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Underwater Robot with a Buoyancy Control System Based on the Spermaceti Oil Hypothesis - Development of the Depth Control System -

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***Abstract*— The goal of this paper is to develop a robot control system using a microcomputer for an underwater robot with a buoyancy control system based on the spermaceti oil hypothesis. Sperm whales have a spermaceti organ in their head that is filled with spermaceti oil. It is said that sperm whales control their buoyancy by melting or coagulating spermaceti oil. In the previous papers proposed an underwater robot with a buoyancy control device using its theory. The robot was radio controlled and it had no sensor. Therefore, the robot could not detect water depth. Also, it was not able to control its own depth. In addition, the robot could not dive because it had no cooling system. In this paper, we built a depth control circuit using a microcomputer and pressure sensor. The pressure sensor detected the robot's depth, and the microcomputer controlled the robot's position. And, we made a new buoyancy control device using a peltier element. A peltier element was used for heating and cooling systems of the paraffin wax. Then, we experimented with the robot control. As a result, we confirmed that when we ordered a target water depth, the robot dived, floated and maintained the depth itself by detecting its own position. In addition, we confirmed that when a disturbance occurs, the robot returned to the former depth.**

Index terms – spermaceti oil, paraffin wax, sperm whale, underwater robot, depth control circuit, pressure sensor, microcomputer

I. INTRODUCTION

THE sperm whale (Physeter macrocephalus) is one of the biggest species of Odontocetib, species of whale that have teeth. The total length and weight of an adult male is approximately 17-20 m and 40-50 tons, respectively [1]. The sperm whale can dive to a depth of 3000 m for more than 2 hours to feed. This ability is considered to be one of the mysteries surrounding sperm whales.

Sperm whales have a spermaceti organ in their head, which is filled with spermaceti oil. There are a number of hypotheses on the role of the organ and the oil. One is that the spermaceti organ evolved as a weapon used in male-male aggression [2]. In another hypothesis, the organ is considered to be a bio-sensor [3].

In the 1970s, Clarke proposed another hypothesis that insists that the spermaceti oil is used for buoyancy control [4]. This hypothesis takes into consideration the difference in the volume of materials between the solid and liquid states, which causes a difference in buoyancy. This buoyancy control mechanism can be considered as one reason why the sperm whale can keep neutral buoyancy in the deep sea.

We focused on Clarke's hypothesis because it seems to be the most useful for underwater robots and vehicles. At present, underwater vehicles, such as submarines and robots, need ballast to enable them to dive deep under the sea, and they must then discard the ballasts and discarding such materials negatively affects the environment. Unmanned Undersea Vehicle (UUV) developed by DeBitetto is controls its own buoyancy by on and off ballast pumps [5]. Variable buoyancy control system (VBS) of Autonomous Underwater vehicle (AUV) developed by Wang et al. is uses water ballast [6]. If we can successfully apply the buoyancy control system based on Clarke's hypothesis, there will be no need to use such ballasts. Therefore, the goal of this study is to develop an underwater robot with a buoyancy control system based on Clark's spermaceti oil hypothesis.

At present, we used paraffin wax as a substitute for spermaceti oil and its volume was changed by heating and cooling. Then, we confirmed that the robot's buoyancy changed [7]-[8]. The robot has some problems. First, because it was radio controlled, it was impossible for it to control its own position automatically. Moreover, because there was no sensor detecting water depth, we weren't able to confirm the robot's depth. Also, the robot didn't have a cooling system. Then, we made a control circuit for the robot using a microcomputer and pressure sensor, and a new buoyancy control device that has a cooling system using a peltier element. A microcomputer controlled the robot, and a pressure sensor detected the robot's water depth. Finally, the robot became able to control its depth itself by detecting the water depth. Also, if a disturbance occurred to the robot, it could return to its former position by itself. Moreover, the robot became able to dive and float. In this paper, we will describe those systems and experiments.

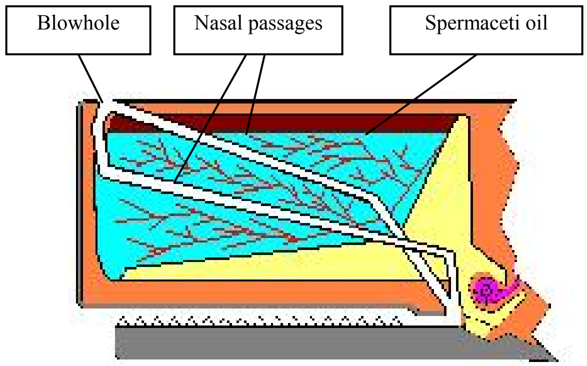

Fig. 1 Schematic diagram of a sperm whale's head

II. PRINCIPLES OF BUOYANCY CONTROL MECHANISM ON CLARK'S HYPOTHESIS

Figure 1 shows a schematic diagram of the anatomy of a sperm whale's head. The spermaceti organ is located in the head and contains spermaceti oil. The spermaceti organ contains capillaries and the nasal passage goes around the organ.

The spermaceti contains about 3 to 4 tons of spermaceti oil, and this corresponds to approximately 8% of the whale's total weight. The melting point of the spermaceti oil is approximately 31°C and it becomes solid at about 33°C [11]. The oil densities at 15 °C and 50 °C are approximately 0.95 g/cm³ and 0.82 g/cm³, respectively [7]. The quality of spermaceti oil is very good and it has been used as an ingredient for candles, lubricants, and so on [7].

According to Clarke's hypothesis, sperm whales heat their spermaceti oil by increasing blood flow to the spermaceti organ to melt the oil, which causes an increase in volume. On the other hand, the oil is cooled by air or sea water going through the nasal passage to congeal, which causes a decrease in volume. These differences in volume cause a change in the whale's buoyancy. This is the basic principle of the buoyancy control mechanism proposal by Clarke.

To apply this hypothesis to underwater robots, we need to use a material that possesses similar characteristics to spermaceti oil, and a mechanism that can change its volume.

III. MECHANISM

A. Substitution of spermaceti oil

Because obtaining real spermaceti oil is impossible, we must use a substitute. We chose paraffin wax, as reported in Ref. [7]. Its melting point is approximately 47°C, density at liquid state is 0.9[g/cm³] and density of solid state is 0.77[g/cm³]. Also, its volume change is 17.1% between both states.

TABLE I
SPECIFICATIONS OF PARTIER ELEMENT

Manufacturer	MELCOR
Product name	CP1.0-127-05L
Maximum current	3.9 A
Maximum voltage	15.4 V
Maximum temperature difference	85 °C
Dimensions	30,30,3.2mm

B. Peltier element

A peltier element is a thermoelectric element using the partier effect. The peltier element's surface has one side that is hot and one side that is cold by passing direct current. Moreover, it is possible to switch between the hot surface and cold surface by switching the direction of the current. Therefore, we used it to heat and cool paraffin wax.

When a peltier element receives electric current, it is consistent with the law of conservation of energy. In short, the quantity of radiated heat is the sum of the quantity of the absorbed heat and electric power of the peltier element. Therefore, it needs a heat sink.

IV. SYSTEM DESIGN

A. Buoyancy control device

We use the mechanism of a syringe and piston, and we attached other parts to it. Figure 2 shows the structure of the new buoyancy control device. The syringe contains 85 g of paraffin wax and nichrome wire. The piston was connected to the syringe by springs to obtain backward force when decreasing the paraffin's volume. It is the same syringe that we reported in Ref. [7]. Two peltier elements are installed in an aluminum plate with a hole because it is difficult to install the peltier elements directly on the syringe. Length and breadth were 50 mm, height was 70 mm and the hole's diameter was 40 mm. Table I shows specifications of the peltier element. We put a heat sink on the peltier elements and painted the sealing material around it. The syringe was put in the hole. From that paper, the syringe could change 0.1 N of buoyancy. However, we could not float the device because its weight is 650 g. Therefore, we put styrene foam on the device to float it easily.

By heating the paraffin wax with the nichrome wire and peltier element, the paraffin wax melted and its volume increased. Then, the piston was pushed to the outside, raising its buoyancy. By cooling the paraffin wax with the peltier element and water cooling, the paraffin wax congealed and its volume decreased. Then, the piston was pushed to the inside, reducing its buoyancy.

A pressure sensor (PGM-02KG) was put in the lower side.

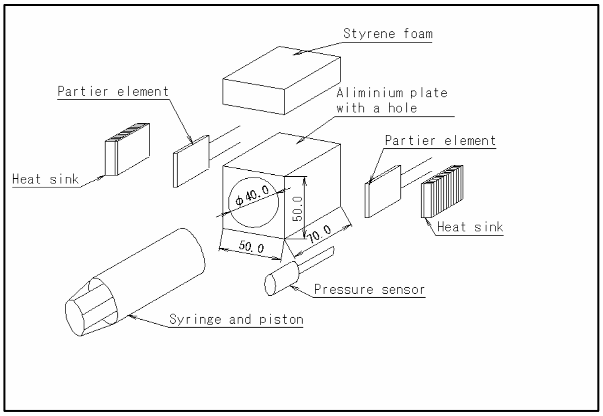

Fig. 2 Structure of buoyancy control device

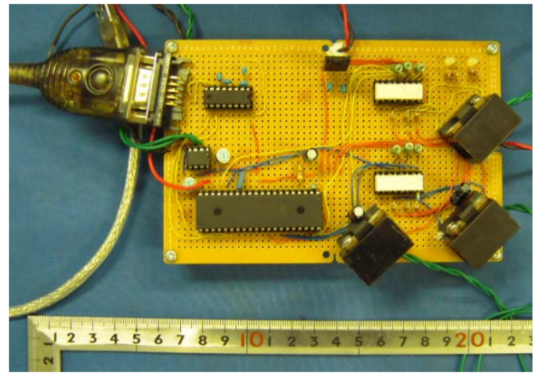

Fig. 4 Photograph of buoyancy control circuit

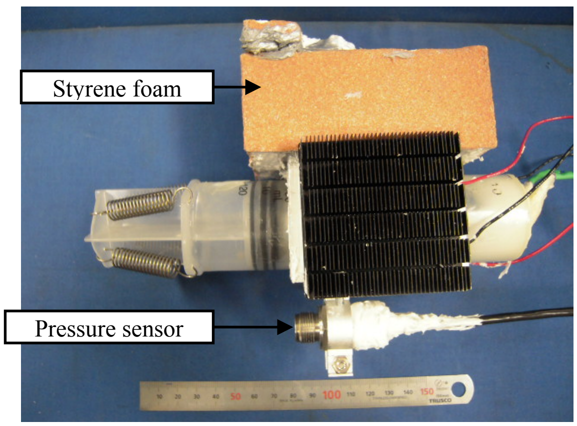

Fig. 3 Photograph of robot control device

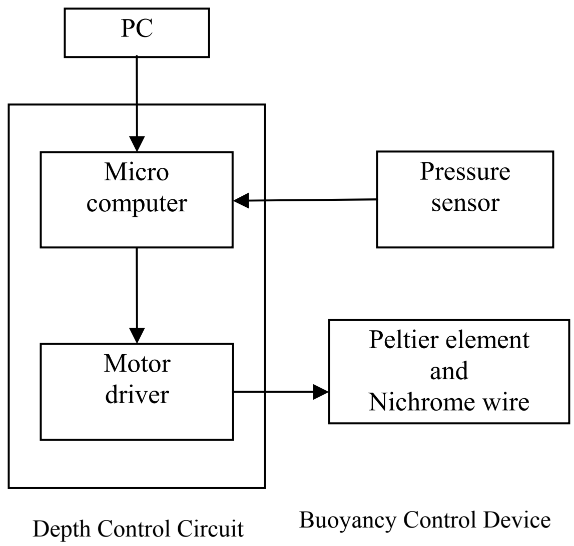

Fig. 5 Block diagram of the system

Figure 3 shows a photograph of the buoyancy control device.

B. Depth control circuit

Figure 4 shows a photograph of the depth control circuit, and Fig. 5 shows block diagram of the system. We used a microcomputer: PIC16F877A. Pressure data from the pressure sensor is converted to water depth by the PIC. Because output voltage of the pressure sensor is too low, it is amplified 801 times by an amplifier (AD623AN). To run the peltier element and nichrome wire, motor drivers (TA8429HQ) were used. Also, for reducing noise, a photocoupler (TLP521-4) was installed between the PIC and motor driver.

The circuit is connected to the PC by RS232C when we use it.

V. EXPERIMENTS

A. Setup

Figure 6 shows the experimental setup of depth measurement. The motor drivers are connected with the peltier elements and the nichrome wire. We put the buoyancy control curcuit in the water, and connected the robot control device with the PC. We supplied electric power from a D.C. power source to the peltier elements and the nichrome wire to heat and cool the paraffin wax. Electric power was 22W in all because of the specifications of the motor driver. Figure 7 shows a flow chart of the robot control. First, we input the target depth from the PC. If the robot's depth is lower than the target, the robot heats the paraffin wax. Then the robot floats. Oppositely, if the robot's depth is higher than the target, the robot cools the paraffin wax, and the robot dives. Also, when the robot reaches the target, it stays on the depth. Table II shows operation of the nichrome wire and peltier elements. When the robot floated, it passed electric current through the nichrome wire and peltier elements. When the robot dived, it passed electric current through the peltier elements only. However, its direction reversed.

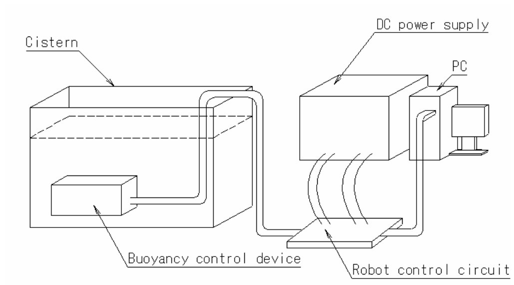

Fig. 6 Experimental setup of depth measurement

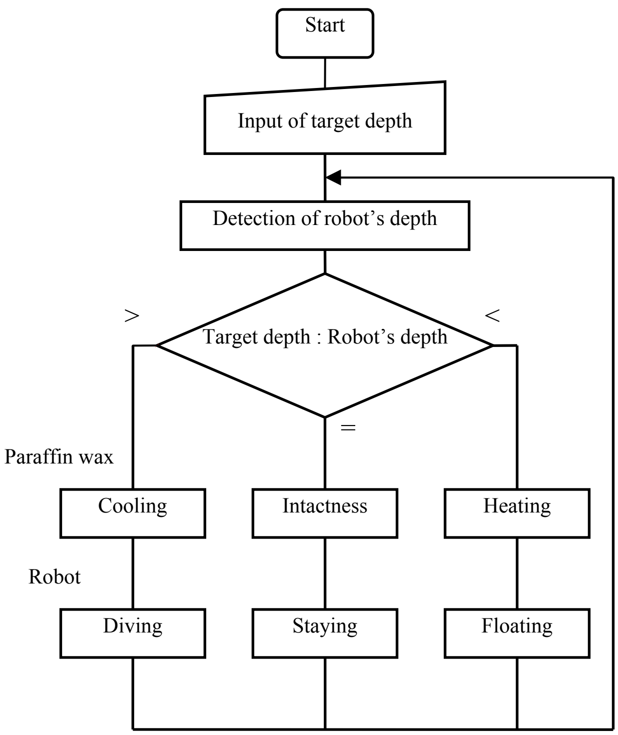

Fig. 7 Flow chart of robot control

B. Diving experiments and maintaining depth

We input the target depth of 0.1[m] from the PC. When the robot arrives at the target, we keep the state for 5 minutes.

After that, we change the target to 0.2[m] in the same way. Figure 8 shows the result. Although the robot exceeded the target once, it recovered. Between 0[m] to 0.1[m], the robot took approximately 7 minutes and, between 0.1[m] to 0.2[m], approximately 10 minutes. Then, it kept the target depth for approximately 5 minutes.

C. Floating experiment and influence of disturbance

We input the target depth that was 0.2[m] from the PC.

TABLE II
ORERATION OF NICHROME WIRE
AND PELTIER ELEMENT

	Floating (Heating)	Diving (Cooling)	Staying
Nichrome wire	ON	OFF	OFF
Partier element	ON(CW)	ON(CCW)	OFF

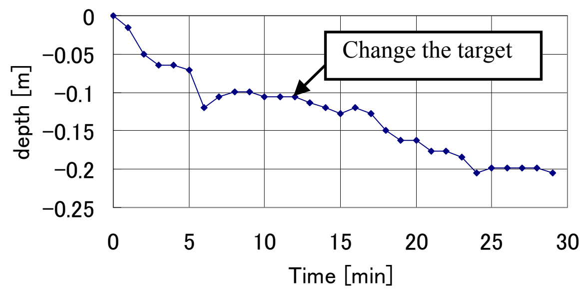

Fig. 8 Diving and maintaining depth of water

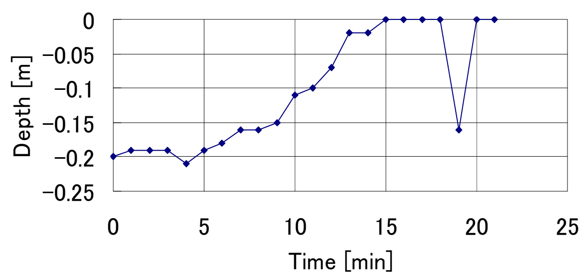

Fig. 9 Floating and influence of disturbance

When the robot arrives at the target, we keep the state for 5mitutes. After that we changed the target to 0.0[m]. When the robot arrives at the target, we keep the state for 5 minutes. After that we provide disturbance by pushing the device.

Figure 9 shows the result. Beginning heating the paraffin wax, the robot began to float in approximately 5 minutes. After that, it reached the surface in approximately 10 minutes. In addition, when disturbance was given, the robot returned to the former position in a minute. In this experiment, we did not measure the extended length of the piston. Therefore, we cannot determine whether the buoyancy the water surface is the neural or over it

VI. DISCUSSION

This robot control circuit can make the robot float and dive. Also, if disturbance occurs to the robot, it can return to the former depth. Furthermore, it is possible to change depth of

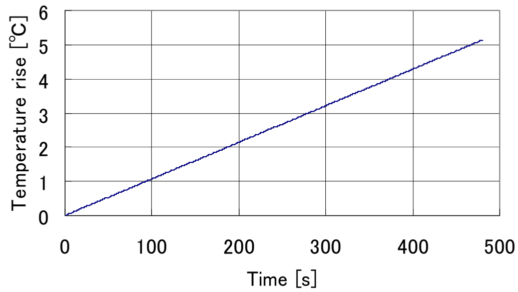

Fig. 10 Temperature rise into time caused by nichrome wire

the robot voluntarily from PC operation, and we can control the robot.

When the robot dived 0.1 m, it took approximately 7～10 minutes. Also, when the robot floated 0.2 m, it took approximately 8 minutes. Response for floating was faster than diving. It is thought to be the effect of the nichrome wire. The voltage was approximately 7.8V, and resistance of the nichrome wire was approximately 20.4Ω. Because output voltage of the motor driver is approximately 80% of input voltage, the input voltage of the nichrome wire is approximately 6.24V. Therefore, joule heat of 8 minutes caused by nichrome wire "Q" is able to be calculated with the following equation.

$$Q = \frac{V^2}{R} t = \frac{6.24^2}{20.4} \times 8 \times 60 = 916\,[J] \quad (1)$$

Therefore, joule heat of a unit time is 1.91[J/s]. Specific heat of paraffin wax is 2.093[kJ/kg • °C]. Temperature rise per a unit time caused by nichrome wire "Δt" is able to be calculated with the following equation.

$$\Delta t = \frac{1.91}{2.093 \times 10^3 \times 0.085} = 1.07 \times 10^{-2} [℃/s] \quad (2)$$

Figure 10 shows temperature rise into time caused by the nichrome wire. The robot began to float in 8 minutes, and temperature rise caused by the nichrome wire was approximately 5.2 °C. Therefore, it is reasonable to think that buoyancy change of heating is faster than cooling by nichrome wire.

In the case of carrying circuit, the robot will be bigger and heavier than that in this paper. Then, it takes much more time for the robot to reach the target depth. Therefore, the robot's main body should be as small and light as possible. Also, to make the robot's response speedy, it is necessary to change the paraffin wax's volume speedily. Therefore, the robot needs much electric power. 22W is the limit of capacity of

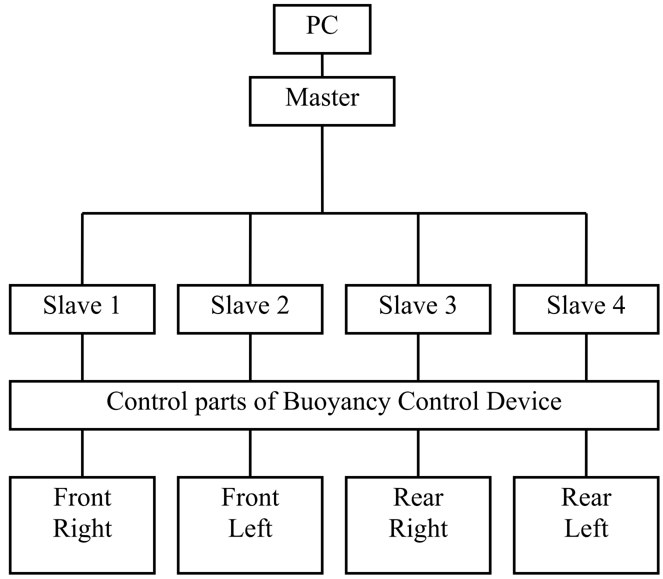

Fig. 11 Robot Control System in future

electric power for the motor driver that we used this time. Therefore, it is necessary to use another motor driver that has higher electric power. As one way to do this, we will use an H-Bridge circuit using transistors. And, we choose new material that specific heat is lower than paraffin wax.

Diving performance is poorer than floating performance. It caused heating and cooling system. Heating system is used nichrome wire and peltire element. However, cooling system is used peltire element only. Therefore, the robot should add other cooling system, or it use cold area.

By carrying a several buoyancy control devices, the robot is able to control its own posture. If we use four buoyancy control devices, the robot can control roll angle and pitch angle. Then, we use four robot control circuits that we made this time, controlling each buoyancy control device. Also, by using master circuit, the robot controls these circuits. Figure 11 shows its system formatting.

VII. SUMMARY AND FUTURE WORK

This paper described an underwater robot that has a buoyancy control system based on Clarke's spermaceti oil. We made the robot's depth control circuit using a microcomputer. We experimented on its action following the target of depth and influence of disturbance. As a result, we confirmed that the robot can control its own position. Therefore, we proved that the robot control device was effective.

However, the performance are poor. Therefore, we have to consider energy efficiency of the buoyancy control device.

And, if excessive heat occurs to the nichrome wire, it shorts because the heat-shrinkable tube coating it splits. Therefore, we need to control the temperature of the paraffin wax by inserting a temperature sensor such as a thermistor.

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