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Gliding, Swimming and Walking: Development of multi-functional underwater robot Glide Walker

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***Abstract*— In order to investigate under the sea, various types of underwater robots have been developed. However, most robots can only perform one type of moving such as screw, water gliding or walking, even though there are some creatures which use various types of locomotion in the wild life. Thus, we propose a new type of underwater robot, the "Glide Walker", which can change its way of locomotion between gliding, walking and swimming depending on the situation. It can be performed by using its two wings with 3 DOFs each and its tail with 1 DOF. This article presents the basic concept, the moving strategy and the mechanical design of the robot in details. Moreover, it also presents the developed prototype, as well as the conducted experiments in which the robot was able to perform the three ways of locomotion successfully. Additionally, it also shows the high manipulation capability and the loop maneuver performance of the robot when in the swimming mode.**

I. INTRODUCTION

Under the sea, where the mystery of the earth is few human expeditions have been conducted. This place contains the remains of primitive lives from an ancient era, being therefore an immense experimental field. However, up until now this has been a frontier for the robots developed until the moment, which has encourage the development of various kinds of underwater robots for investigations under the sea in the recent years. These underwater robots can be mainly classified into Cruising-type, Hovering-type, Gliding-type and Walking-type. Among all the types of underwater robots, the most common is the Cruising-type which has a body equipped with one torpedo type screw and which is able to collects data (e.g.,Urashima developed by JAMSTEC [1]). Hovering-type robots, which have several screws in all directions, have the ability of controlling position and posture. Because of this ability, these robots are also equipped with a manipulator and are used for investigation of the seabed. One example is the Shinkai 6500 [2], robot developed by JAMSTEC for deep sea investigation as its name suggests. It is equipped with six screws which are divided into two for main propulsion, two for side movements and two for vertical movements. It is also equipped with a manipulators which is used to collect objects. Gliding-type robots basically don't have any screw but have a wing like a glider to propel by using gravity force or buoyancy force developed. As they consume energy only to control its buoyancy, they can cruise longer distances than a screw equipped underwater robot,Therefore, they are used for observation of wide areas under the sea. Additionally, Gliding-type robots don't emit any disturbance such as noise, vibration and wave to the environment. Some Gliding-type robots have been already developed as commercial products [3], [4]. Arima et al. developed a new gliding-type robot which is equipped with two screws instead of ballast to go underwater, and can perform three dimensional maneuver with controllable wings [5]. To investigate the sea bed, the ability to move slowly along the bottom of the sea is needed. For Cruising-type, Hovering-type and Gliding-type robots, this is a very difficult task once there are continuous currents under the sea and those robots do not have any legs or hands to keep themselves still. To achieve this task, the walking-type underwater robot was developed [6], [7]. Juan, B.H. et al studied multi-legged ROV "CR200 [8], [9]" for investigation of the seabed under strong current. This robot has six legs and two out of them are also used as arms for precise manipulation.

Although these underwater robots were designed for one specialized way of moving, in the wild life there are some creatures which performs several types of locomotion. For example, the abyssal fish "Tripod fish (Bathypterois atricolor)Fig.1(a)" has long rays and can stand with a special fin like a tripod in order to save energy. Another example is the "Epaulette shark (Hemiscyllium ocellatum)Fig.1(b)" which is well known as "Walking shark". This fish can not only swim, but also can move on rough terrains, such as coral reefs, by using its fins in a way similar to walking. For terrestrial animals, these changes of way of locomotion

(a) Tripod fish

(b) Walking shark

Fig. 1. The creature which uses several motion

Fig. 2. Glide Walker

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are very difficult because of the gravity force. However, for underwater animals, these changes are not that difficult as the gravity, which limits the diversity of motion of creatures, is compensated by the buoyancy force, making it a proper environment for the appearance of this multi-functional creatures. However, until now there is no underwater robot which can change its way of moving like the above fishes. Thus, inspired by these unique multi-functional creatures, we decided to develop such underwater multi-functional robot. We believe that such multifunctional robot can be applicable in a large range of work fields, such as sea bottom exploring. In this paper, we proposed a new type of multi-functional under water robot, the "Glide Walker (Fig.2)", which has wings for water gliding but is also equipped with multiple motors to actuate the wings. By using these degrees of freedom, it can alternate its way of locomotion between gliding-mode and walking-mode. After explaining the modes of the Glide Walker, we will describe the mechanism of the robot, as well as the experimental results.

II. CONCEPT OF GLIDE WALKER

As explained previously, gliding is effective for long distance travelling, and walking is also effective when investigating the seabed. But conventional robots cannot achieve these tasks simultaneously. Therefore the concept of Glide Walker is to satisfy both gliding and walking by changing its motion. Glide Walker is based on Water Glider, but it is equipped with three actuators at the base of the wings and one on the tail. Due to these extra degrees of freedom, the wings can perform several different motions. Even though our purpose is not to make a biomimetic robot, we were inspired by some underwater creatures like those previously mentioned. Basically it looks like an ordinary water glider, and it can be controlled in a three dimensional space by using its actuators like an air plane. However, once the robot folds and sticks out its wings to the lower part of the body, it can transform in order to make use of the walking-mode. In the walking-mode, it can walk swinging each wings, resembling the movement of the legs of a biped. Additionally, this variable wings also allows the robot to swim, and several swimming motions are possible such as flapping like a bird and paddling like a breast stroke. By changing the modes depending on the situation, Glide Walker can make use of each mode's characteristic. One operation strategy of Glide Walker is shown in Fig.3. At first the robot dive into the sea in gliding-mode and travel to an investigation area without consuming energy. After reaching close to the investigation area, the robot changes to the walking-mode and investigates the seabed closely. After finishing the investigation, the robot changes to the swimming-mode and swim towards to the surface of the sea or towards another place to conduct the investigation.

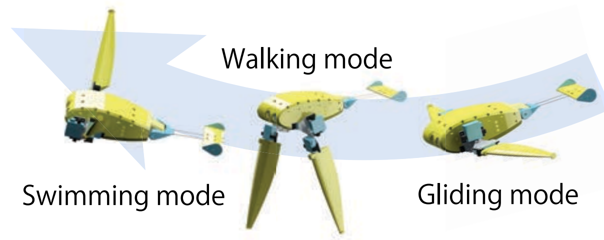


Fig. 3. Strategy of Glide Walker

III. LOCOMOTION MODES OF GLIDE WALKER

In this section, the locomotion modes of Glide Walker are explained in details.

A. GLIDING MODE

In gliding mode, as shown in Fig.4 the robot expands its wings and glides. By making the weight of the robot larger than its buoyancy, it goes downward maintaining its *glide angle* without adding any propulsion forces. While gliding, pitch and roll can be controlled by the *angle of attack* of the main wings and tail, in the same manner as an air plane. The center of lift force can be adjusted by changing the angle of sweepback of the main wings.

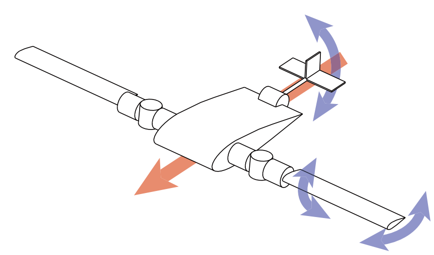
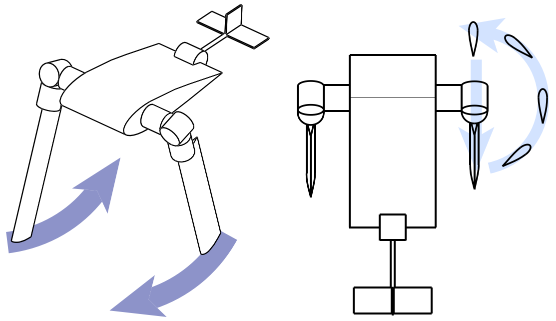


Fig. 4. Gliding-mode

B. WALKING MODE

In walking-mode as shown in Fig.5 (a), the main wings are bended towards the bottom. Using the main wings as legs, it walks like a biped. However because of the limited range of motion of the wings, the foot print of the supporting wing cannot be under the center of gravity and it cause tumbling in the roll axis. Therefore, in order to balance the roll axis, the swinging wing generates a lift force as shown in Fig.6. Additionally, by using its tail, it can stabilize its tilt around the pitch axis.

When it stops and stays in a standing posture, it can stand like a tripod using the tail as the third supporting leg.



(a) Walking-mode (b) Trajectory of wing edge

Fig. 5. The creature which can transform its motion

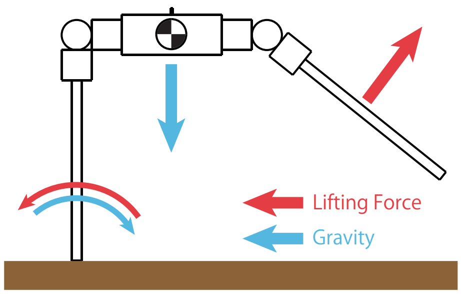


Fig. 6. Front view of walking-mode

C. SWIMMING MODE

In swimming mode, it can swim with several motions of the main wings and the tail.

The first swimming motion is the paddling motion shown in Fig.7. This motion is based on breast stroke. When the wings paddle towards the body, the surface of the wings are perpendicular to the traveling direction of the robot and generate thrust force by pushing the water backward. When the wings go back to expanding position, in order to avoid the generation of backward force, the wings are rotated until the surface of the wing becomes parallel to the traveling direction. By repeating these motion, the robot can swim forward. The disadvantage of this motion is that the propulsion force cannot be generated constantly. Only in the paddling phase the wings generate a thrust force.

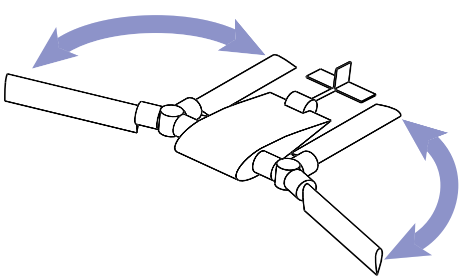


Fig. 7. Paddling Motion

The second motion is the flapping motion shown in Fig.8. This motion is similar to the swimming motion of a Manta ray(Manta birostris). The wing is constantly flapping which produces a lift force which propels the robot. In order to generate a lift force constantly, the pitch of the wings are changed as shown in Fig.8. When bringing down the wing, the *angle of attack* is directed downward, but when bringing up the wing, the *angle of attack* is directed upward. Also by changing the stroke direction, it is able to produce a propulsion force to all direction around the pitch axis.

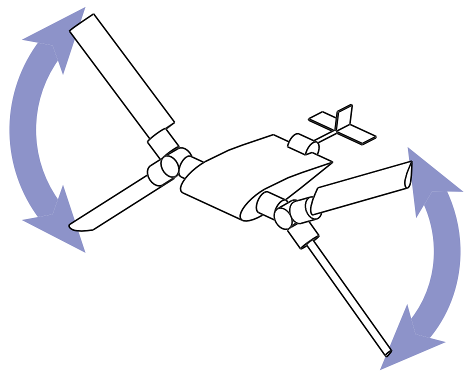


Fig. 8. Flapping Motion

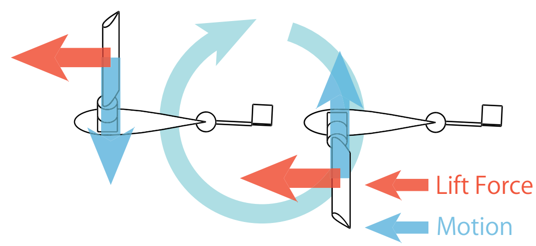


Fig. 9. Mechanism of generating thrust force by flapping

The tail equipped with one actuator also can generate propulsive force regardless of the wing motion. The motion of the tail is just a simple oscillation as shown in Fig.10. However, by connecting the tail with an elastic shaft, there is a phase delay between the base of tail and the tail itself. We expect this delay of phase improves the efficiency of the tail propulsion.

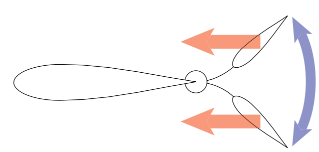


Fig. 10. Tail Motion

IV. DESIGN OF GLIDE WALKER

The appearance of the Glide Walker is shown in Fig.11, and its specifications are shown in TABLE I.

A. HARDWARE

In order to fabricate a streamlined and light body easily, we used a 3D printer from Objet co. ltd., and the material

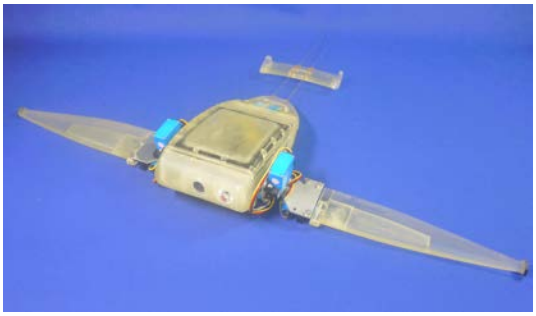


Fig. 11. Photo of Glide Walker

TABLE I

SPECIFICATION OF GLIDE WALKER

Weight	1.06 kg
Submerged weight	0.03 kg
Height	62 mm
Width	617 mm
Length	320 mm
DOF	7 (Wing 3×2 + Tail 1)
Wing span	500 mm
Mean chord	77 mm
Horizontal tail volume	0.5
Vertical tail volume	0.03

used was FullCure720. The aerofoil used for the main wing and the tail was a modified SD8020 which maximum thickness is 20% of the chord. The reason why we adopted a thicker aerofoil (SD8020 has 10.1% thickness normally) was to strengthen the parts made by the 3D printer. At the ends of the main wings, we attached *end-plates* to reduce the *induced drag* and make the soles for the walking motion. We also used a modified SD8020 which maximum thickness was 30% of the chord for the body, because we needed space for the CPU, battery and other electronic components.

The weight of Glide Walker was designed to be a little heavier than its buoyancy in order to allow it to glide downward naturally and walk on the bottom of the water. However, the weight of the main wings was balanced with its buoyancy in order to prevent the wings position from affecting the posture of the body.

As shown in Fig.12 and Fig.13, each wing has 3 DOFs and the tail has 1 DOF. In order to simplify the design, we used waterproof RC servo motors (HS-5086WP by Hitech Co. Ltd). Due to this design, the Glide walker can perform various ways of locomotion as shown in Fig.5 - 8. The motors on the wings are also used to control the *attack angle*, the *sweepback angle*, and the *dihedral angle*. The tail wing and the base of tail is connected by a piano wire because we expected that the phase delay of the swing motion would increase the thrust force as mentioned above. The tail wing is connected to the piano wire by a clamp in order to allow the adjustment of the position of the tail wing. The tail wing is composed of one horizontal plate and two vertical plates. The horizontal plate works not only as a horizontal tail wing, but also as a propeller when the tail motor is actuated. The vertical tail wings work as protectors of the horizontal plate when they are hit by the bottom of the water or some obstacles. This protection is needed once the horizontal tail is too thin in order to avoid water resistance.

Additionally, the Glide Walker has a small camera and a high-brightness LED inside its body in order to record the view from the robot as shown in Fig.14.

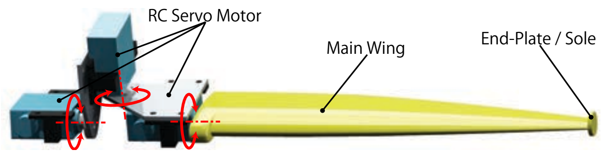


Fig. 12. Mechanism of Main Wing

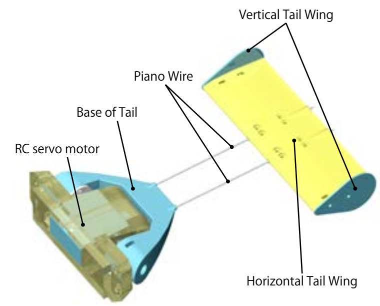


Fig. 13. Mechanism of Tail Wing

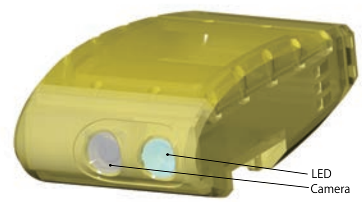


Fig. 14. Camera and LED

B. CONTROL SYSTEM

Fig.15 shows an overview of the system of Glide Walker. The proportional control system, Japan Remote Control Co., Ltd., is used as a remote controller and a receiver. The radio frequency is 72MHz, a low frequency radio wave which allows the usage in shallow water depth. The microcontroller inside the robot receives the signal from the receiver, and generates motions for each modes. It sends position data to each RC servo motor thtough PWM signals.

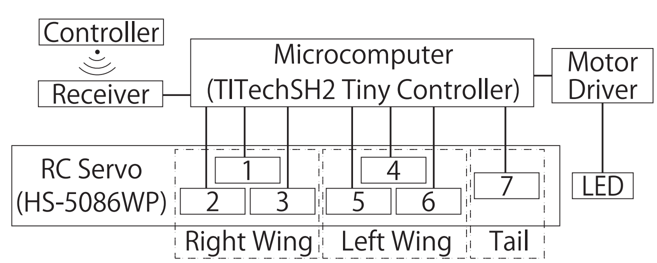


Fig. 15. System of Glide Walker

V. EXPERIMENT

In order to confirm its performance, we conducted experiment of each mode. We also compared the velocity and thrust force of each mode.

A. GLIDING EXPERIMENT

To evaluate performance as water glider, we tested gliding-mode with some initial velocity added by a hand. The robot successfully glided in the water by adjusting *angle of attack* and *sweepback angle*. Since the exactly center of gravity is not on the center of the main wing but located on the front side, gliding became stable with *forward swept wing*. Gliding angle at steady state measured from the picture shown in Fig.16 was almost 30 degree. Compare to other water glider [10], this value is not superior, but we consider this is not a serious problem because our robot has ways to generate thrust.

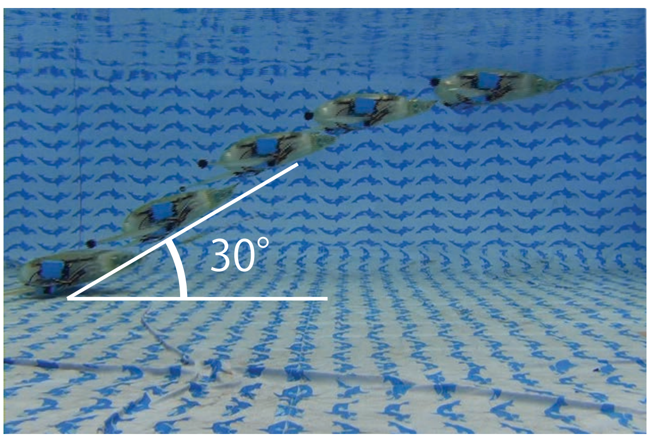


Fig. 16. Experiment of Gliding: The photo was captured every 0.6s.

B. PADDLING EXPERIMENT

As shown in Fig.17, the robot could propel using the paddling motion. However, once the thrust force generated by this motion is not continuous, after each stroke the robot sinks a little bit. Thus, the horizontal motion is achieved by changing the thrust force direction a bit upward and controlling the tail angle to compensate its sinking.

C. FLAPPING EXPERIMENT

As shown in Fig.18, the robot could also propel using the flapping motion. This motion shows the best performance among all the modes, because it can generate thrust force almost continuously. The pitch axis is also controlled by the tail. Additionally, it can also control the yaw motion by changing the amplitude of flapping between the left and the right wing, and by rolling through the change of the center of oscillation. Because of its high manipulation capability, the robot could perform a loop maneuver with this motion as shown in Fig.19.

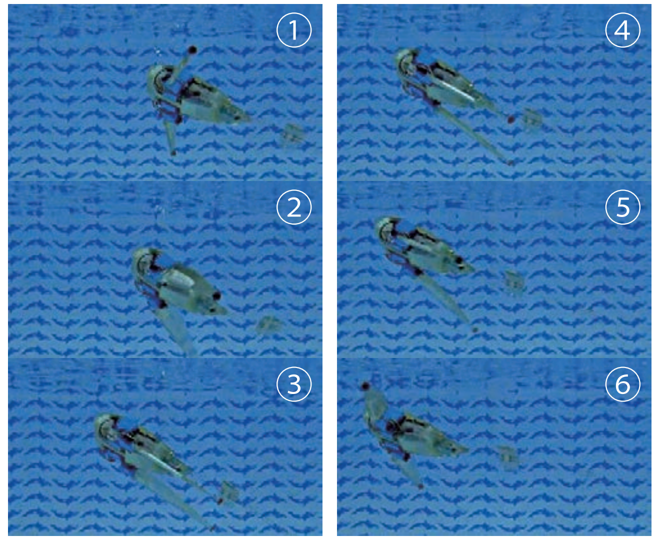


Fig. 17. Experiment of Paddling: each photo was captured every 0.2s

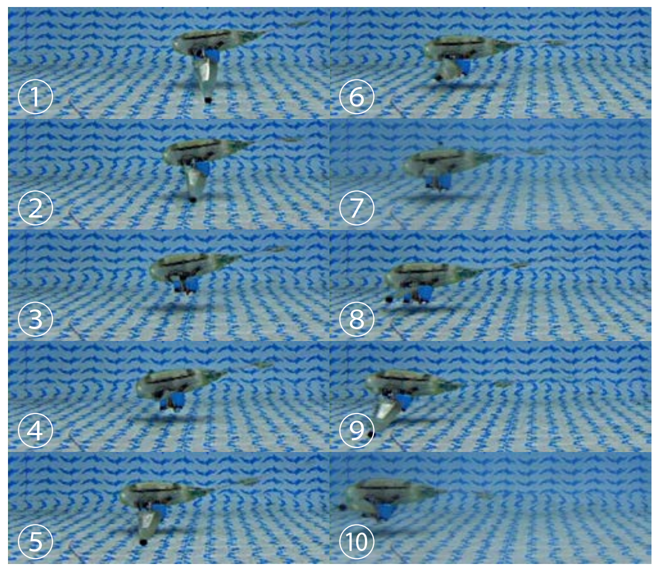


Fig. 18. Experiment of Flapping: each photo was captured every 0.1s

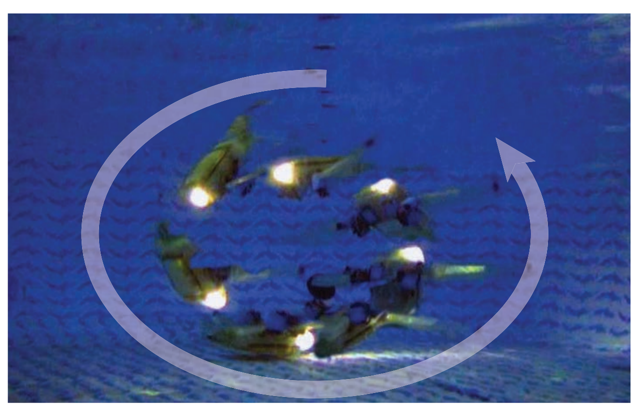


Fig. 19. Experiment of Loop Maneuver: each photo was captured every 0.6s

D. WALKING EXPERIMENT

Fig.20 shows the walking experiment. The robot could walk at the bottom of the pool, when the distance between the body and the bottom of the pool was about 20cm. Although the feet didn't always touch the bottom, it could travel stably keeping its distance from the bottom controlling its tilt around pitch axis by using the tail.

However, we concluded that the robot couldn't walk when the position of the body was higher due to instability of rolling.

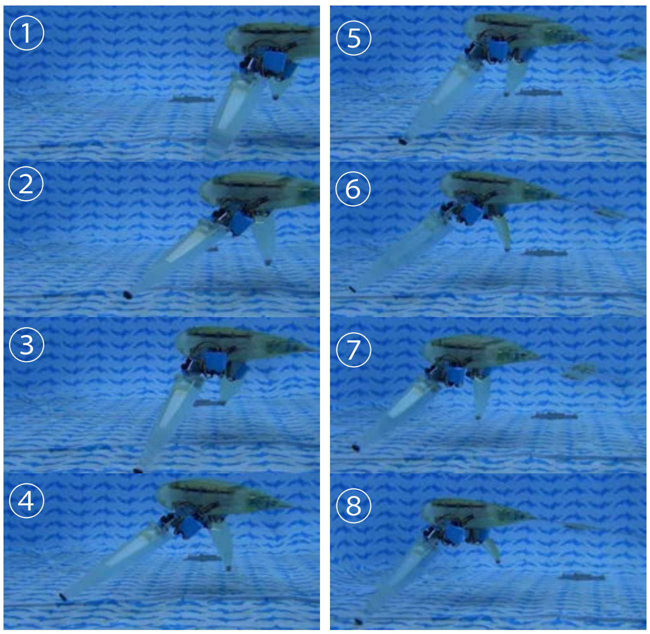


Fig. 20. Experiment of Walking: each photo was captured every 0.6s

E. Comparison of each mode

TABLE.II shows the velocity and the thrust force of each mode. The thrust force of the glider-mode and the walking-mode could not be measured. The velocity of the gliding mode is horizontal.

From this table, it can be concluded that the flapping mode is faster without the tail motion.

In terms of maximum thrust force, paddling mode is higher than flapping mode. This indicates the paddling mode might be instantaneously faster than flapping mode, but since the motion is intermittent, the average speed is slower than when in theflapping mode.

TABLE II
COMPARISON OF EACH MODE

Mode	Average velocity[m/s]	Maximum thrust force[N]
Gliding	0.29	No data
Paddling	0.3	7
Flapping	0.47	4
Walking	0.06	No data
Tail	No data	2

VI. CONCLUSION

In this paper, we proposed a new type of underwater robot named "Glide Walker" which can perform several different motions such as gliding, swimming and walking. Then we discussed each motion, and after that we explained in details the design of the developed Glide Walker. We have also shown the results of the experiments conducted with the Glide Walker, which shows it can move inside the water using several motions.

As a future plan, we will add some sensors to the robot such as an acceleration sensor and current sensor to measure the energy consumption of each motion. We believe these devices allow us to develop a translation motion algorithm which automatically selects the mode depending on the robot's tasks and environments in order to optimize its energy efficiency and velocity.

Additionally, we will consider to put a new tail mechanism which has 2 DOF and is able to be used as a rudder and an elevator in order to improve its yaw axis manipulation capability.

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