Drag Force Based Propulsion Mechanism for Underwater Robots
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Abstract
This paper introduces a new propulsion mechanism for underwater robots to explore the ocean bottom and other maricultural applications. Various types of existing bionic fish stimulated from real fish are advanced nowadays so that disparate from those types of fish, bionic shrimp mechanism inspired from shrimp swimming is contributed. Focusing on the swimming method of paddling limbs of shrimp, a paddle-type propulsive method is developed that applies the motion of the abdomen during swimming of the shrimp. The experimental results of the propulsive motions using the developed prototype are demonstrated and analyzed to evaluate the effectiveness of propulsive forces.

Keywords: underwater robot, paddle, drag force.

1. Introduction
The ocean covering over 70% of our planet’s surface is the life force of Earth. According to surveys, more than 80% of our ocean remains unmapped, unobserved, and unexplored. Meanwhile, Japan is a maritime nation surrounded by sea on all sides. For that geographical reason, sea explorations in Japan have been paid attention to scientists and/or engineers for the observation of mysterious living things and underwater resources.

Toward the contribution to sea explorations, unmanned underwater robotic systems need a propulsion device for moving around desired areas. The propulsion device generates thrust to have a system move in an assigned direction. According to thrust-generation methods, existing propulsion mechanisms are roughly classified into three types: screw propellers(1), pectoral fins(2), and caudal fins(3). In practice, the propulsion device for the explorations have mainly used screw propellers. The screw propeller is to transmit torque generated by rotations into thrust. The main feature of propellers is highly efficient thrust so that they can be largely useful in marine transportations. Propeller fans are capable of controlling pitch motions. However, there exist several limitations of propellers. The main weakness is a cavitation phenomenon, resulting in a great deal of noise, damage to blades, vibrations, and a loss of efficiency. Another problem is the sudden stoppage or breakdown due to the entanglement in nearby algae and garbage caused by the rotation of the blades. To make matters worse, the marine creatures are injured when they come into contact with the blades.

This paper introduces a novel robotic swimming mechanism for underwater robots. To overcome these limitations above, based on swimming motions generated by abdomen limbs of shrimp, a paddletyped propulsion mechanism is proposed as illustrated in Fig. 1. Since the shrimp swims by paddling their limbs, this swimming motion does not rotate at high speed and cavitation does not occur. Specifically, the propulsion mechanism allows to employ phase difference between paddling motions by individual paddles, resulting in enhancing more propulsive force. Unlike screw propellers employing lift force, the proposed mechanism uses drag and then moves its platform forward with the drag force as a propulsion. For that reason, the proposed mechanism allows to explore the nearby seabed, not available to other propulsions. This paper explains detail on the proposed mechanism. The effectiveness for the mechanism is evaluated through extensive experiments.

2. Problem Statements
Shrimps have an organ called swimming legs, which are named pleopods in a biological terminology, near the
abdomen and behind the front legs. Although the shrimp swims with the small organ relative to its body, four pairs of pleopods are moving like a paddle to generate forward thrust. Specifically, each pair of pleopods with a different time lag starts and continues to paddle. When the movements of the pleopods are represented by a graph of angle variations with respect to time, the variations can be drawn as a sinusoidal pattern. Moreover, the time lag of the paddling in terms of each pleopod appears regularity to a certain extent. In the rest of this paper, this time lag is referred to as phase difference. More interestingly, the shrimp does not shake its whole body while swimming. This means the paddling by pairs of pleopods of the shrimp does not employ another driving motion to swim.

This paper addresses how to design and develop a paddle-typed propulsion device that imitate shrimp’s swimming motions. As a first step toward imitating shrimp swimming, the pleopods are investigated by studying biological papers and observing the swimming motions of real shrimps. From an engineering viewpoint, swimming motions by artificial pleopods as called paddles are modeled to apply this into a propulsion device. By realizing the mechanical motions, a propulsion prototype is designed. Using a prototype, extensive motion experiments, such as forward movement and turning on a two-dimensional plane are conducted to verify the effectiveness. Based on the developments, the next direction is to verify whether our propulsion device can be used for an underwater robot.

3. Drag-Based Propulsion

3.1 Driving Force: Drag

This paper aims to imitate the pleopods based swimming movements by using a motor instead of muscles. To realize the swimming motions, the pleopods are simplified as paddles which are used for rowing a boat. Note that, differently from screw propellers outputting lift, the paddle-based swimming motion uses drag. Drag is generally the force that acts on the surface of an object and prevents its movement. Similar to the lift force, it is a force proportional to the square of the speed on the paddle, and it is generated in the direction opposite to the paddling direction. Based on the principle, the paddle motions allow an object to move forward with that force as a driving force.

To help clearly understanding the propulsive force generated by paddling, Fig. 2 shows the conceptual illustration of paddles. To begin, the coordinate system of a propulsion device including paddles is explained. Its traveling direction is \( \hat{y} \), and 90 degrees clockwise from \( \hat{y} \) is \( \hat{x} \). where \( \hat{x} \) and \( \hat{y} \) intersect at the origin \( O \). The opposite of the gravity direction \( \hat{g} \) passing through \( O \) is defined as \( \hat{z} \). Similar to the number of pleopods, four pairs of paddles are considered. The four paddles with the same length in the one side are uniformly located. And the end point of each paddle \( e_i \) is fixed by using each pivot. Specifically, the straight line \( \hat{H} \) passing through individual pivots is parallel to \( \hat{y} \).

Next, as shown at the right side in Fig. 2, the center of the \( i \)-th paddle \( D_i \) where \( i \) indicates to 4 from 1 is considered as its representative point. A local coordinate system with respect to this point represented by the \( i \)-th origin \( O_i \) is set. Furthermore, the opposite of \( \hat{g} \) is expressed as \( \hat{z}_i \). A horizontal vector \( \hat{y}_i \) with respect to \( O_i \) is defined by rotating 90 degrees from \( \hat{z}_i \) counterclockwise. \( \hat{y}_i \) and \( \hat{z}_i \) are parallel to \( \hat{y} \) and \( \hat{z} \), respectively. Finally, it is assumed that drag applied to \( O_i \) is regarded as overall drag applied to \( D_i \). When the drag is decomposed according to \( \hat{y}_i \) and \( \hat{z}_i \), the component force in \( \hat{y}_i \) is defined as the propulsive force in this paper.

3.2 Four Pairs of Paddles

As referring to a biological paper(4), the shrimp exercises the swimming legs in order from the rear side with a phase difference. As illustrated in Fig. 3, the reason for this distinct motion is that the next swimming leg moves before the backward flow caused by the previous movement disappears. By performing this series of swimming motions on all pleopods, it is considered that a higher propulsive force than normal paddling can be generated.
To imitate the phase-difference swimming motions, a model is formulated. As illustrated in Fig. 2, the angle between the line passing through \( O_i \) and \( e_i \) and \( \vec{H} \) is defined as \( \alpha_i \). Then, \( \alpha_i(t) \) indicates the swimming state of \( D_i \) according to time with respect to \( \vec{H} \) and is given:

\[
\alpha_i(t) = \theta_i + a \cos(\omega t + \theta_i),
\]

(1)

where \( \theta_i \), \( \theta_i \), and \( \omega \) are \( D_i \)'s initial value, phase difference, and angular velocity, respectively. Moreover, \( a \) denotes the amplitude parameter.

4. Paddle-Propelled Mechanism

Figure 4 shows our fabricated paddle prototype composed of a base unit and a blade unit. First, the base unit plays in a role connecting a motor to the blade unit for pulling an oar (paddling). Secondly, the blade-unit prototype has a length of 65 mm, width of 16.7 mm, and thickness of 1.2 mm.

The proposed propulsion device reciprocates the paddles in the water. When pulling the oar in the direction opposite to the traveling direction, a force is generated in the backward direction. By trial-and-error learning, two approaches to the mechanical designs for paddles are proposed to decrease the loss of propulsive force. To make it easy for water to flow at that time, the blade part is bent into a V-shaped pattern from the center line in the direction of travel. In addition, a passive foldable part is devised to be used at the connection between the base unit and the blade. When the paddle is moved backward, it bends from the foldable part due to the resistance of water, and the blade unit remains folded backward to prevent the generation of thrust in the backward direction. Once the paddle is moved forward, the stopper in the base unit is applied in order to prevent it from being bent due to water, resulting in generating the thrust and advancing under water. Practically, a spring is incorporated between the base and the blade so that the blade returns to its original position immediately before the backward movements.

Figure 5 shows the prototype design and its dimensions.

The prototype is composed of three components: paddle device, electronic and control module including batteries, and prototype frame. In the prototype, the paddle device is positioned at bottom part. The electronic parts and batteries are arranged in the both sides and the upper part of the prototype. Specifically, the motors are lay out at the interior of the bottom part.

Fig. 4. Fabricated paddle prototype.

Fig. 5. Developed prototype.

Fig. 6. Control architecture of paddle-based prototype.

Next, details on individual components are explained. Figure 6 presents the control architecture based on wireless controlled prototype. First, the paddle device is introduced in previous section. Secondly, the electronic and control module includes servo motor, microcontroller, motor driver, Bluetooth kit, and so on. The Arduino Uno Rev3 ATmega328 microcontroller controls the operations of the prototype according to commands sent by a host controller through the KeeYees HC-05 Bluetooth kit. The microcontroller forwards the control signals moto the TowerPro SG90D-5 servo motors through the VKLSVAN PCA9685 motor driver after the modulation of the pulse width modulation (PWM). Specifically, the motor driver allows eight servo motors to be controlled simultaneously. Eight motors the same as the number of paddles are installed, and the paddles are directly connected to individual rotating shafts of the motors. Finally, a 9V alkaline battery is used as the power source to operate the microcontroller, and a 3.7V lithium battery is used to supply power to the motors.
5. Evaluation Experiments

First, we performed simulations to examine whether the formulation of Eq. (1) generates a desired sinusoid pattern, and whether the combinations of individual sinusoid patterns generate the phase difference. Figure 7-(a) shows the simulation results for individual trajectories based on Eq. (1). In this graph, horizontal and vertical quantities indicate time and radian values, respectively. In this formulation, the amplitude $a$ and the angular velocity are set to 1.5 and 10.65 rad/s respectively. Specifically, the phase difference between individual sinusoid equations is initially given by 0.07 rad. As expected, depending on each of initial values, the sinusoid patterns with the phase difference are generated successfully.

When the formulation was coded by employing four servo motors, we check whether the motions of individual base units in the hardware configuration exhibit sinusoid patterns while rotating. The hardware configuration is presented in the Fig. 7-(b). From the left side to the right, the order of the base units is assigned from 1 to 4. During the rotation motions of the units, we shot the movements. The captured video is applied to a commercial motion analysis software in order to obtain the two-dimensional coordinates of individual base units according to time. From the obtained data, trajectories for the end points of the unit were built. Figure 7-(c) shows the trajectory data generated by individual units. To visualize the unit movements, trajectories are colored, from the left side, in red, blue, violet, and black. Despite implement by using motors, the desired sinusoid patterns and the assigned phase difference are clearly seen in the results. From the result, we can confirm that the combination of the proposed formulation allows to generate the paddle motions with the sinusoidal pattern.

Fig. 7. Experimental results for comparison of paddling motions depending on Eq. (1).

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Next, we check whether the developed paddle-typed propulsion prototype provides continuous sinusoidal patterns in the water. To evaluate the effectiveness of the proposed propulsion mechanism, the developed prototype is prepared to be paddled on water. Similar to previous experiments conducted in the water, the captured video is analyzed to obtain movement data and the comparison between the visual data and input signals is applied. Figure 8-(a) presents snapshots for a series of paddling motions. Due to phase difference, the different postures of individual
paddles at each time are clearly seen in the results. The variations of the postures according to time are plotted in Fig. 8-(b) as the trajectories of individual paddles. Despite paddling generation in the water, input parameters such as amplitude, period, and phase differences are maintained. As a result, we verified that the proposed paddle-based mechanism and its prototype could generate sinusoid patterns with phase difference.

Since another objective in this paper to evaluate the proposed propulsion mechanism, the developed prototype is set to be swam on water and to collect experimental data conducted on the water plane. For this reason, polystyrene foam is attached around the prototype to float on water. The main body with the float attached is moved from the top of the water in the vinyl pool to the two-dimensional movements of straight, swiveling, eight-shaped, and S-shaped by the operation from the PC, and the situation is photographed from directly above. The captured video as shown in Fig. 9 is applied to motion analysis software, and it is regarded as a coordinate point on the two-dimensional plane of the prototype, and its trajectory is confirmed.

6. Conclusions

In this paper, we studied on a mechanism to increase efficiency while taking advantage of the paddle-typed propulsion. Specifically, a paddle type propulsion unit could control the movement, focusing on the improvement of propulsive force due to phase difference in shrimp paddling. In order to verify the mobility of the proposed paddle-typed propulsion device, we conducted an operation experiment such as analysis of the trajectory of the two-dimensional motion and measurement of the propulsive force using the developed prototype, and evaluated the effectiveness of the propulsion method. As a result, it was confirmed that this propulsion unit has a certain motion performance that can be used as a propulsion unit for a robot. It was also confirmed that the phase difference in shrimp swimming exercise can be effective in increasing propulsive force. In the future, we plan to develop three-dimensional elements into the research content and develop them into a propulsion machine that can work underwater.

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References