Hindawi Publishing Corporation
ISRN Robotics
Volume 2013, Article ID 541643, 7 pages
http://dx.doi.org/10.5402/2013/541643

Research Article

New Volume Change Mechanism Using Metal Bellows for Buoyancy Control Device of Underwater Robots

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Received 30 November 2012; Accepted 19 December 2012

Academic Editors: G. C. Gini, D. M. Lyons, and D. K. Pratihar

We propose a new volume change mechanism using a metal bellows for a buoyancy control device of underwater robots and vehicles. Our proposed buoyancy control method utilizes the volume change caused by the phase-change of materials. We chose paraffin wax as a phase-change material because its volume change exceeds other candidates. Our proposed device consists of a metal bellows and an aluminum housing that contains paraffin wax and water. The paraffin wax is heated and cooled by a nichrome wire and a peltier device. We conducted two experiments and confirmed that the heat sink in the aluminum housing increases the speed of the buoyancy change and that the thickness of the air layer is crucial for efficient insulating. Then, we built a prototype robot with the four devices and confirmed that the robot can change its buoyancy up to its maximum value.

1. Introduction

Buoyancy control is an essential ability for underwater robots and vehicles to submerge and surface. Currently, many underwater vehicles control their buoyancy by discarding or taking on ballast. However, this method is harmful to the environment because releasing materials into the water harms organisms. Also, discarding ballast water can introduce nonnative species to an area; this is the ballast water problem [1]. To solve this problem, a buoyancy control device has to be developed without material exchange.

We focused on the hypothesis of a buoyancy control mechanism of sperm whales proposed by Clarke in 1978 [2–4]. He posited that sperm whales control their buoyancy by changing the volume of the spermaceti organ in their head by cooling and heating the sperm oil in it. This hypothesis is attractive because this buoyancy control method is achieved without material exchange, although it is not perfect [5]. The solid and liquid phases can also withstand high pressure in the deep sea because the volume change can be used as an actuator [6]. Therefore, we built a buoyancy control device based on Clarke's hypothesis.

There are other methods that use volume change, for example, an electrical motor that moves pistons [7, 8]. Recently, a thermal glider was developed that utilizes phase change of material to increase and decrease its buoyancy and pitch angle [9]. Also, it utilizes the temperature difference between the sea surface and the deep sea to achieve phase change of a material. However, its phase change mechanism and material remain unknown.

To change the buoyancy, a buoyancy control device has to change its own volume; some volume change mechanisms exist. We tested two types. One is a syringe and piston mechanism, and the other is a mechanism that exploits rubber stretching [10, 11]. However, they have some disadvantages. For the syringe mechanism, smooth contraction may be hampered, because the coagulating material (in this study, paraffin wax) disturbs the piston motion. The seal between the syringe and the piston is another problem. In the rubber stretching mechanism, the rubber has a durability problem. Therefore, we focused on a metal bellows as a new volume change mechanism because it does not have the sealing problem. In respect to durability, a metal bellows outperforms rubber. However, in the contracting motion, the same problem as with the syringe mechanism will arise. Therefore, we introduced a mechanism to avoid this problem.

In this paper, we propose a new volume change mechanism with a metal bellows. We examined the effect of the heat sink and the air layer to increase the efficiency of the heat transfer and insulating abilities. Then we designed and built a prototype robot using the four devices and confirmed that it can change its own buoyancy.

2. New Volume Change Mechanism

2.1. Outline of Proposed Mechanism. The main idea of our new mechanism is to utilize metal bellows for the volume change mechanism, which we introduce because a metal bellows is expected to withstand high water pressure and to have higher endurance than other mechanisms. Also, a sealing mechanism is easier to build than a syringe and piston mechanism. However, if the inside of a metal bellows is filled with material for a volume change, the coagulated material would prevent the metal bellows from smooth contraction. Therefore, a mechanism has to be installed to avoid this problem. We solved it by pouring water in the metal bellows, which has a lower melting point than paraffin wax, and put the paraffin wax outside of the metal bellows. We will explain this mechanism later.

In this paper, we used paraffin wax as a volume change material because the volume difference between the solid and liquid states is approximately 17%, which is larger than other substitutes [7]. Although its melting point is approximately 47°C, which is higher than real sperm oil, we believe that paraffin wax is one of the best substitutes for it.

2.2. Details of Mechanism. Figures 1, 2, and 3 show a schematic drawing of a section of the new mechanism, its rendered drawing, and a photograph of the device, respectively. This device can be divided into two parts: upper and lower. The upper part consists of a peltier device, an aluminum block with a hollow, an aluminum plate, an acrylic cylinder, and rubber. The lower part consists of a metal bellows, rubber, and a thin metal plate with a small hole. The metal bellows used in this paper can withstand 1 MPa of pressure, which is equivalent to the water pressure at a depth of 100 m. All of the parts except the acrylic cylinder are connected tightly by screws and bolts (Figure 2).

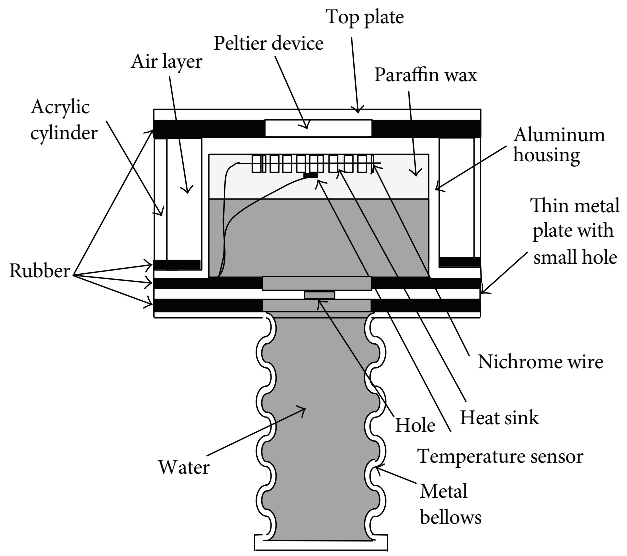


Figure 1: Schematic drawing of a section of device.

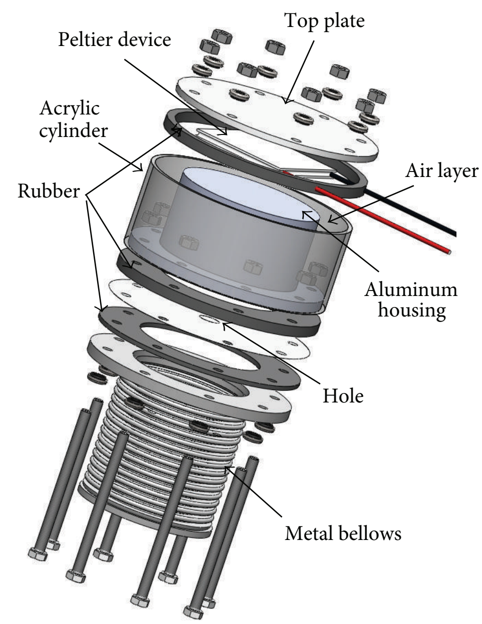


Figure 2: Drawing of device.

Rubber was inserted to prevent the water and the paraffin wax from leaking. Paraffin wax was poured to the hollow of the aluminum block. Water was poured to the remaining part of the block and the metal bellows. A thin metal plate with a small hole was put on the metal bellows. Because the density of the paraffin wax is less than that of water, paraffin wax always remains on top of the water. However, if the device is inclined, the paraffin wax gets inside the metal bellows. This plate has a small 10 mm diameter hole (as shown in Figures 1 and 2) that prevents the paraffin wax from getting into the metal bellows. This is the mechanism that achieves smooth contracting motion.

An acrylic cylinder surrounds the aluminum block, and there is an air layer between the block and the cylinder. This air layer and acrylic cylinder provide insulation. By altering the thickness of the acrylic cylinder, the thickness of the air layer can be changed. A heat sink is put on the hollow of the aluminum block, and a nichrome wire is placed around the heat sink. A peltier device is put on the aluminum block.

Figures 4 and 5 show a section and a photograph of the interior of the aluminum housing. A heat sink is on the bottom of the hollow. A nichrome wire is around the heat sink, and a thermistor is installed on the center of the heat sink.

The diameters of the top aluminum plate and the metal bellows are 100 and 66 mm. The height of the metal bellows is 69 mm. The total height of the device is approximately

Figure 3: Photograph of device.

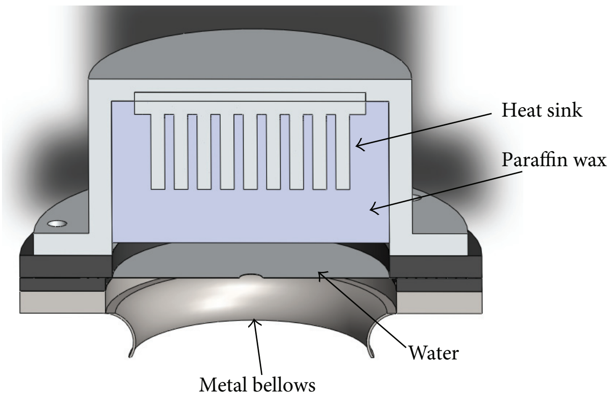


Figure 4: Section of upper part of device.

125 mm. The metal bellows can be extended 4 mm from the initial length. Its total weight is 1.2 kg. The diameter of the small hole of the thin metal plate is 10 mm.

Buoyancy difference F between the liquid and solid phases can be calculated by the following equation:

$$F = \rho_W g (V_l - V_s) = \rho_W mg \left(\frac{1}{\rho_l} - \frac{1}{\rho_s} \right), \quad (1)$$

where ρ_W is the water density (approximately 1000 kg/m^3), m is the mass of the paraffin wax (60 g), and ρ_l and ρ_s are the densities of the paraffin wax in the liquid and solid phases. The device contains 60 g of paraffin wax. Based on the relationship between the values of the buoyancy change and the needed heat from our experiences in this study, we chose 60 g as the mass. The densities of the paraffin wax at 25°C (solid) and 70°C (liquid) are 9.01×10^2 and 7.69×10^2 kg/m^3. By substituting these values into (1), we obtain 0.11 N of buoyancy change.

Figure 6 shows a schematic diagram of the control system. The signals for driving the peltier device and the nichrome wire are sent from a PC to a microcomputer (PIC), which operate them. The temperature data are recorded on the PC through an A/D converter.

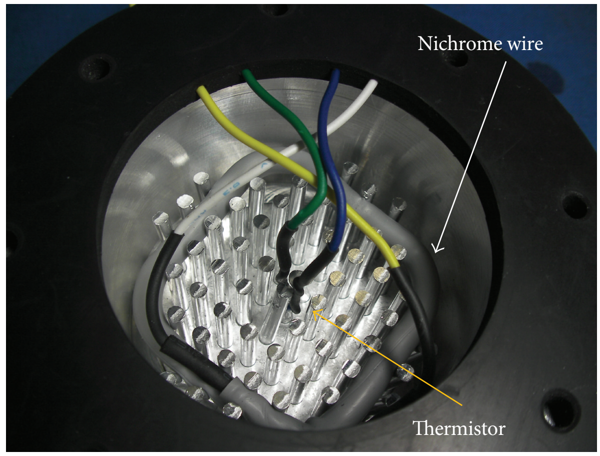


Figure 5: Photograph of interior of hollow of aluminum housing.

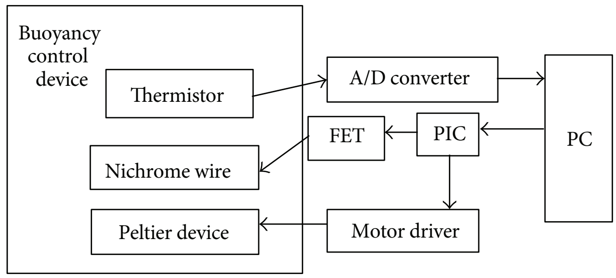


Figure 6: Control system.

Table 1: Electrical condition of nichrome wire and peltier device.

		Voltage (V)	Current (A)
Without heat sink	Nichrome wire	36	1.2
	Peltier device	6.3	2.3
With heat sink	Nichrome wire	33	1.3
	Peltier device	6.3	2.2

3. Effect of Heat Sink and Air Layer

In this paper, we tested whether our developed system can achieve efficient heat transfer to the paraffin wax and insulation. We examined the effect of a heat sink and the thickness of the air layer in the device on the buoyancy change.

3.1. Effect of a Heat Sink in the Hollow of the Aluminum Block. First, we compared the buoyancy change of the device with a heat sink to one without. Figure 7 is a schematic drawing of the experimental setup. The device was submerged in a small water tank and connected to a beam fixed to the water tank. Strain gauges were glued on the beam to measure the buoyancy force. We heated the device for 1800 s with a nichrome wire and a peltier device and cooled it for 1800 s with only the peltier device. The electrical conditions are shown in Table 1.

Figure 8 shows the result. With a heat sink, the ratio of the final buoyancy change to the expected value (0.11 N) was

Table 2: Electrical conditions of nichrome wire and peltier device.

Thickness of air layer	Device	Voltage (V)	Current (A)
0 mm	Nichrome wire	33	1.3
	Peltier device	6.3	2.2
2 mm	Nichrome wire	36	1.2
	Peltier device	6.3	2.6
12 mm	Nichrome wire	36	0.7
	Peltier device	6.3	2.6

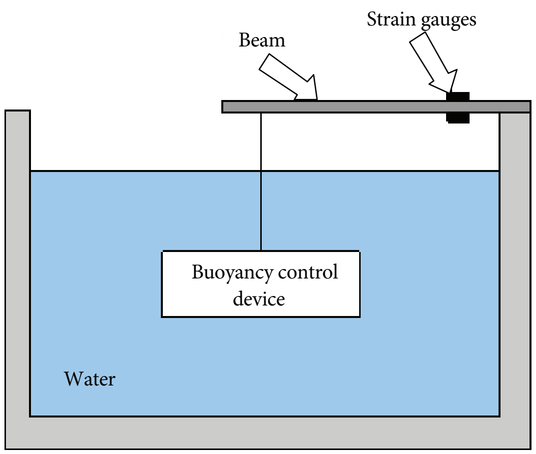


Figure 7: Schematic drawing of experimental setup.

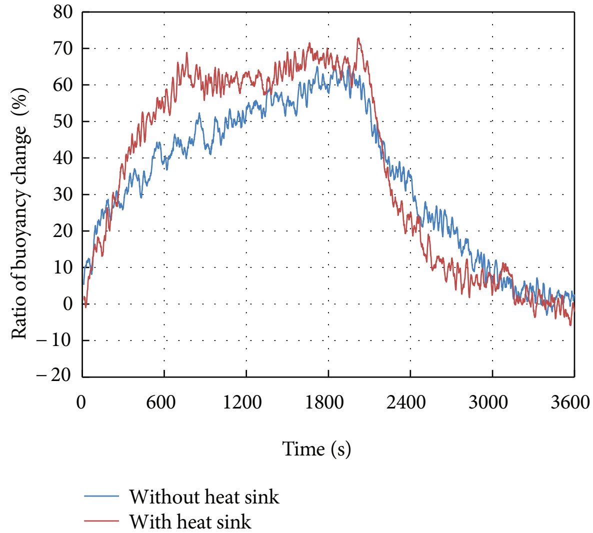


Figure 8: Result of buoyancy change.

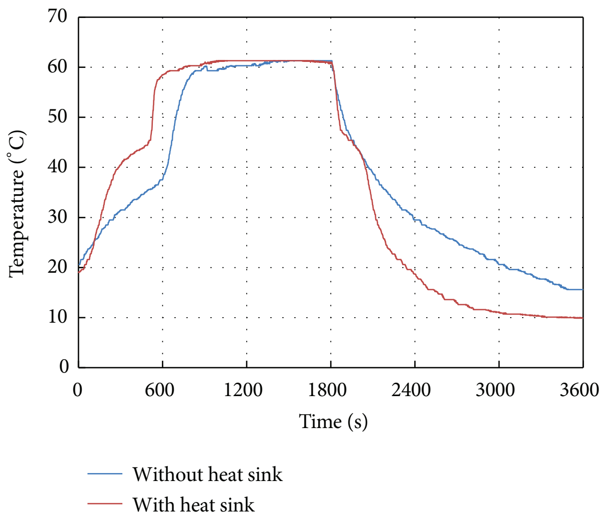


Figure 9: Internal temperatures.

approximately 70% and 60% without a heat sink. Although the difference is small, the speed of the buoyancy change with a heat sink is faster than without it. This tendency can be seen in Figure 9, which shows the internal temperatures. The results mean that the effect of a heat sink can be expected in the buoyancy change speed. However, the buoyancy change is smaller than expected, probably due to inadequate insulating. Therefore, we conducted a second experiment.

3.2. Effect of Thickness of Air Layer. To examine the insulating effect, we prepared three acrylic cylinders with different thicknesses. Each cylinder can be installed in the device. The thicknesses of the air layers were 0, 2, and 12 mm. A thickness of 0 mm means that there is no air layer. The experimental setup and the method are the same as in the previous section. The electrical conditions are shown in Table 2. The 0 mm conditions are the same as the conditions with the heat sink shown in Table 1. Thus, the experimental data of 0 mm in Figures 10 and 11 is the same as the result with the heat sink in Figure 5.

Figure 10 shows the results of the buoyancy change. The air layer thickness increased, and the buoyancy change also increased. For example, the ratio of the buoyancy change to the expected value (0.11 N) in 12 mm is approximately 90%, and in the case of 0 mm thickness, it is below 70%, confirming that the air layer works well. Its thickness should be as great as possible.

Figure 11 shows the internal temperature, which is slightly different because of the differences of the water temperatures. From this figure, the highest temperature after 1800 s of heating is 60°C in the 0 mm thickness. However, its buoyancy change is the worst. This means that heat dissipated to the outside and not all the paraffin wax melted. Because the temperature sensor is in the center of the heat sink, the temperature of the wall of the aluminum block should be lower than that of the center. In the case of 2 and 12 mm, the highest temperature is almost the same. However, their buoyancy change is different because of the insulating ability of the air layer.

4. Prototype Robot

4.1. Design and Dimensions of Robot. After concluding that our proposed mechanism works well and a heat sink and air layer should be installed to achieve an efficient heat transfer based on the results of the previous sections, we designed

Table 3: Dimensions and specifications of prototype robot.

Weight (kg)	8.6
Width (m)	0.42
Height (m)	0.20
Length (m)	0.54
Theoretical value of maximum buoyancy change (N)	0.45

Table 4: Electrical conditions in experiment on each device.

	Peltier device	Nichrome wire	Control system
Voltage (V)	6.30	36.3	14.0
Electric current (A)	2.26	1.15	0.04

Table 5: Electrical conditions in experiment using prototype robot.

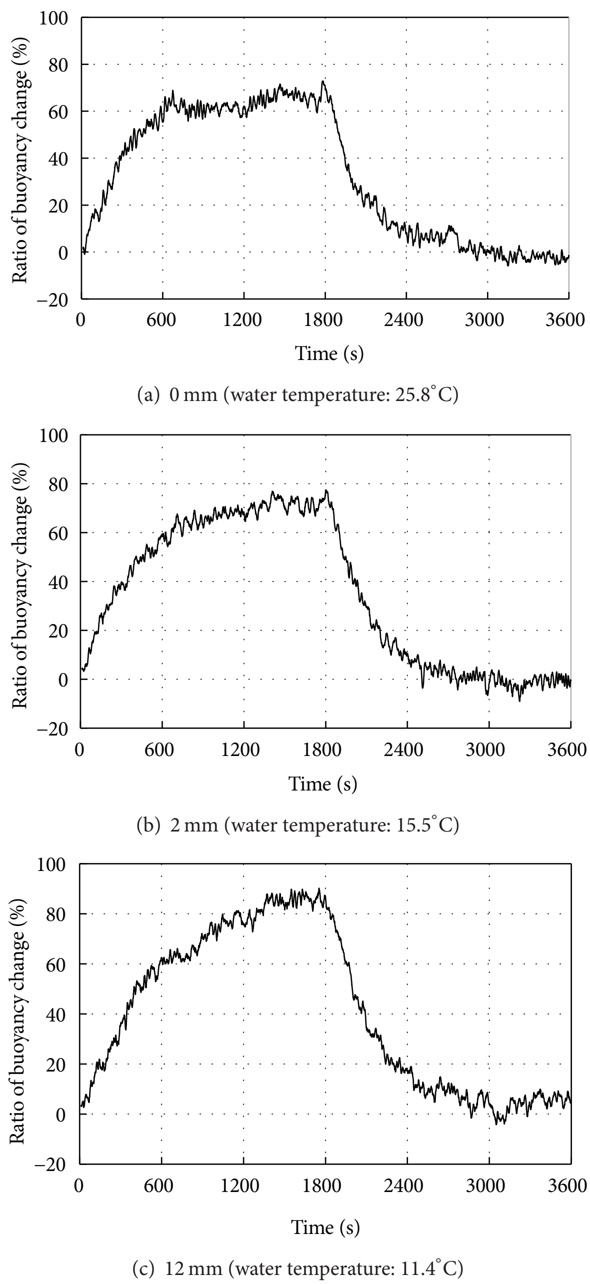
	Peltier device	Nichrome wire	Control system
Voltage (V)	6.31	30.2	14.0
Electric current (A)	0.02–2.79	6.26	0.08

and built a prototype underwater robot (Figure 12). It has four buoyancy control devices, which are arranged on the following positions on the robot's body: right front, left front, right rear, and left rear. We used four devices to achieve posture control by choosing the number of heating and cooling devices. The dimensions of the robot are shown in Table 3. The theoretical value of the maximum buoyancy change is approximately 0.45 N, which is the sum of the four devices.

The control circuits in the robot body were covered by an acrylic cylinder and spheres. A power source and a PC were placed on the outside, which means that our prototype robot is tethered.

4.2. Experiments. First, we measured the buoyancy change and the internal temperature of each device. In this experiment, each device was heated for 1800 s and then cooled for 1800 s. The experimental setup is the same as in Figure 7. The water temperature of the water tank was 22.1°C, and the electrical conditions are shown in Table 4. Figures 13 and 14 show the buoyancy and temperature changes of each device. All the devices have almost the same characteristics and achieved the expected maximum buoyancy change.

Next, we measured the buoyancy change of the prototype robot. The electrical conditions and the result are shown in Table 5 and Figure 15. The water temperature was 17°C. In this experiment, the devices were heated for 5400 s and cooled for 2800 s. Figure 15 shows that the robot can obtain the expected maximum buoyancy change (0.45 N). In the cooling period, the buoyancy returns to 0 N within about 2500 s, which is faster than the heating period. One reason for this larger heating period and smaller cooling period is the water temperature of the small water tank, which may affect the water temperature in the aluminum block and the bellows and the paraffin wax temperature.



(a) 0 mm (water temperature: 25.8°C)

(b) 2 mm (water temperature: 15.5°C)

(c) 12 mm (water temperature: 11.4°C)

Figure 10: Buoyancy change in each air layer thickness.

5. Discussion

5.1. Metal Bellows and Other Mechanisms. The metal bellows used in this study can withstand 1 MPa of pressure, which is almost the same water pressure in 100 m of water. Although we have not evaluated the resistance pressure of the other parts of the mechanism yet, the mechanism with a metal bellows is useful for underwater robots because it almost achieved the maximum buoyancy change. The proposed buoyancy change mechanism can be used for investigations of shallow continental shelves and lakes, if other mechanical parts withstand that pressure.

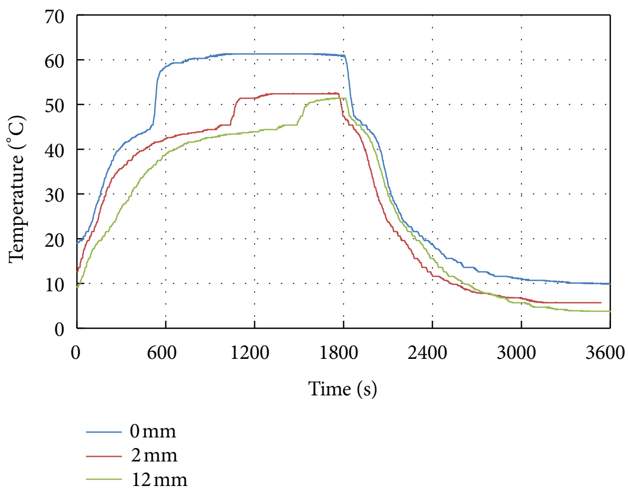


FIGURE 11: Temperatures of paraffin wax.

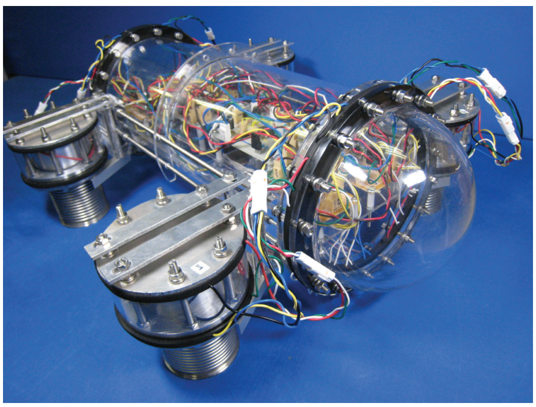


FIGURE 12: Photograph of prototype robot.

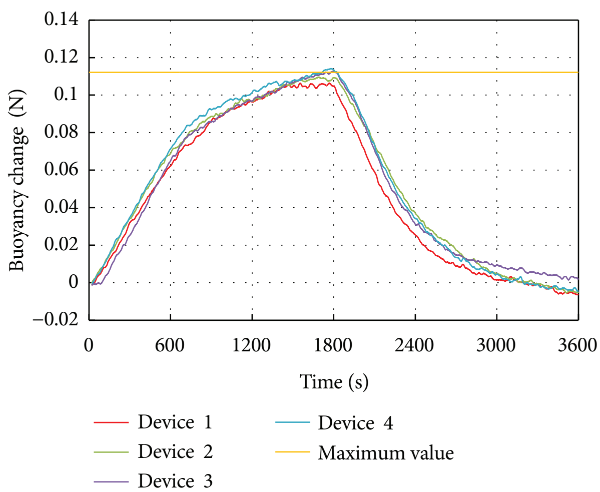


FIGURE 13: Buoyancy change of each device.

We put the four devices on our prototype robot. However, small differences of their performances exist (Figure 13), which will cause a posture change. In that case, another posture control mechanism may be needed.

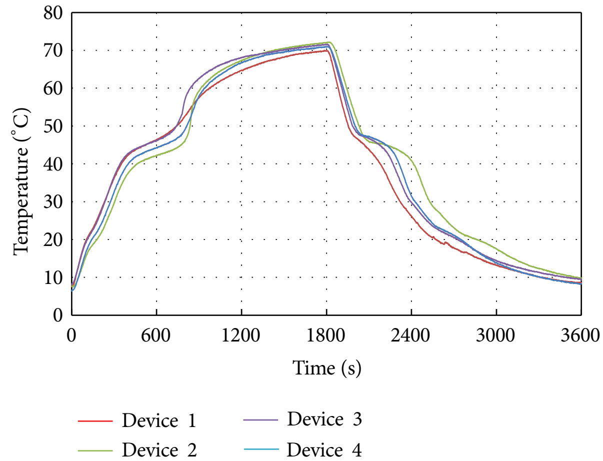


FIGURE 14: Temperature change of each device.

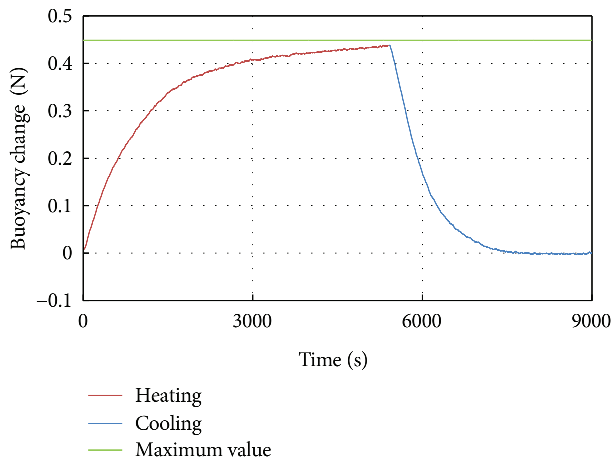


FIGURE 15: Buoyancy change of robot.

From Table 2, we can calculate the supplied power to one device with a 12-mm air layer to cool it as follows: 36 V × 0.7 A + 6.3 V × 2.6 A = 34.6 W. If we use the same four devices, we need 138 W. This value remains large and should be reduced for building a real robot with our proposed devices.

Although we built devices with other mechanisms with piston and rubber stretching [10, 11], we cannot directly compare their results because we used different paraffin wax masses. However, the cooling and heating times were reduced by decreasing the mass of the paraffin wax. Therefore, we believe that dividing the paraffin wax into small portions is one promising method.

5.2. Effect of Air Layer. By using a heat sink and a large air layer, the efficiency of the heat transfer can be increased. However, the time for obtaining the maximum buoyancy change remains large. One explanation of the problem is an inefficient heat transfer mechanism. For example, much heat dissipates to the outside of the bellows through the water in it during the heating period. To prevent such heat dissipation, we have to design a more efficient heat transfer mechanism. For example, we may recover and utilize waste heat in a propulsion system to heat the paraffin wax. Conversely, we have to release much heat to the outside in the cooling period. As described in the previous section, dividing paraffin wax into smaller portions is one idea. Searching for other phase change materials with lower melting points is another challenge. In the deep sea, since the water temperature will decrease and affect our device, we have to develop a more efficient insulating mechanism or find a material with a lower melting point.

6. Conclusion

In this paper, we proposed a new mechanism for a buoyancy control device with a metal bellows. We experimentally confirmed that a heat sink increases the speed of the buoyancy change and that the thickness of the air layer is critical for efficient insulating. Then, we built a prototype robot using the four proposed mechanisms with a metal bellows.

The next step in this research is to achieve posture and depth control. Also, we want to evaluate the response of the robot posture and the depth control system to such disturbances as waves. The response time presented in this paper is too slow and must be reduced approximately a few minutes at least. Another challenge to attain our goal is to find a new phase change material whose melting point is much lower than that of paraffin wax to reduce the response time and the energy consumption. To attain that goal, we also have to build a mechanism for a more efficient heat transfer. After solving these problems, we want to build a real underwater robot or vehicle and control its depth and posture.

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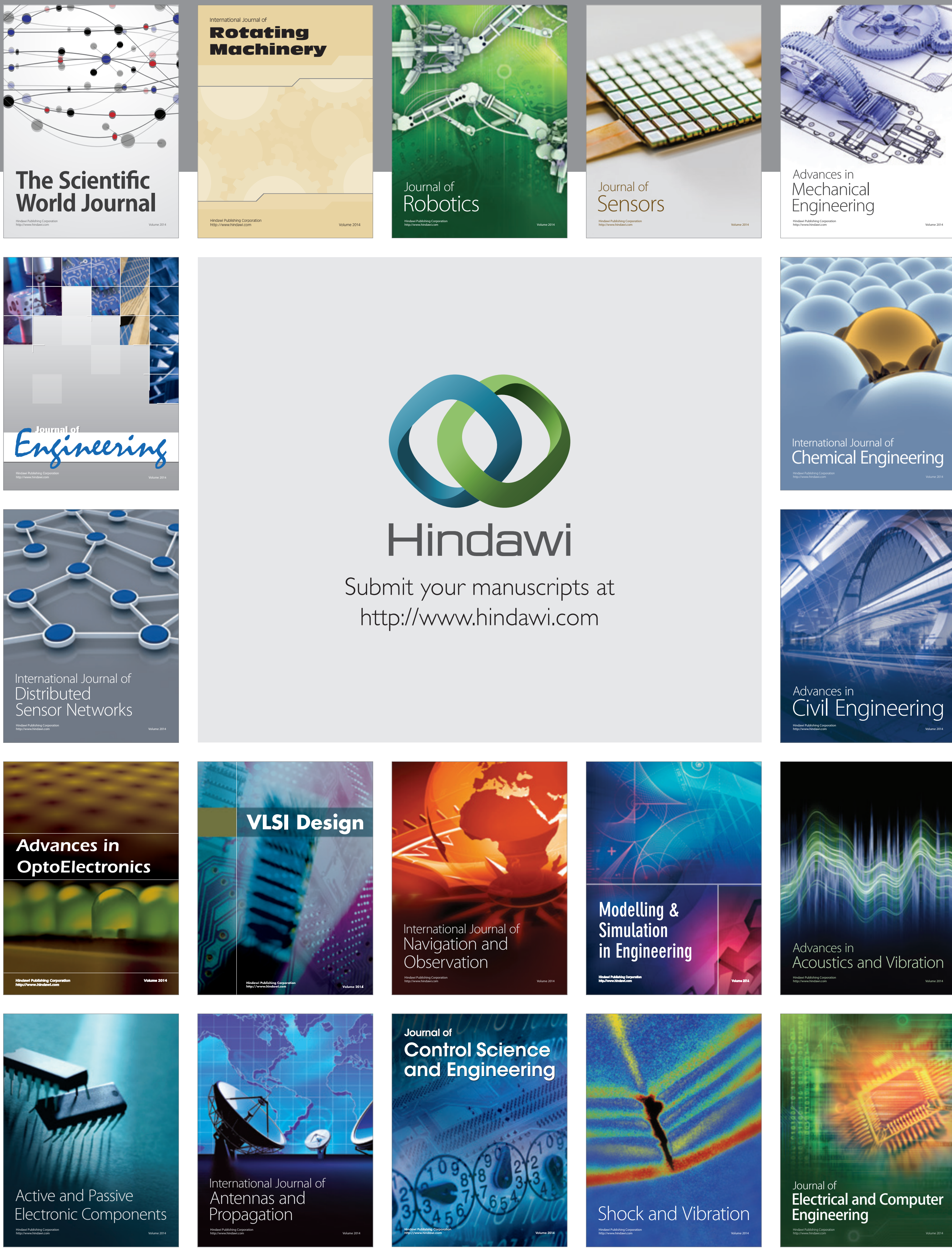
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