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Development of a New Manta Robot Considering the Propulsive Resistance

Kota Mikuriya, Keigo Watanabe, Yukito Hamano, Isaku Nagai
Graduate School of Natural Science and Technology
Okayama University
Okayama, Japan
mikuriya-k@usmm.sys.okayama-u.ac.jp

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***Abstract*— In recent years, biological research of an aquatic life is carried out actively. The sea is a dangerous environment for humans, so that we cannot investigate an aquatic life for a long period of time. In addition, conventional underwater robots have a common mechanism for propulsion with screw propellers. Noises generated by screw propellers have a possibility of giving a bad effect on the biological behavior. On the other hand, biomimetic robots can investigate aquatic lives without affecting them significantly. Our laboratory has developed a Manta robot that has propulsion mechanisms with pectoral fins, mimicking the pectoral fin of the manta ray. Conventional Manta robots have a problem that its swimming speed is insufficient for investigating aquatic lives. In this paper, we develop an autonomous Manta robot that is excellent in the propulsion performance by taking account of propulsion resistance caused by the body shape. Several experiments are conducted to show the effectiveness of the proposed method, in the point of the swimming speed and propulsive efficiency.**

***Index Terms*— Manta robot, autonomous underwater vehicle, propulsive resistance.**

I. Introduction

In terms of marine resources development, biological research of an aquatic life is important. However, the sea is a dangerous environment for humans, so that one cannot examine aquatic lives for a long period of time. The development of underwater exploration robots is expected for the biological research of aquatic lives [1]. Conventional underwater robots are equipped with screw propellers for propulsion. Noises generated by the screw propeller give a negative effect on the biological behavior. In addition, aquatic animals and plants are involved in the screw propeller, so that it may be stopped [2][3]. On the other hand, biomimetic propulsion mechanisms such as pectoral fins have an advantage of low radiation noises and they do not catch animals.

Our laboratory has developed a conventional Manta robot that has propulsion mechanism with pectoral fins, which are constructed by mimicking the pectoral fin of the Manta ray. The Manta robot generates the propulsive force by undulating a propulsor consisting of the right and left pectoral fins, and can make a forward and backward motions, turning motion, and diving motion. The Manta robot can swim in the same way as actual aquatic lives without making a sound, so that it investigates aquatic lives, without affecting objects to be investigated and environments.

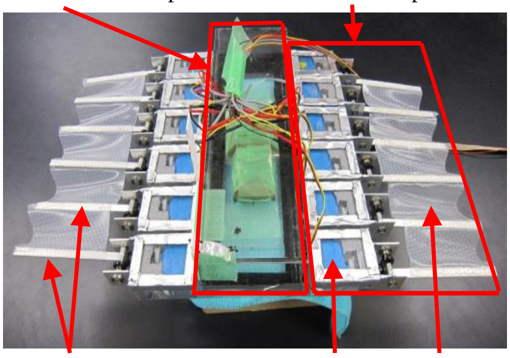


Fig. 1. Manta robot

However, it is expected that the swimming speed of the developed Manta robot is insufficient for the biological research, because the swimming speed of the Manta robot does not reach to those of many aquatic lives. In addition, there is a problem that the constraint about the power cable prevents the robot motion from moving freely.

In this research, we would develop an autonomous Manta robot that is excellent in the propulsion performance by taking account of the propulsive resistance. The propulsion performance of the Manta robot is improved by adopting a streamline shape, which has a less propulsion resistance as the body shape of the robot. In addition, letting the Manta robot be autonomous can exclude a problem that a power cable interrupts the motion of the Manta robot. In this paper, after giving an overview of the Manta robot, we describe how to improve the propulsion performance. Furthermore, a new Manta robot is developed and it confirms the effectiveness of the proposed method through several experiments.

II. Manta Robot

The appearance of the conventional Manta robot developed by our laboratory is shown in Fig. 1. The size of such a conventional Manta robot was 385 [mm] in length, 685 [mm] in width, 75 [mm] in height, and 5.9 [kgf] in weight. The conventional Manta robot consisted of a float in the center of the robot and a pair of propulsion mechanisms with pectoral fins. Each propulsion mechanism with a pectoral fin was composed of six fin-rays, where the fin was covered with the

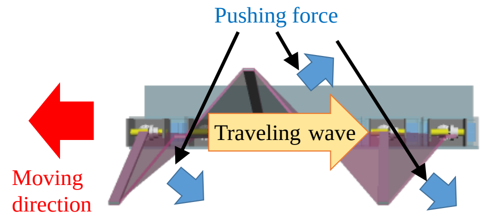


Fig. 2. Forward motion

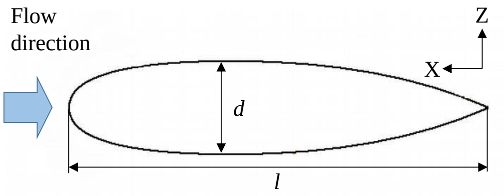


Fig. 3. Streamline shape

thin cloth made from acrylics connected between fin-rays. Each fin-ray was independently driven by each servo motor. The Manta robot generates a propulsive force while undulating the propulsion mechanisms with pectoral fins.

III. Waveform with Fin-rays

As shown in Fig. 2, the Manta robot forms a progressive wave at fins on both side, and moves forward by pushing the water to the rear of the robot. Assuming that this progressive wave is to be a sine wave, the angle of the *k*-th fin-ray counted from the front, θ_k [rad], is expressed by the following formula:

$$\theta_k = \theta_{k0} + \theta_{max} \sin(2\pi f t + (k-1)\varphi) \quad (1)$$

where *t* [s] denotes the time, θ_{max} [rad] a maximum angle of the fin-ray, *f* [Hz] the frequency of the fin-ray, and φ [rad] the phase difference between the adjacent fin-rays. Furthermore, θ_{k0} [rad] is the initial state position of the *k*-th fin-ray, counted from the front.

IV. Improvement of Propulsion Performance

The propulsion resistance is reduced by improving the body shape, for the objective of improving the propulsion performance of a Manta robot,

A. Propulsion resistance in water

The propulsion resistance in motion in a fluid is divided into a form drag and a skin friction drag. The skin friction drag is determined by the surface area of the object and the viscosity of the fluid. On the other hand, the form drag denoted by *D* is given by:

$$D = C_D\left(\frac{1}{2}\rho U^2\right)S \quad (2)$$

Here, C_D is the form drag coefficient, ρ is the density of a fluid, *U* is the flow velocity, and *S* is the reference area. The C_D is determined by the shape of the robot and Reynolds number, which is generally obtained by experiments. Moreover, the

Reynolds number is a dimensionless quantity characterizing

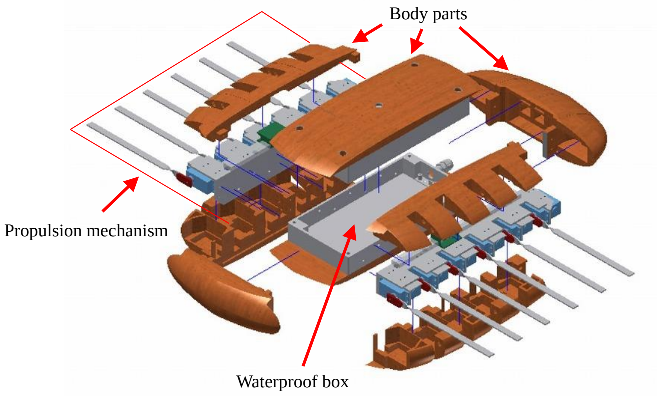
Fig. 4. New Manta robot

Fig. 5. The structure of a new Manta robot

the flow conditions. Therefore, Eq. 2 shows that it is necessary to reduce the form drag coefficient C_D to reduce the propulsion resistance of the robot in water.

B. The Shape for Low Form Drag

It is known that the body shape of aquatic lives has low propulsion resistance to swim efficiently in the water. The



shape for the low propulsion resistance is called a streamlined shape. In order to reduce the propulsion resistance of the Manta robot, a streamlined shape is adopted to the body shape of the robot. As shown in Fig. 3, the shape for a low form drag coefficient is determined by the results of wind tunnel experiments about a streamlined solid of revolution conducted by Fuhrmann and Abbott[4]. There is the slenderness ratio on determinants of the body shape to minimize the propulsion resistance while keeping the volume constant. When Eq. 3 is satisfied, the form drag coefficient becomes the smallest.

$$l = 4.5 \times d \quad (3)$$

The Manta robot with a low propulsion resistance is realized by applying this shape to the cross-sectional shape in the X-Z plane.

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V. Development of a New Manta Robot

We develop a new autonomous Manta robot that has a high propulsion performance. The appearance of the new Manta robot is shown in Fig. 4.

A. Specification and structure of the new manta robot

The size of the new Manta robot was 405 [mm] in length, 620 [mm] in width, 90 [mm] in height, and 5.3 [kgf] in weight. The new Manta robot is AUV (Autonomous Underwater the Vehicle) that is not retrained by the cable. By incorporating a battery as a power source, the robot can be operated for 30 or more minutes at the maximum load. Also the Manta robot is equipped with a control circuit and an inertial measurement unit for acquiring the position and attitude of the robot. A streamlined shape is adopted to the body shape of the robot. Fig. 5 shows the structure of the new Manta robot. The new manta robot is composed of a waterproofed box, a propulsion mechanism with two pectoral fins, and exterior body parts as a float.

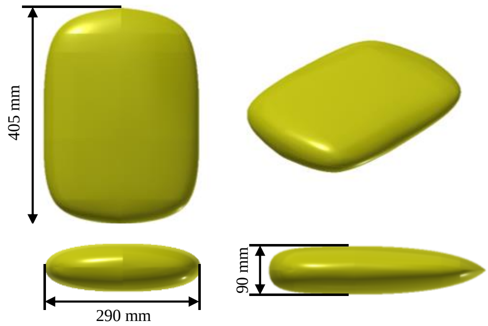

Fig. 6. Body shape

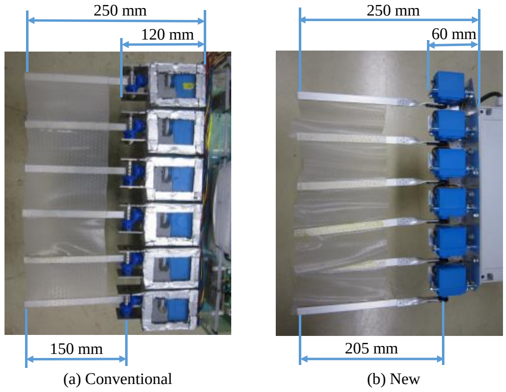

Fig. 7. Improvement of the propulsion mechanism

B. Design of the body shape with a streamline shape

The body shape of a new Manta robot is designed by using Autodesk Inventor. The body shape of the Manta robot is not a perfectly prolate spheroid as represented in a streamline shape, that is, it is laterally wide shape, such as squashed from above and below. Therefore, as shown in Fig. 6, a streamline shape with small propulsion resistance is adopted as the cross-sectional shape of the longitudinal direction of the robot, whereas the cross-sectional shape in the right-and-left direction is nearly elliptical.

By outputting the body parts with a 3D printer, a complicated shape can be easily realized and a function to float is induced by providing a space inside of the part.

C. Improvement of a propulsive mechanism with a pectoral fin

Downsizing of a propulsive mechanism with a pectoral fin was performed. The conventional propulsive mechanism with a pectoral fin and the improved one are shown in Fig. 7. The use of HS-5646WP, a waterproof servomotor, in the improved mechanism can exclude a bevel gear for changing the direction of the rotation, a waterproof container for waterproofing the servo motor and a stern tube for taking out a rotational force from the waterproof container. As a result, the width of the mechanism for driving the fin-ray is downsized to 60 [mm] from 120 [mm], and furthermore an improvement in the propulsive efficiency can be expected because there is no more power loss due to the stern tube and the gear.

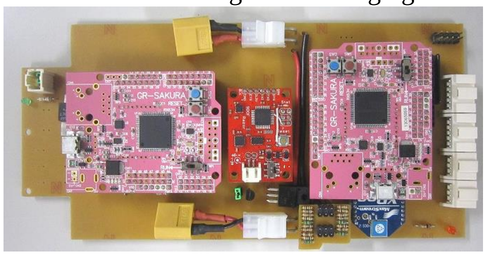

Fig. 8. Control circuit

D. Control system

A control circuit built in the robot is shown in Fig. 8 . The new Manta robot can move autonomously in water by mounting the Li-Po battery and the control circuit. To operate the robot, a command is sent to the GR-SAKURA microcomputers within the robot from the controller such as a PC on the ground through a radio wave. The movement of a fin-ray for propulsion is realized by utilizing the feedback control of the servo motor. Ammeter or voltmeter can be equipped to detect the overload applied to the servo motor

In addition, it is possible to detect the position and attitude of the robot by using an inertial measurement unit and store the corresponding data to the SD card by using the data logger.

VI. Comparative Experiments in Propulsion Performance

A. Experimental method

In this experiment, the propulsion performances are compared between two robots, which have different body shapes. The propulsion performance of the Manta robot is discussed from two phases: i.e., one is the swimming speed to the propulsion force and the other is the power consumption to the swimming speed. A conventional Manta robot with a rectangular body shape and the improved Manta robot with a streamline body shape are used in the experiment, where each robot mounts the same fin. Fig. 9 shows the pool used in the experiment, whose size is 3000 [mm] in width, 2000 [mm] in depth and 750 [mm] in height, where the water level is 700 [mm] in the experiment. The method for measuring the swimming speed of the Manta robot is based on obtaining an average velocity of the robot, where the time required for swimming straightly during 1 [m] distance is counted, starting from a static state underwater. Note here that the number of trials was three for each robot in this experiment.

Fig. 9. Experiment environment

TABLE I. PARAMETERS OF THE TRAVELING WAVE

	θ_{max} [rad]	ϕ [rad]	f [Hz]
Conventional manta (a)	0.436	0.349	0.8
Conventional manta (b)	0.523	0.436	0.9
Conventional manta (c)	0.610	0.523	1.0
Improved manta (a)	0.317	0.349	0.8
Improved manta (b)	0.380	0.436	0.9
Improved manta (c)	0.443	0.523	1.0

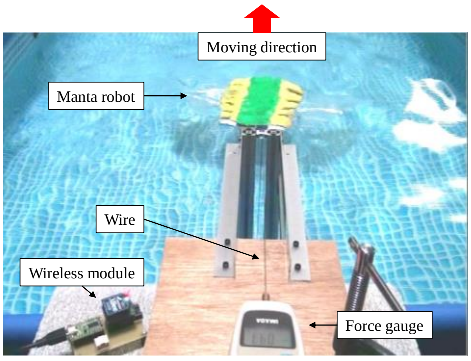

Fig. 10. Measurement of propulsive force

The parameters related to the traveling wave to be generated in the fins are shown in Table 1. Here, as can be seen from Fig. 7, both robots are different in the length of fin-ray because they are different in mechanism. To compose a same traveling wave in the fin of both robots, a different maximum angle of fin-ray is to be set, depending on the length of fin-ray. As shown in Fig. 10, the propulsive force of the Manta robot is measured by using a force gauge connected to the robot through a wire. The power consumption of a propulsive mechanism with pectoral fins is measured by a current meter and a voltmeter that are mounted on the control circuit. The snapshots are given in Fig. 11 for one sample measurement of the improved Manta robot.

B. Experimental results and considerations

The experimental results are shown in Fig. 12 and Fig.13. It is seen from Fig. 12 that the improved manta robot has high propulsive speed for the propulsive force, compared to the conventional Manta robot. From this result, it is considered that the improved manta robot has low propulsive resistance, compared to the conventional manta robot.

(a) 0 s (b) 3 s

(c) 6 s (b) 9 s

Fig. 11. One sample view of swimming of the improved Manta robot

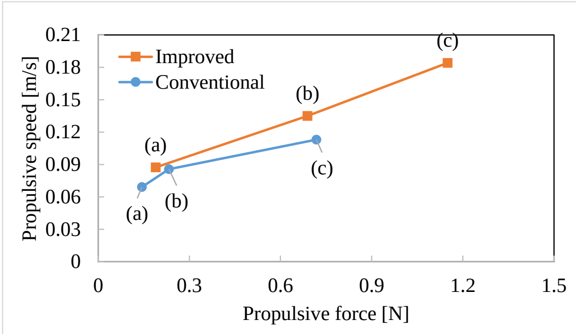

Fig. 12. Propulsive speed against the propulsive force

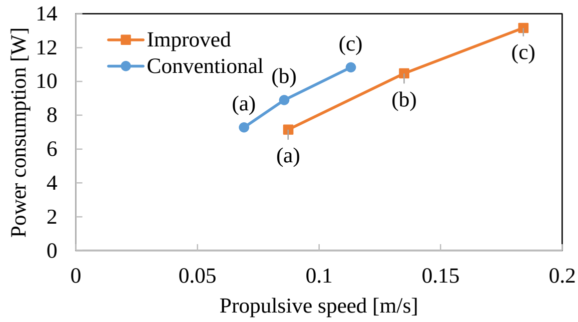

Fig. 13. Power consumption against the propulsive speed

As for propulsive speed, it is seen from Fig. 13 that the improved manta robot can swim with less power consumption, compared to the conventional Manta robot. From this result, it is considered that the improved Manta robot has high propulsion efficiency, compared to the conventional Manta robot. Thus, it is considered that the improvement of the body shape of Manta robot is effective for improving the propulsion performance.

VII. CONCLUSION

In this paper, we developed the new autonomous Manta robot that is excellent in the propulsion performance by considering the propulsive resistance. A propulsion resistance is reduced by applying a streamline shape to the body shape of the robot. Then, we conducted a comparative experiment of a propulsion performance with improved Manta robot and conventional Manta robot. As a result, it was confirmed that the propulsive resistance was reduced and that the propulsion efficiency was also improved.

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