefore, the pitch angle θ of the vehicle in Eq. (3) depends only on the angle θ_{BG} of the float blocks. Table I and Table II show the weights, buoyancy forces, and positions of the center of gravity and buoyancy corresponding to the two cases. Those centers of gravity and buoyancy are on the x–z plane because of the left–right symmetry of the vehicle. In Table II, the center of gravity and buoyancy of the manipulators only are described because the other parameters are equal for both the move-mode and arm-mode.

The initial position of the movable float blocks of the BG system is in an upward direction ($\theta_{BG} = 0$). The initial pitch angle of the vehicle is 0 deg when the vehicle is horizontal, as shown in Fig. 6.

Figure 9 presents numerical results of the relation between the rotational angle of the BG system and the pitch angle of the vehicle corresponding to the move-mode and arm-mode. In the move-mode and arm-mode, the angle θ_{BG} of the float blocks is approximately proportional to the pitch angle θ. When the angle θ_{BG} equals zero, an 11-deg difference exists between the move-mode and arm-mode. Therefore, the vehicle inclines downward in the arm-mode.

IV. EXPERIMENTAL VALIDATION OF THE 1-DOF BG SYSTEM

In previous section, we discussed general considerations for pitch and roll control of the vehicle. We developed a 1-DOF (pitch) test model to investigate the performance of the BG system.

In this section, we present some experimental results related to the performance of the 1-DOF BG system mounted on the vehicle. For one experiment, the variable pitch angle of the vehicle is investigated. In the other experiment, main-

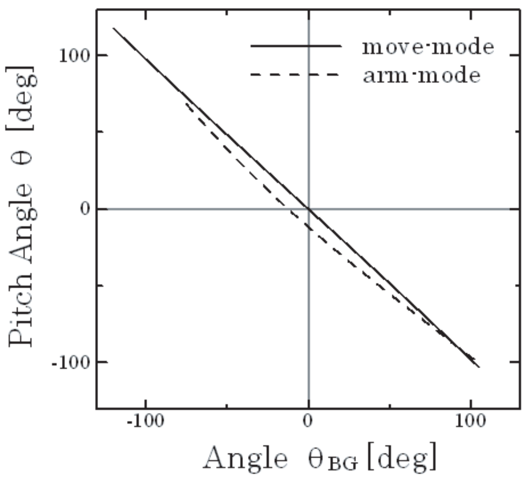

Fig. 9. Numerical results of BG system

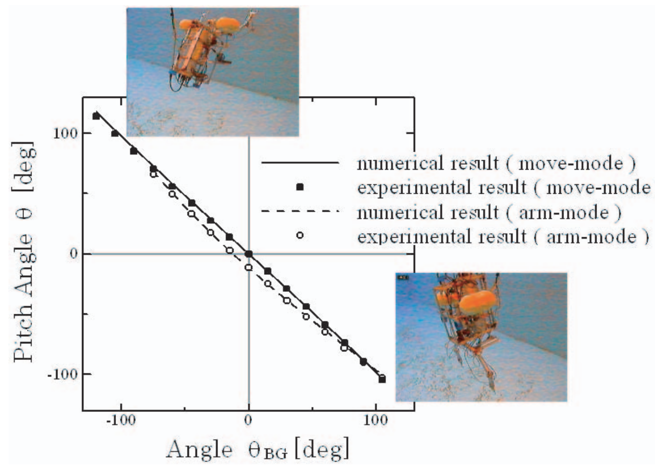

Fig. 10. Experimental results of BG system

taining attitude control during the motion of the manipulators is conducted.

A. ATTITUDE CHANGE CONTROL

In addition to the numerical study, we investigated the relation between the rotational angle of the BG system and the pitch angle of the vehicle corresponding to the move-mode and arm-mode. Figure 6 shows that, in the move-mode, the manipulators are located on both sides of the vehicle. Figure 7 shows that, in the arm-mode, the manipulators are located in front of the vehicle. The initial position of the movable float blocks of the BG system was in a vertical arrangement ($\theta_{BG} = 0$). The initial attitude angle of the vehicle was 0 deg when the vehicle was horizontal, as portrayed in Fig. 6.

The experimental results with the numerical results in the previous section are presented in Fig. 10. Each plot shows the average of the pitch angles measured using a full 360 degree range clinometer (PRO 3600 Digital Protractor: sample rate 1.9[Hz]) inside the vehicle for 10 [s]. The experimental results agree with the numerical results. In move-mode, the proposed attitude control system was able to change the vehicle pitch angle between -120 and $+105$ deg. On the other hand, the proposed system was able to change the pitch angle between -75 and $+105$ deg in the arm-mode. Figure 11 shows the attitude variation of the vehicle in the arm-mode during the experiment. The vehicle was initially facing downward; the vehicle was facing upward in the end.

B. ATTITUDE KEEPING CONTROL

The weight of the UVMS including the manipulators and the BG system is about 56 [kg]. The weight of the manipulators is 11.2 [kg]. Therefore, 20 percent of the total weight is attributable to the manipulators. In such a case, the vehicle attitude becomes unstable during motion of the manipulators. We present an experimental result of the attitude keeping control during the motion of the manipulators.

Changing from the move-mode (Fig.6) to the arm-mode (Fig.7), the vehicle inclines downward at about a 11-deg angle. To cancel the incline of the vehicle, the BG system is controlled in this experiment.

As described in Section 3, the pitch angle of the vehicle depends on both the joint variables $\boldsymbol{\theta}_M$ of the manipulators and the angle θ_{BG} of the float blocks. The angles $\boldsymbol{\theta}_M$ of the manipulators can be measured by optical encoders attached to the motors. Therefore, the desired angles θ_{BG} of the float blocks are solvable when the pitch angle θ equals zero. That is to say, the following equation:

$$\tan\theta = \tan 0 = -\frac{r_{gx}(\theta_{BG}, \boldsymbol{\theta}_M) - r_{bx}(\theta_{BG}, \boldsymbol{\theta}_M)}{r_{gz}(\theta_{BG}, \boldsymbol{\theta}_M) - r_{bz}(\theta_{BG}, \boldsymbol{\theta}_M)} \tag{7}$$

is solved for the angle θ_{BG}. The solution θ_{BG} is set as the desired angle for the movable float blocks; a PI feedback controller for the BG system is implemented on the computer inside the vehicle.

Equation (7) was solved numerically using sequential search; the computation time was about 2 [ms]. The sequential search function was included in the control program for the UVMS. The execution time was about 30 [ms] per control loop that includes the sequential search, PI feedback control action, serial communication and data save.

This experiment was also conducted in a diving pool. Figure 12 shows time series data of the vehicle pitch angle θ from the move-mode in Eq.(5) (0–23[s]) to the arm-mode in Eq.(6) (47–72[s]) through the joint variables (23–47[s]) given as

$$\begin{aligned}\boldsymbol{\theta}_M &= (\theta_{M1}, \theta_{M2}, \cdots, \theta_{M8})^T \\ &= (0, -90, 90, 0, 0, 270, -90, 0)^T. \end{aligned} \tag{8}$$

The solid line represents the result of the attitude-maintenance control; the dashed line is the case of no-controller of the BG system. With no control effort, the pitch error was 10–11 [deg] in the arm-mode. On the other hand, the addition of feedback control reduced the pitch error and the error was limited to less than 3.3 [deg]. Results show that the BG system can improve the static stability of the vehicle.

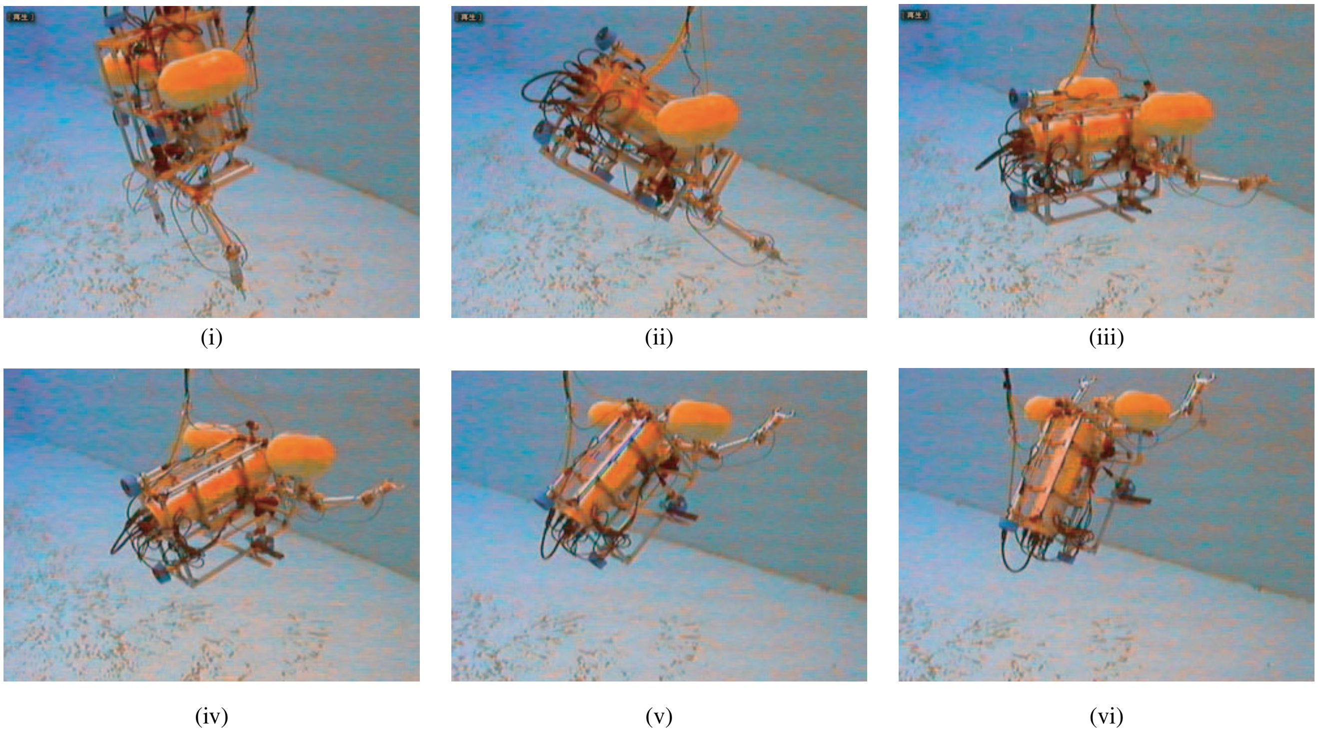

Fig. 11. Attitude change control of the BG system

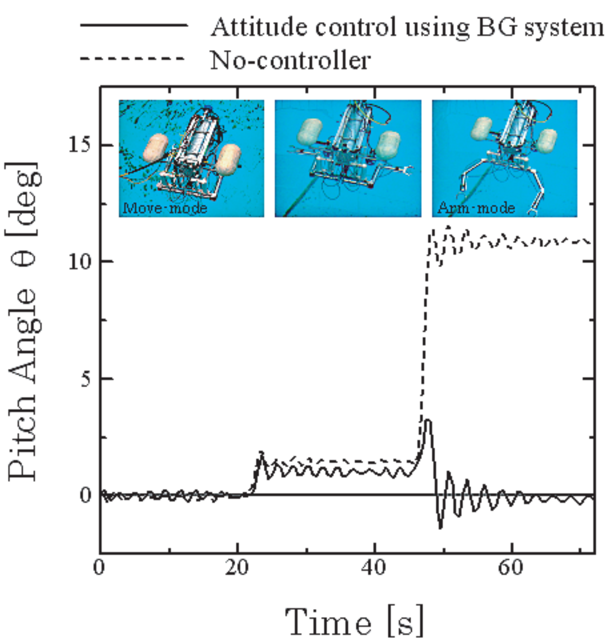

Fig. 12. Attitude-keeping control of BG system

C. DEMONSTRATIONS

Several demonstrations of the UVMS were performed in a diving pool. In the demonstrations, one operator manually input desired joint variables $\boldsymbol{\theta}_M$ of the manipulators, the desired angle θ_{BG} of the BG system, and desired thrust forces from a keyboard, and the on-board computer inside the UVMS executed PI feedback control to the desired values.

As a demonstration, the UVMS removed an old tire from a diving pool, as depicted in Fig. 13. After holding the tire (i) in Fig. 13, the operator manually input the desired angle θ_{BG} from a keyboard. The vehicle inclined upward by changing the positions of the float blocks and thereby hove the tire (ii). The vehicle was able to change the pitch angle. For that reason, it was easy for an operator to control the UVMS (iii)(iv). 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. One of our future works will be to achieve the automatic attitude control by using additional sensors even if the UVMS holds an unspecified object.

As another demonstration, shown in Fig. 14, an operator inspected the bottom of a boat using the UVMS. During the inspection, the UVMS was made to face upward using the BG system.

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

As described in this paper, we proposed an attitude control system (BG system) for small UVMSs. The proposed attitude control system is based on position control of the center of buoyancy. Control of the center of buoyancy is accomplished using movable float blocks.

We derived the static model of UVMSs with an attitude control system, and explain how to control the vehicle attitude based on the model. Based on the model, we presented a numerical study of a test model we developed.

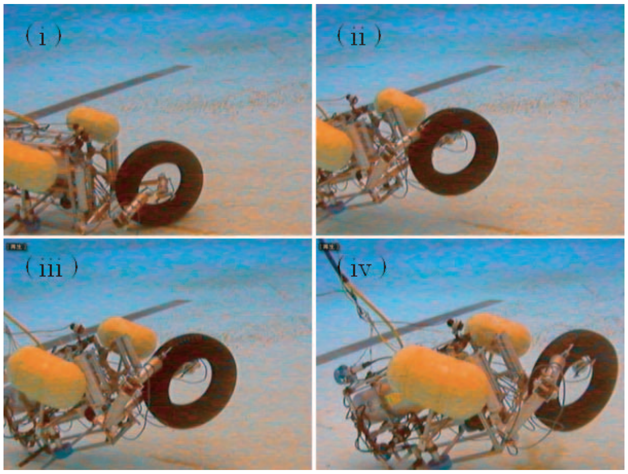

Fig. 13. Removal of an old tire (demonstration)

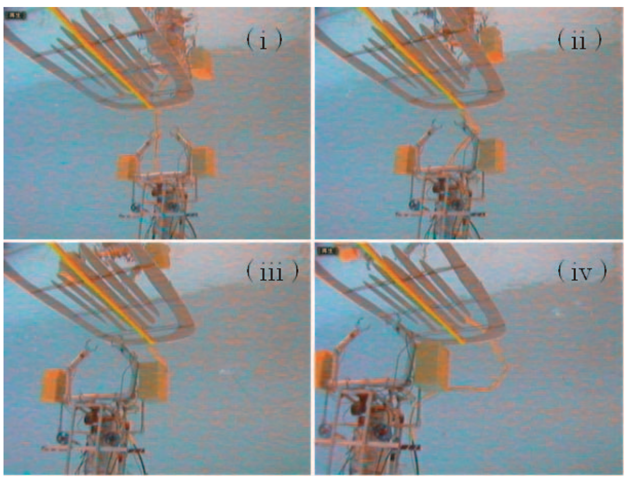

Fig. 14. Inspection of the bottom of a boat (demonstration)

The effectiveness of the attitude control system was also verified through some experimental results. We confirmed in one experiment that the proposed system could change the pitch angle of the vehicle between -120 and $+105$ deg. In the other experiment, attitude-maintenance control was conducted. The result was that the proposed system was able to maintain the horizontal attitude of the vehicle during the motion of the manipulators.

Additionally, several demonstrations of the UVMS with the attitude control system were performed in a diving pool.

B. Future Work

The angular velocity of the movable float blocks was slow (about 3 [deg/s]). For that reason, it is difficult for this BG system to maintain the vehicle's attitude during dynamic motion of the manipulators or under dynamic disturbances. To overcome this problem, a new BG system to generate dynamic motions is currently being designed. We should investigate the hydrodynamics effects of our vehicle in order to realize dynamic motions.

Additionally, we will theoretically investigate the performance of a multi-DOF BG system to realize not only pitch angle control but also roll angle control of the vehicle.

VI. ACKNOWLEDGMENTS

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