Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Compact Swimming Robot with Continuum Water Jet Nozzle for Rapid Turns ⋆

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Abstract: In this paper, a swimming robot capable of rapid turns not only horizontally but also vertically in an underwater environment is proposed. The robot utilizes a wire-driven continuum water jet nozzle, which can be oriented in an arbitrary direction and allows the robot to turn in a small radius. In this study, the deformation characteristics of the nozzle were first experimentally investigated, and the nozzle was then implemented in the robot. The performance of the robot was experimentally investigated in an underwater environment. The results indicated that it was capable of a high angular velocity, and could accomplish 180 degree turns within a tactical diameter that was smaller than its body length.

Keywords: Robotics, Robots, Flexible arms, Soft robotics, Swimming Robots, Underwater vehicles.

1. INTRODUCTION

1.1 Background and Purpose

In recent years, surveying narrow spaces where human entry is difficult is being increasingly performed using remotely operated robots. For example, to investigate the pedestal where cooling water had accumulated in the Fukushima nuclear power plant, Toshiba Corporation developed a screw-propelled underwater robot called "Mini Manbo" [1]. Underwater robots with swimming capability are required for exploration of such narrow places. These robots must be small and capable of moving and turning quickly in three dimensions so as to avoid obstacles. In order to achieve these goals, a mechanism is required that allows the robot to quickly follow the operator's commands.

Generally, there are two methods for controlling the movement of vessels in water. One is the use of a rudder. Among vessels using a rudder, submarines are also capable of up and down movements. In order to steer submarines, a system called an X rudder is used. It attains vertical and horizontal lift by arranging four winged rudders in an X shape. By controlling them independently, three-dimensional movement in arbitrary directions can be achieved. However, the turning radius using rudders is usually several times the length of the ship [2]. Therefore, it is unsuitable for exploration where obstruction of vision occurs due to the turbidity of water or where obstacles often need to be avoided. The second method is to use multiple thrusters. This method is widely used for underwater exploration robots called remotely operated underwater vehicles (ROVs). Such ROVs were developed for various purposes and have various shapes. However, when an improvement in propulsion ability is required, the thrusters must become larger with respect to the robot body, so it is not a preferable method for miniaturization to use multiple thrusters. Consequently, it seems necessary to seek other methods that have not yet been used for small submersible robots.

The purpose of the present study is to propose and develop a swimming method for a small underwater robot capable of turning quickly within a small radius.

1.2 Related Work

Screw propellers are widely used in ships. In the studies on small underwater robots, there are various methods of propulsion, including biomimetic robot that moves the tail fin to simulate the movement of real fish, and swimming using instantaneous force by elastic body.

Claphan and colleagues developed iSplash-II which swims by imitating the movement of fish moving the tail [3]. It has a body with low fluid resistance imitating actual fish and converting high speed rotation of one motor into translational motion that moves the tail fin to the left and right. The 320 mm long robot can swim very fast, i.e. 11 body length per second (3.7 m/s). On the other hand, three-dimensional swimming such as turning and levitation has not been realized.

Liu and colleagues presented a kinematics model to observe and imitate the C-shape swivel (CST) of fish to realize the swimming ability of fish [4]. Also, in order to implement this, a 4 joint fish robot with a total length of about 800 [mm] was created. This assumes that behavior

⋆ This study was supported by a Grant-in-Aid for Scientific Research 16K06188 from Japan Society for the Promotion of Science (JSPS).

can be realized by decomposing and approximating fish tail fin behavior into a series of gestures. The created robot behaves like a fish and achieves a maximum angular velocity of 110 [deg./s]. However, when compared with the actual fish, the turning speed is slow and a better mechanical design is required.

Yamada et al. proposed a swimming robot with an elastic closed loop structure using snap-through buckling with bending and torsional deformation of a band-shaped elastic body [5]. This robot fixes both ends of a band-shaped elastic body and instantaneously performs a swinging motion using the resistance of the fluid by attaining a sudden large deformation via the proposed buckling mechanism in water. It can perform rapid turns of about 135 deg./s during the propulsion state. However, turning due to an instantaneous force has a fixed rotation angle, and is not suitable for three directional change. Also, it is difficult to construct a slim machine structure.

Takesue et al. developed a robot that swims like a fish by vibrating the fins using the resonance of the elastic body [6]. This robot produces a propulsive force by a built-in vibration motor swinging an elastic plate, which acts as a tail fin. Also, turning can be performed by attaching an elastic plate to the side of the body. By changing the mounting position of the elastic plate, this 51 mm robot can achieve the 3.2 body length per sec (165 mm/s) and the minimum turning radius to 24.9 mm, and the shortest time to turn 360 deg. by 3.4 s. However, it is difficult to move underwater, and three-dimensional swimming has not been achieved.

From these studies, it can be said that a swimming robot capable of three-dimensional swimming with miniaturization and high swing performance is unrealized.

1.3 Our Proposal

In this paper, we propose the use of a wire-driven flexible water jet nozzle to realize a high-performance swimming robot [1]. In the proposed mechanism, the thrust direction can be quickly changed by rotating a water jet. This is similar to a jet ski, which is like a water motorcycle, and is steered by a water jet instead of a propeller.

The swimming robot created using the proposed mechanism is shown in Fig. 1. The robot to be developed advances straight by water jet propulsion driven by a DC motor. For the swing mechanism, a deformable continuum manipulator mechanism is used for the continuum water jet nozzle, and by being made to be drivable by three servomotors, it is possible to change the direction of injection in all directions. As a result, the swimming robot can directly convert the propulsive force into the lateral force during the straight movement, so that the swing robot can quickly turn with a small turn. As a propulsion device, a water jet is generally smaller than a propeller screw mechanism. In addition, because the mechanism converts the force of the same water jet for turning, it is realizing small size and light weight as an underwater robot capable of three dimensional swimming.

[1] The earlier version of this study was presented at a Japanese conferences [7], but here we propose a swimming robot with a new mechanism, i.e., a largely deformable wire-driven continuum tube as a flexible water jet nozzle which drastically improves the turning performance of the robot.

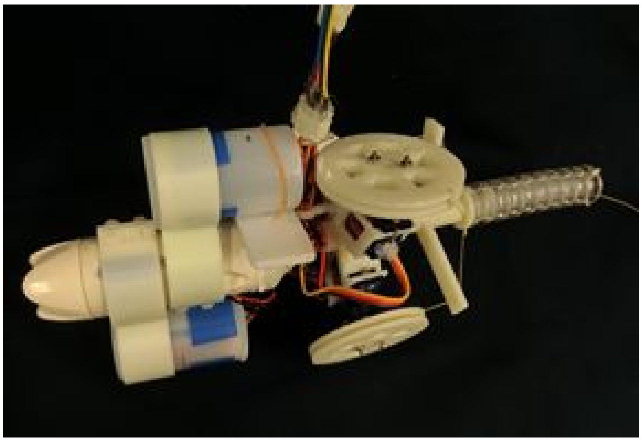

Fig. 1. The proposed swimming robot

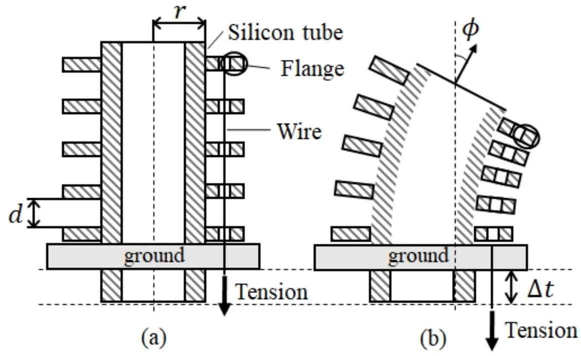

Fig. 2. Deformation mechanism of the continuum water jet nozzle by wire tension. (a) Wire is not pulled. (b) Wire is pulled.

2. DEFORMATION MECHANISM FOR WIRE-DRIVEN CONTINUUM WATER JET NOZZLE

In this section, we describe a small swimming mechanism with a wire-driven continuum water jet nozzle. Fig. 1 is an overall view of the mechanism. A wire-driven continuum water jet nozzle is a type of continuum manipulator, and it causes curvature by pulling a wire attached to the tip [8, 9]. Fig. 2 shows the state into which the continuum water jet nozzle deforms according to the pulling of the wire in the figure.

2.1 Mechanism

As shown in Fig. 1, the wire-driven continuum water jet nozzle consists of a continuum body of a hollow silicon tube (inner diameter 8 mm, outer diameter 10 mm), a wire, a flange for passing the wire through, and three servo motor (SG92R, Tower Pro, JAPAN) pulleys, which are mounted onto a base molded by a 3D printer. To control the servo, a microcomputer (Arduino UNO, Arduino SRL, Italy) is used, and is connected to an external power supply using a cable. The servo was subjected to waterproofing treatment so that it could be submerged completely underwater together with the main body. The junctions of cables

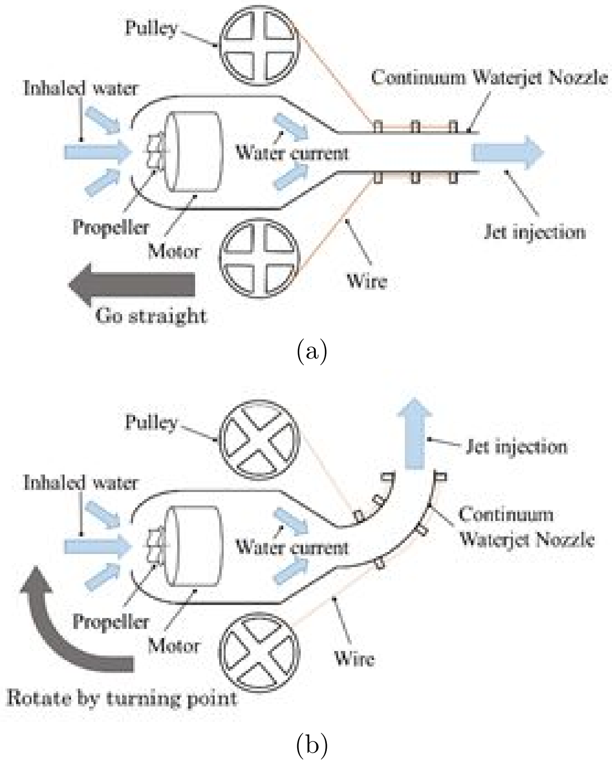

Fig. 3. Deformation mechanism of the continuum water jet nozzle using wire tension (a) Wire is not pulled. (b) Wire is pulled.

and parts were filled with liquid silicone, and waterproof grease was used between the gear and the motor housing to prevent flooding.

2.2 Behavior

Fig. 2 shows how the continuum water jet nozzle curves under the tension of the wire. As shown in Fig. 2(a), a number of flanges are adhered to the side surface of the continuum water jet nozzle. Of these, the wire is attached to the most distal flange, as shown in Fig. 2(b), and by applying a downward force, tension is generated, and the flange can be pulled downward. At this time, the moment due to the distance from the center acts, and only one side of the continuum water jet nozzle contracts, and thereby curvature occurs. The continuum manipulator prepared in this study is deformed in all directions by equally arranging three wires at 120 degrees each and controlling the pulling amounts. Fig. 3 shows how to change the water jet by bending the continuum water jet nozzle. As shown in Fig. 3, it is possible to change the direction of the water flow by the continuum water jet nozzle using a hollow continuum object such as a silicon tube. The continuum water jet nozzle has the property of continuously curving unless buckling occurs. Without buckling, it keeps the inner diameter constant [8], and loss of internal water flow is prevented. Therefore, the injected water jet can change its direction while maintaining its momentum.

Fig. 4 is a series of photographs taken to show the shape change of the continuum water jet nozzle. Fig. 4(a) shows the process of curving occurring at the maximum speed from the initial state, and Fig. 4(b) shows the return to the initial state after curving. From 0.133 s to 0.167 s in Fig. 4(b), it can be seen that the vibration of the continuum water jet nozzle converges. In Fig. 4(a), the restoring force of the elastic body acts in the direction opposite to the pulling direction of the wire, and in (b), since it acts in the same direction as the loosening of the wire, a time difference occurs between the two deformations.

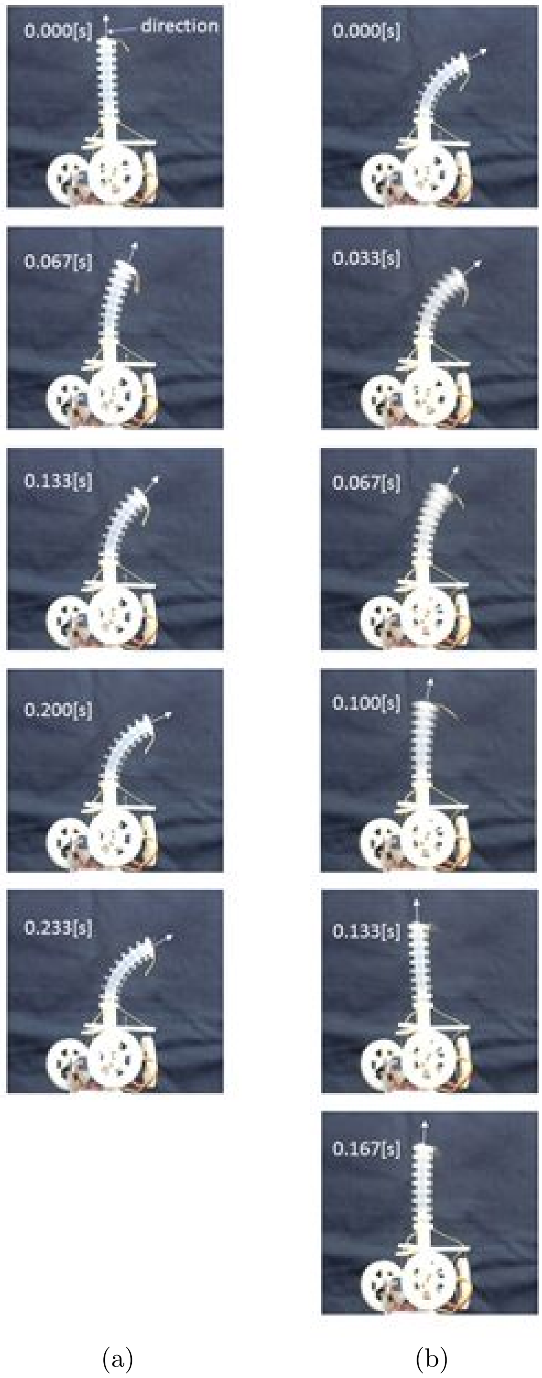

Fig. 4. Deformation of wire-driven continuum water jet nozzle. (a) The wire is pulled and the continuum water jet nozzle deforms. (b) The wire is released and the continuum water jet nozzle returns to its initial position.

Fig. 5. Buckling of a silicon tube

2.3 Bending characteristic

It is known that when an elastic body is deformed, buckling occurs when a compressive load above a certain level is applied. Even in the silicon tube used in this mechanism, deformation due to buckling occurs as shown in Fig. 5, when the tension is increased above a certain level, and the cross-section of the flow path becomes smaller. Generally, the load necessary for buckling is inversely proportional to the square of the length of the structure. Therefore, it becomes more difficult for buckling to occur as the length of the structure becomes shorter. Therefore, in this mechanism, buckling was prevented without changing the length of the continuum water jet nozzle by splitting the structure into multiple units by bonding together multiple flanges. To prevent buckling, the distance between flanges is set to $d = 6.5$mm (see Fig. 2) which results in 9 flanges along the nozzle.

In addition, when the continuum manipulator has a large frictional force, hysteresis, which is a deviation from the initial shape, occurs after bending. At this time, if the deviation from the origin is large, it will be difficult for the swimming robot to return to rectilinear motion after the turn. In chapter 3 we will examine the extent to which hysteresis occurs under water flow conditions.

3. DEFORMATION EXPERIMENT ON CONTINUUM WATER JET NOZZLE

The hysteresis of the curved shape was measured when the continuum water jet nozzle, which is an elastic body, is deformed. In the experiment, the continuum water jet nozzle was placed in water, and was photographed while being deformed by a certain angle and then returned to its original state.

3.1 Experimental method and results

A water jet generator was attached to the wire-drive continuum water jet nozzle and a water flow was generated. This situation is shown in Fig. 6. Next, after deforming the continuum water jet nozzle by gradually driving the servo motor and pulling the wire, the servo angle was returned to the initial position. For comparison, the same experiment was carried out in the air. At the maximum torque of the servo, it was found that the tip angle was $\phi = 99$ deg.

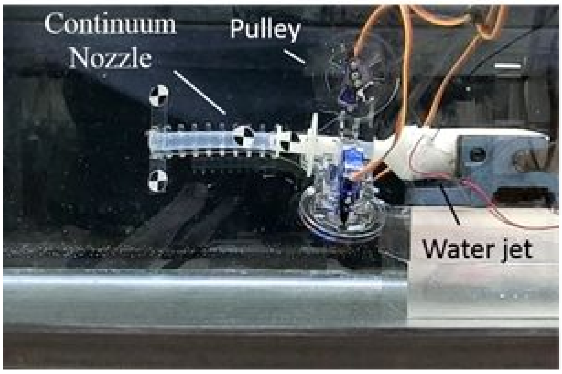

Fig. 6. Bending experiment of the continuum water jet nozzle in water

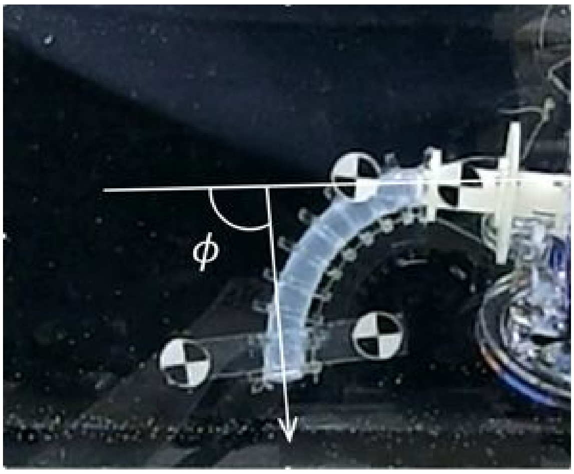

Fig. 7. Angle of tip of maximum pulling length at the wire

The state of deformation at this time is shown in Fig. 7. Moreover, it was confirmed that it returned almost to its initial state by the restoring force of the continuum water jet nozzle.

3.2 Analysis and discussion

Fig. 8 shows the relationship between the nozzle and servo angles in water. The relationship is seen to be linear. Usually, the relation between the pulling length at the wire and the bending at the continuum water jet nozzle. Fig. 9 shows the relationship between the nozzle and servo angles in air. As can be seen from comparison with Fig. 8, the maximum bending angle decreased in water. This is thought to be due to the fact that the water jet produces a restoring force. The difference is about 7 degrees, which is considered to be a problem for the development of swimming robots.

4. DEVELOPMENT OF COMPACT SWIMMING ROBOT

The small underwater swimming robot developed in this study can be rotated three-dimensionally in the vertical and horizontal directions by deformation of the continuum water jet nozzle causing water jet propulsion. Although a metal wire was used in Chapter 3, a Kevlar fiber was used here. This is because the shape of the metal wire is likely to be deformed.

Fig. 8. Relationship between angle of nozzle and servo rotation angle about the behavior in water

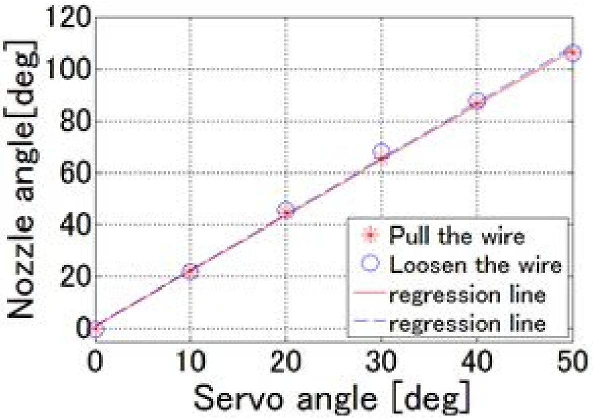

Fig. 9. Relationship between angle of nozzle and servo rotation angle about the behavior in air

4.1 Mechanism

The robot consists of a front water jet generator, a rear wire-driven continuum water jet nozzle, and a float for balance adjustment. In order to prevent the robot from overturning due to rolling when swinging, a Styrofoam fitting was cut out and a blade for balance adjustment was attached to it. To control the robot, a signal was sent by the cable using a joystick (Thumb Joystick, Grove). Fig. 10 shows three views of the robot, and Table 1 lists its specifications. As can be seen from the front view and side view, the robot is small enough to fit inside a cylinder with a diameter of 117 mm. A lithium polymer ion battery was built into the lower part of the front water jet and was used as the power supply. It also functions to suppress rotation in the roll direction by lifting the upper part. Since the robot operates underwater, the servo motor was waterproofed. Of the total weight of 220 g, the water jet propulsion device was 75 g and the continuum water jet nozzle was 125 g.

4.2 Behavior

The robot can eject water sucked into the water jet generator. When this happens, by deforming the continuum water jet nozzle in accordance with the operation of the joystick, the robot can be rotated in an arbitrary direction.

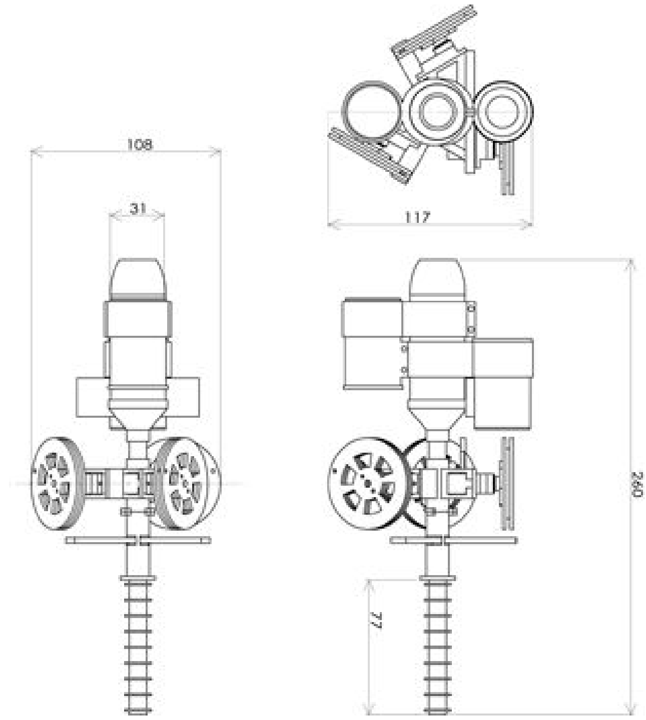

Fig. 10. Top, front, side views of the swimming robot

Table 1. Specification of swimming robot

Length [mm]	260
Width [mm]	108
Height [mm]	117
Mass [g]	220
Turning circle [mm]	222

Fig. 11 is a series of photographs taken of the robot swiveling horizontally to the left. It is moving in a straight line at 0.00 s, and immediately after this deformation occurs and is completed in 0.20 s. The swinging of the swimming robot starts simultaneously with the deformation. However, from 0 to 0.5 s, the robot shifts to the right from the original route. From 0.5 to 0.8 s, the robot turns in place, almost without changing its position. From 0.8 s, the continuum water jet nozzle begins to return to its original shape, the deformation is completed at 1.0 s, and the transition to the state of traveling in a straight line is completed. It is possible to do this without a time lag because changing from movement in a straight line to turning and returning to straight-line movement are all performed continuously.

In order to achieve three-dimensional swimming, the robot has the ability to move in the vertical direction. Fig. 12 shows how the robot rotates vertically and dives. By bending the continuum water jet nozzle downward, the pitch is reduced, and by moving straight in this state, the robot can dive. Likewise, it is possible for the robot to float by deforming the continuum water jet nozzle in the upward direction.

5. SWIMMING PERFORMANCE

The swimming performance was evaluated by experiment. The robot was operated underwater, and its ability to travel in a straight line and turn was evaluated. The water

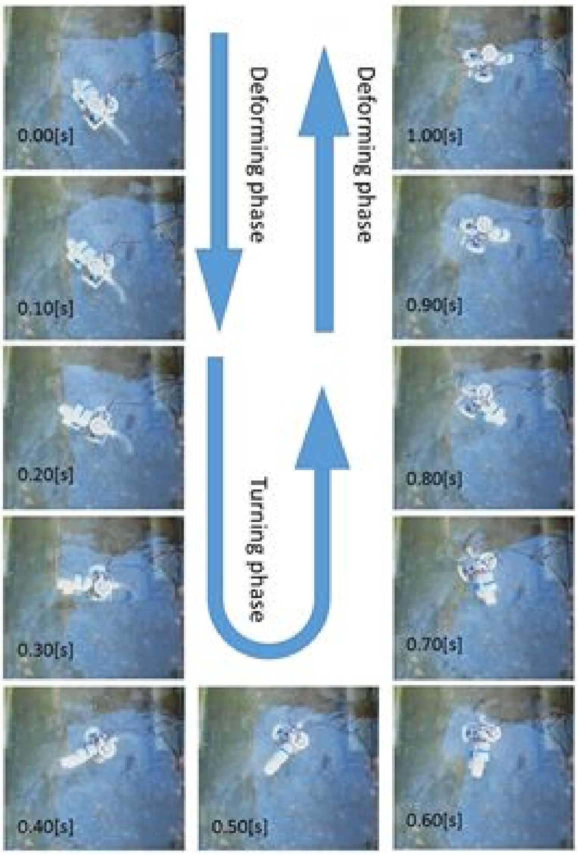

Fig. 11. Top view of the turning motion of the swimming robot

tank used for the measurement was 1800 mm × 600 mm × 600 mm in size.

5.1 Swimming in a straight line

The robot was first made to move in a straight line and its swimming speed was measured. The average speed was determined to be 0.25 m/s.

5.2 Turning performance

The turning performance index in this study was that used for ships [2]. It is based on the transverse distance, the longitudinal distance, and the turning radius during a 90 degrees turn. In Fig. 13, "advance" refers to the distance travelled in a direction parallel to the original course, and "Transfer" refers to the distance travelled in a direction perpendicular to the original course. The turning angular velocity is also considered.

The change in the robot position with time in Fig. 11 is analyzed and shown in Fig. 14 for the robot tip, the center of gravity and the rear part (the base of the continuum water jet nozzle). The arrows indicate the movement direction of the robot.

Evaluation of turning performance by turning radius With respect to the effectiveness of the initial rudder, as a measure of the turning performance, the lateral distance, the longitudinal distance, and the turning radius at the

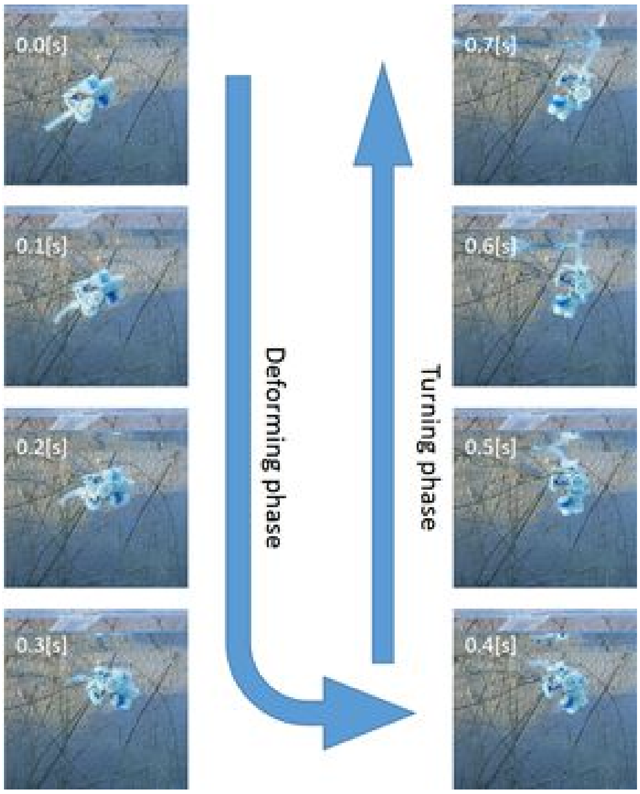

Fig. 12. Side view of the dive motion from surfacing

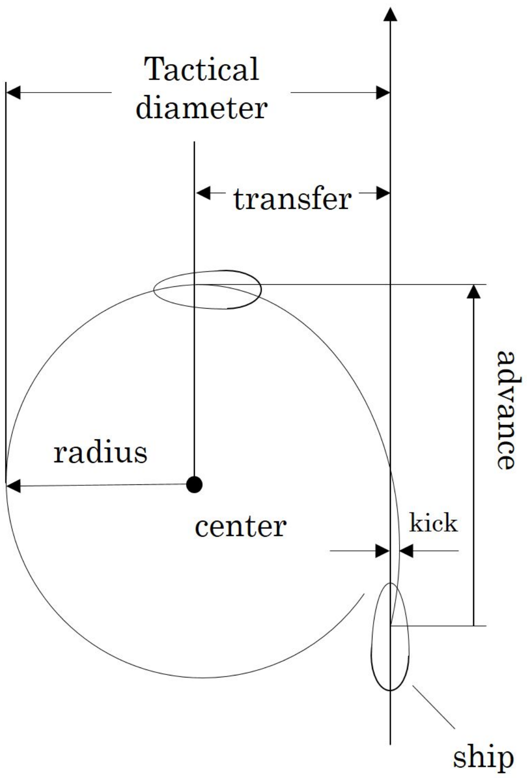

Fig. 13. Turning a ship using a rudder

time of 90 degrees turning are divided by the body length, respectively, and this is taken as a measure of the large angle changeable needle performance. The turning radius is the distance from the turning center to the center of

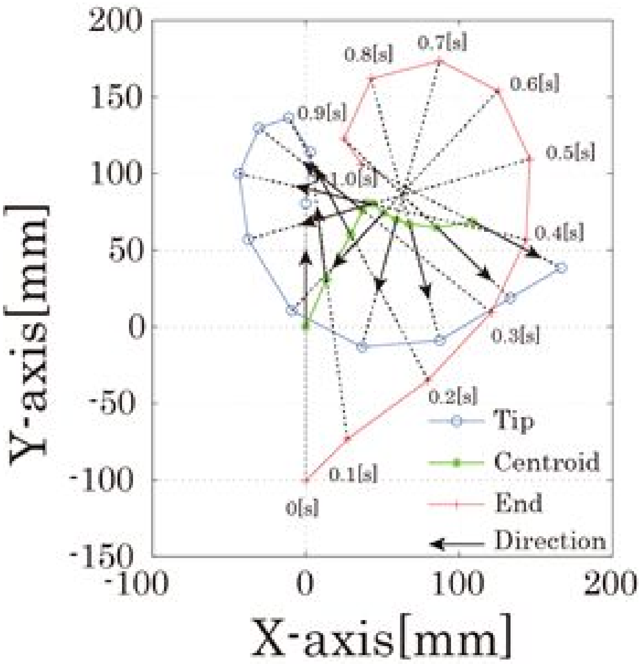

Fig. 14. The orbit of robot turning motion

Table 2. Turning performance of the swimming robot

Advance / Body length	0.23
Trancefer / Body length	0.45
Turning radius / Body length	0.069

gravity. From Fig. 14, it can be seen that circular motion is occurring from 0.5 to 0.8 s, so we can regard the distance between the turning center and the center of gravity as the turning radius. If the intersection of the dotted lines at 0.5 and 0.8 s is the turning center, the average turning radius is 16.9 mm. Unlike in the case of turning a ship shown in Fig. 13, since the robot is moving to the right from the navigation route, the lateral distance is always a negative value. Table 2 shows the turning performance normalized by body length. For an average ship, the normalized turning radius is 3-10. Despite a ratio of the standard that is different in size from the swimming robot, the swing radius/body length ratio for the robot is 0.069, which indicates a very small turning diameter compared to using a rudder.

Swing angular velocity and trajectory In this study, one of the development objectives is to have a quick swing speed. Fig. 15 shows the change in angular velocity with elapsed time during a turn, based on Fig. 14. The curve is drawn by using Matlab function Butterworth filter. It can be seen that starting at about 0.3 s, the angular velocity stabilizes to a certain extent after an initial increase. The average value during the stable period is 291 deg./s.

Next, the trajectory of the route traced by the robot is described. Focusing on the rear part of the robot in which the force acts first with the ejection of water, as shown in Fig. 14, the locus traces a gentle curve at the beginning of the turn, but it gradually becomes sharp at 0.5 s and converges to a locus close to a circular arc. This state is called steady turning motion. Next, the trajectory of

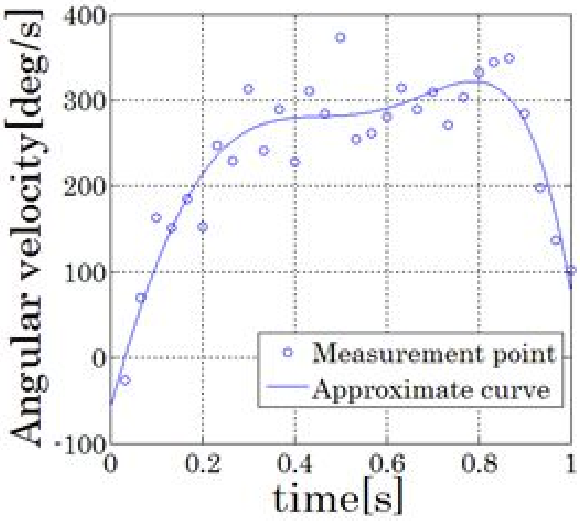

Fig. 15. Time course of angular velocity

the center of gravity starts moving a significant amount, but after a certain time this movement becomes less. This seems to be influenced by the time until the deformation of the continuum water jet nozzle is completed.

Although the robot generally turns to the left, it initially drifts strongly to the right when its center of gravity moves in the opposite direction to the turn direction. This occurs from 0.1 to 0.4 s, after which the center of gravity moves in the traveling direction. This phenomenon is referred to as kick. When a ship turns, the distance traveled due to kick is about 1% of the body length, but in the swimming robot in the present study, a kick distance of about 23% occurred. It is thought that this is due to a large force in the direction opposite to the turning direction.

In Fig. 14, looking at the dotted line connecting the tip and the rear, we see that it intersects at one point at 0.5 to 0.8 s, and this point is the turning center. That this occurs at this time is presumed to be because the change in angular acceleration is the same gentle change seen in Fig. 15, because the inertia in the Y direction which it had at the time of moving in a straight line and the inertia in the X direction caused by the kick balanced with the viscosity of the water.

From these experiments, comparing the maximum swing speed of 110 deg./s for the swimming robot created by Liu et al. [4] and the swing speed of 135 deg./s for the swimming robot created by Yamada et al. [5], it was shown that turning is possible.

6. CONCLUSION

6.1 Results of this study

In this study, we developed a wire-driven continuum water jet nozzle for use in a robot capable of three-dimensional swimming, and swinging with a small turning radius, and evaluated its performance. The robot was propelled by a water jet. Experiments in water showed that the robot had a turning radius of 16.9 mm (body length ratio of 0.069) and was capable of high-speed turning at 291 deg/s during steady circular motion. In addition, turning was possible if there was a clearance space of 222 mm on one side (0.85 in body length ratio) of the original route. The robot was shown to be capable of swiveling almost without moving in a steady turn.

6.2 Future prospects

Although the swimming robot proposed in this study could turn in a small circle, the center of gravity moved when departing from a straight line. This phenomenon seems to be caused by a force exerted in a direction other than the rotation direction before the continuum water jet nozzle deforms. One possible countermeasure is to control the DC motor producing the water jet on order to reduce the water flow in accordance with the deformation of the continuum water jet nozzle, or enhance the deformation using a quick response servo motor.

Also, this study has not attempted to optimize the body itself. Therefore, it is necessary to consider factors of the design, such as reducing the fluid resistance and increasing the speed of linear movement, increasing the lift of the side, and suppressing the influence of kick.

REFERENCES

[1] Toshiba Corporation: INVESTIGATION INSIDE PRIMARY CONTAINMENT VESSEL (PCV): DEVELOPMENT OF SUBMERSIBLE CRAWLING ROBOT TO SURVEY INSIDE PCV OF FUKUSHIMA DAIICHI UNIT 3, International Decommissioning Research and Development Organization HP, published on June 15, 2017 (Accessed 2018-2-22)

[2] Seizo Motora, Hull dynamics, The Japan Society of Naval Architects and Ocean Engineers, pp.33-51, 2005. (In Japanese)

[3] Claphan, Richard James., Hu, Huosheng.: iSplash-II: Realizing Fast Carangiform Swimming to Outperform a Real Fish, Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014), 1080/1086, 2014.

[4] Jindong Liu., Huosheng Hu: Mimicry of Sharp Turning Behaviours in a Robotic Fish, Proceedings of the 2005 IEEE International Conference on Robotics an Automation(ICRA 2005), 3329/3334 2005.

[5] A Yamada, A., Y. Sugino, H. Mameda, H. Mochiyama and H. Fujimoto: An Impulsive Turning Mechanism for Swimming Robots Based on Repeated Snap-through Bucking, Proceedings of the 13th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2010), pp. 25.2-260, 2010.

[6] Naoyuki Takesue, Takashi Mitsuzumi, Mikiro Nagasawa: Proposal of Miniature Aquatic Robot Utilizing Resonance of Elastic Plate, Proc. 2015 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2015), pp.1719-1724, 2015.

[7] S. Takahara, H. Mochiyama: Compact Swimming Mechanism with Flexible Waterjet Nozzle, No.15.1 Proceedings of the 2015 JSME Conference on Robotics and Mechatronics, pp. 17-19, 2015.(In Japanese)

[8] Hirose, S., T. Kado, Y. Umetani: Tensor Actuated Elastic Manipulator, Proc. of the Sixth World Congress on Theory of Mechanisms, 978/981, 1983.

[9] Kaiwen Hsiao and Hiromi Mochiyama: A Wire-driven Continuum Manipulator Model without assuming Shape Curvature Constancy, Proc. of the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 436-443, 2017.