“Cheap” Underwater Locomotion: Morphological Properties and Behavioral Diversity

Marc Ziegler*, Fumiya Iida*† and Rolf Pfeifer*
*Artificial Intelligence Laboratory, University of Zurich
Andreasstrasse 15, CH-8050 Zurich, Switzerland
†Locomotion Laboratory, University of Jena
Dornburgerstrasse 23, D-07743 Jena, Germany
[ziegler,iida,pfeifer]@ifi.unizh.ch

Abstract— **Toward adaptive underwater locomotion, this paper presents the experimental results of a fish-like swimming robot that we have newly developed. By using motor control with only one degree of freedom, this robot exhibits surprisingly rich behavioral diversity in three dimensional underwater environment. This paper focuses on some of the behavior variations this robot exhibits, i.e. forward, turning, and vertical movement, which are required for the underwater three dimensional navigation. The visual behavior analysis shows that, even though there is only one motor, these behavior are possible because this robot exploits the unique interaction with the environment derived from the morphological properties of the robot. Moreover, some of the behaviors demonstrated by this robot have a considerable similarity to those of biological systems, which would also contribute to understand the adaptive behavior of animals. Based on the experimental results, we speculate further issue on “cheap” underwater locomotion.**

I. INTRODUCTION

Diversity of animal’s morphology is particularly impressive in the underwater world. It has been uncovered that various properties of morphology have been optimized for the efficient locomotion in the evolutionary process (e.g. [1], [2], [3]). In this paper, we explore such morphological properties for the purpose of underwater robot locomotion. There seem to be many properties involved in generating rich behavioral diversity in nature. For example, components in an animal’s body can have very different material properties, e.g. high stiffness in the skeleton, high elasticity in the skin tissue, and muscles can provide the function of elasticity-damper regulation. An interesting implication is that there is no clear distinction between actuation and material properties in terms of controlling the body and behavior. It has been only partially understood how morphology, actuators, and control are related to each other in order to achieve adaptive locomotion. As demonstrated by many other biologically inspired robotic projects, the proper exploitation of morphological properties significantly contribute to energy efficient locomotion with less control and computation (e.g. [4], [5], [6], [7], [8]). The motivation of this paper is, therefore, to explore such “cheap” mechanisms, which exploits the constraints derived from underwater environment for the purpose of locomotion. We expect that this synthetic approaches provide additional insights for our understanding of both biology and robotics.

Based on the detailed behavior analysis of the biological systems (e.g. [3], [9], [10]), fish-like robots successfully demonstrated the behavior primitives such as forward and turning movement [11], [12], [13], [14], [15], [16], [17], [18]. One of the major contributions of this paper is to add another variation of swimming robot model, but the simplest one.

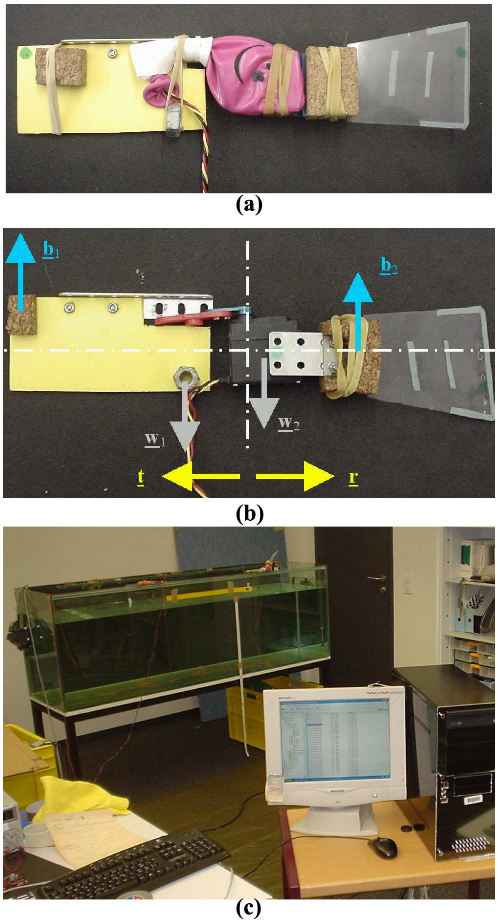
The main question addressed in this paper is how a robot is able to steer itself in the three dimensional space under water with minimal control. Although an underwater robot has to deal with many control such as maintaining the stability of attitude, forward, turning, backward movement, and more generally navigation, most of these functional primitives cannot be separately discussed, but everything has to be done with one body. Therefore, the investigation of a minimalistic design strategy is of particular interest for adaptive underwater locomotion.

In order to achieve rich behavioral repertoire with minimal actuation, the robot has to exploits the morphological properties and the interaction with the environment. With notable exceptions [19], [20], [21], the movement of fish-like swimming generally uses kinematic control in which the pre-determined trajectories of the body movement are tracked by multiple body segments, actuators, and strict feedback control. Important and useful morphological properties are often not explicitly considered.

In what follows, we will first explain the experimental platform. The variations of behavior generated by the simple control will then be presented. Finally we discuss the further issues with a few concluding remarks.

II. DESIGN OF MORPHOLOGY AND CONTROL

The design strategy of the newly developed fish robot called “Wanda”, is based on the concept of “cheap design” [8], [22]. In this concept, the designer of the robot should consider how to exploit the constraints derived from the body and the ecological niche, rather than equipping many actuated degrees of freedom and a computationally demanding control architecture. By following this policy, we have developed a series of fish-like robots, each of which has only one standard servomotor. Given this constraint, the interest of our research project has been how to make the robot swim freely in a three dimensional water tank by changing the morphological



(a)

(b)

(c)

Fig. 1. (a) A photograph and (b) the components of the fish robot. The forces acting on this body is illustrated by arrows. (c) A photograph of the water tank used in the experiments.

configuration. We found that, by having a proper morphology, the robot is able to swim around in the three dimensional environment

The morphological design of the robot is shown in Figure 1. The front part is made of hard foam plastic. The size of this front part is roughly the same as the rear part, which consists of the servomotor and the tail-fin. The crank arm of the servomotor is fixed to the front plate through an L-profile aluminium piece. In the rear part, the body of the servomotor is connected to the tail-fin with two pieces of large cork in order to compensate the floating balance of the entire body. The dimension of the robot is approximately 280mm long, 55mm high, and 30mm wide. The total weight of the robot results in 110g, and the density is slightly larger than that of water, i.e. the robot sinks at 50 mm/sec without actuation.

As it becomes clear later in this paper, an important morphological feature in the underwater environment is the floating balance. We found that, in order to take advantage of the single motor control in three dimensional space, we implemented a light material in the head of the robot and a heavy material in the middle of the body.

Another significant morphological property for the swimming performance of the robot is the material of the tail-fin. Since we have no sensory feedback, the material property of the fin has to be carefully chosen so that it generates the desirable water vortices for propulsion. We have evaluated three different materials as shown in the next section.

For actuation, we employed a commercially available servomotor Hitec HS5945MG. The limit of the rotation angle of this motor is approximately 85° to both right and left sides. The electricity and control signals of the motor are provided by external power supply and a PC through a light cable. In order to evaluate the morphological properties, we used the simplest motor control, i.e. the sinusoidal angular oscillation, which is determined as follows:

$$P(t) = Asin(\omega t) + B \tag{1}$$

where P is the position of the motor at time t, A and B are the amplitude and the offset of the sinusoidal motor oscillation, respectively. The speed of the oscillation is determined by the frequency parameter ω. In the rest of this paper, we will explore the robot's behavioral diversity by varying these three parameters. Note that we have implemented no sensors in this robot (except for the internal feedback loop of the servomotor), thus the control is fully open-loop.

III. EXPERIMENT

By using the robotic platform described above, we analyzed the behavior of the robot by changing both the control parameters and the material properties. In this section, we explain the experimental setup, and then we show the experimental results of forward, turning and vertical movement.

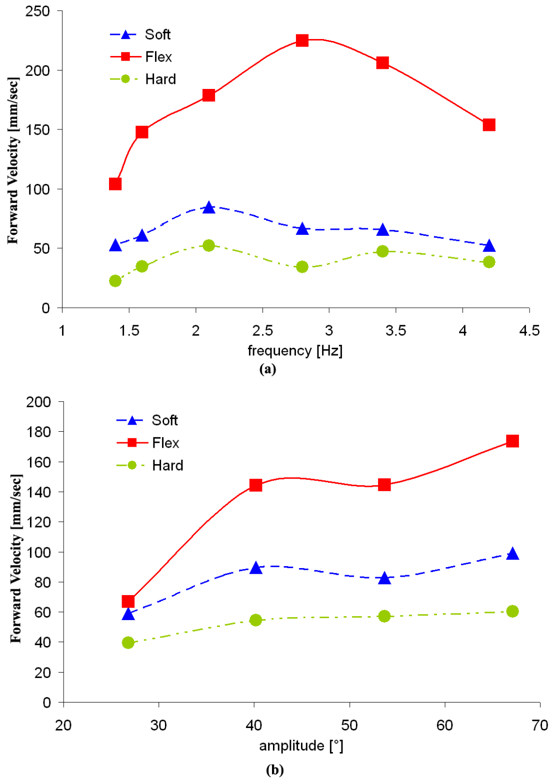
A. *Method*

All of the experiments were taken in a water tank, a size of 180 x 40 x 60 cm (Figure 1(c)). The walls are made of glass, where light sources were installed on two sides, and there is a black background on one side for the purpose of visual analysis.

In order to evaluate the performance of the swimming robot, we made use of a visual behavior analysis setup by tracking a point on the robot's body in the image sequences. To capture the images, we used a high-speed camera, Basler A602fc (resolution 656x490 pixels, frame rate 100fps with a 16 bit grayscale, IEEE 1394 interface). The image sequences were registered in a PC and analyzed by using a standard motion tracking algorithm. By extracting the position of the fish robot in the registered images, the two dimensional trajectories of the swimming behavior were estimated. The accuracy of analysis method is the error rate of 0.56% for the measurement of time, and 1.09% for the measurement of the geometry.

B. *Forward Movement*

The first behavioral variation of the robot is forward swimming. By setting the offset parameter $B = 0.0$, i.e. the center of the motor oscillation is at the middle with respect to the body axis, the robot generally swims straight forward.



(a)

(b)

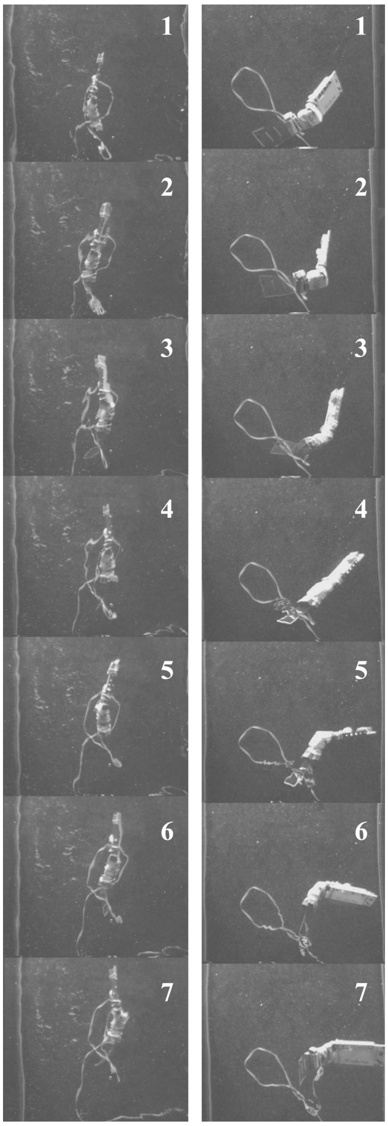
Fig. 2. Forward velocity of three different material properties. The difference of velocity with respect to the control parameters of frequency (a) and amplitude (b).

Here we analyzed the effect of three different materials of the tail-fin with respect to the control parameters of frequency ω and amplitude A. These three variations of tail-fins have the same shape but the different elasticity and weight. The first material, labeled “Soft”, is a very soft foam plastic, which requires almost no force to be bent. The second material, labeled “Hard”, is made of very stiff foam plastic (the same material as used for the front part of the robot), which can hardly be bent, thus there is no deformation during swimming. The third and last material labeled “Flex” is a flexible plastic foil. Its characteristics lies in between the other two materials, which bends when forces act on one side. During the experiments, Flex material exhibits a spring like behavior, in which it generally bends as the tail-fin is oscillated.

Forward Velocity

Figure 2 shows the mean forward velocity estimated by the above-mentioned visual tracking analysis. We recorded the behavior of the robot while it starts swimming at the end of water tank until it reaches the other end. The mean forward velocity is estimated by measuring the horizontal movement of the robot while it swims at the constant velocity.

Firstly, the forward velocity is measured at six different frequencies between 1.4 and 4.2Hz, and the amplitude was set at a constant value of 40°. Figure 2(a) shows the influence of material properties with respect to the frequency parameter.



(a) **(b)**

Fig. 3. Two different swimming gaits observed during the forward movement experiments.

A clear peak for each material indicates the optimal frequency for 40° amplitude. The results show that the material property significantly influences the mean forward velocity.

In the next experiment, the amplitude is varied between 26.8° and 67.1°, and the frequency was set to a constant at 2.1 Hz. Figure 2(b) shows the relation between amplitude of the tail-fin and the mean forward velocity with the three different materials. As in the experiments with the frequency parameter, Flex material shows the best performance. An interesting characteristics is that the peak forward velocity was achieved at the same amplitude of 40° and it shows more unstable locomotion behavior as the amplitude becomes higher than these peaks and shifted into a different swimming “gait”. As shown in Figure 3(b), the robot swims with a large swing of the frontal part, compared to the normal

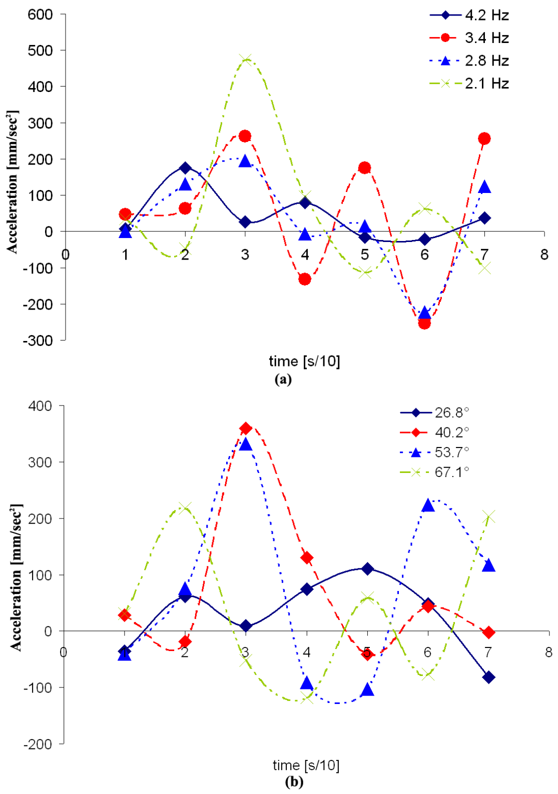


Fig. 4. Time-series changes of acceleration with respect to the control parameter of frequency (a) and amplitude(b).

gait (Figure 3(a)). Because of its morphological property of floating balance described previously, the robot fish not only bends but also rolls. This roll movement seems to produce a different kind of water vortices, which might cause a fast but unstable forward swimming. Interestingly, however, the dynamic behavior of this gait was significant only with Soft and Flex materials, but not with Hard material. This has to be investigated further in the future.

It is also interesting to note that, whereas the soft and hard materials reach the highest velocity at 2.1 Hz, flexible material reaches its peak at 2.7 Hz (Figure 2(a)). This implies that the control parameters are highly dependent on the material property of the tail-fin for better performance of forward velocity. This is somewhat biologically plausible since some of the animals seem to change the stiffness of the body when they decrease the body oscillation frequency [23]. In addition, it can also be said that the robot is potentially able to control the forward velocity by changing the material property (e.g. elasticity), if there would be an elasticity regulator.

Acceleration
¿From the same experimental data, we now analyze the characteristics of acceleration. We measured the time-series changes of acceleration from the rest position (the robot was floating without actuation) until 0.8 sec. This analysis was conducted only with Flex tail-fin. The smooth curves were obtained by measuring the tracking frame rate of 1/10 second.

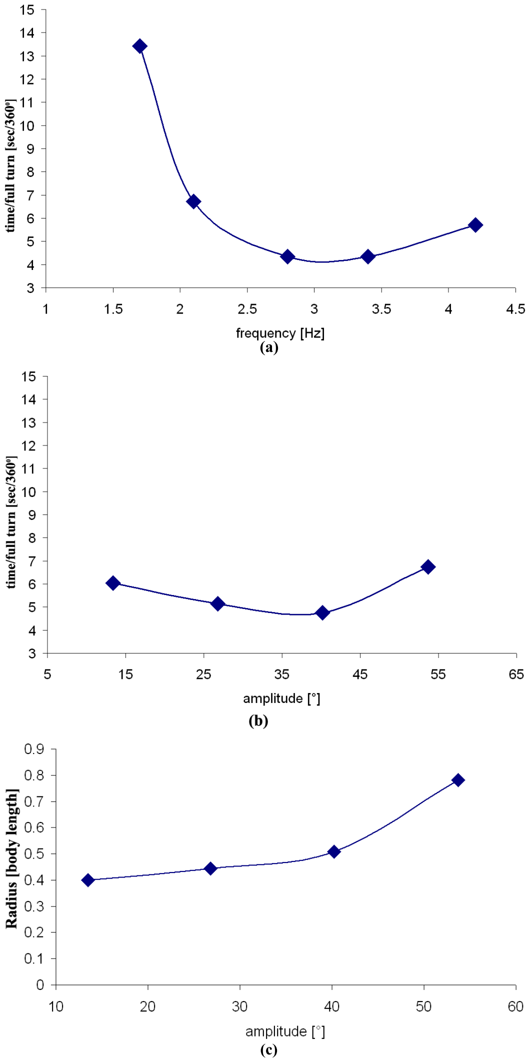


Fig. 5. Performance of turning movement. The durations of full turn with the control parameter of frequency (a) and amplitude (b). (c) The turning radius with respect to the amplitude control parameter.

Figure 4 shows the results of the analysis, and the curves show a significant oscillating character, which is because of the waggling of the tail-fin. The peaks of acceleration were generally occurred at the second strokes (at 0.3 sec). Figure 4(a) shows that the best acceleration was achieved when the frequency was lower by comparing the peaks at 0.3 sec. From Figure 4(b), the best performance was also obtained at the second strokes, when the amplitude is relatively large such as at 40° or 54°. These results could provide a direct association to the quick start behavior, the so-called "C-Start" and "S-Start"[10], which is observed in nature in a sense that the initialization of swimming should be at lower frequency for the quick start.

C. Turning Movement

Adding an offset parameter B to the sinusoidal control induces turning movement. Here we investigate how the fish robot exhibits fast turning movement with a small turning

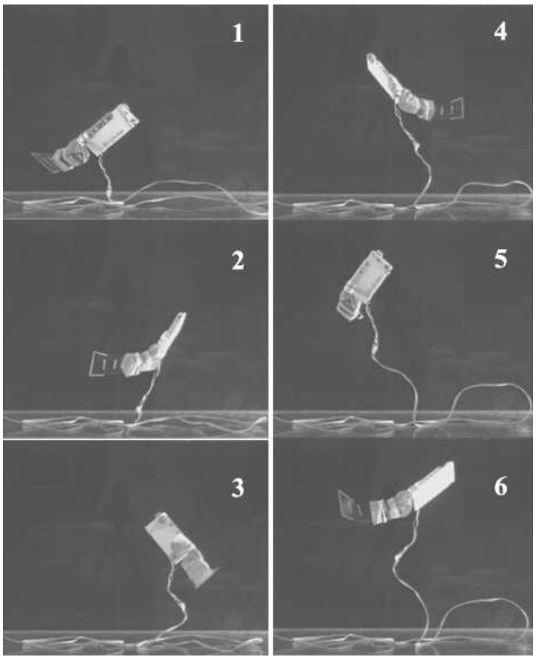


Fig. 6. A sequence of typical upward movement.

radius can be achieved.

Firstly, we examined the effect of the frequency parameter for the turning movement. We have set both of the amplitude and the offset parameters at 40°, and varied the frequency between 1.7 to 4.2 Hz. Because of the same offset and amplitude values, the fish robot turns at the constant turning radius, but the angular velocity was different as shown in Figure 5(a). Obviously, this result of the turning movement is very well matched to that of the forward velocity shown in Figure 2(a) in the sense that the maximum angular velocity was achieved at 2.8Hz as is also the case with the maximum forward velocity.

A complicated characteristics of the turning movement was observed when we changed the amplitude parameter. The turning experiments were conducted by varying the amplitude parameter and the frequency was set constant at 3.3 Hz. Figure 5(b) shows that the turning angular velocity is more or less matched to the characteristics of forward velocity shown in Figure 2(b). However, the turning radius almost linearly increases as the amplitude increases. In other words, although it was not possible with the frequency, the amplitude parameter is capable of influencing both turning radius and the angular velocity. Namely, it swims slowly in a big circle at the amplitude of 54°, but rapidly in a big circle at 42°.

Note that this turning movement is closely related to the vertical movement that we describe in the next subsection.

D. Vertical Movement

Since this robot has only horizontal actuation of the tail-fin, it is a crucial issue how it is able to swim upward and downward. This robot is, however, capable of the vertical movement in a number of different ways by exploiting morphological properties.

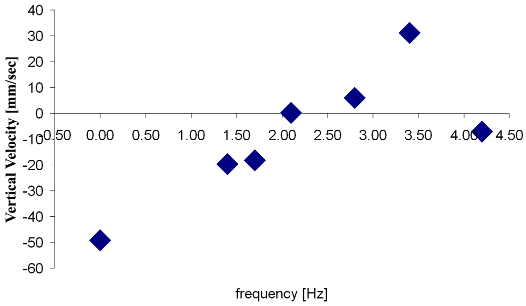


Fig. 7. The velocity of vertical movement with respect to the frequency parameter. The plot at 0.0 Hz indicates the natural sinking rate without actuation.

For the vertical movement, there have been several different approaches explored in the past; by adding buoyancy by means of airbladder; by adding extra fins; by bending the whole body upward or downward; by changing the center of mass. Whereas most of these approaches require additional actuation and control, here we again attempt to employ a minimalistic method in which the robot exploits the body weight distribution of the fish robot. As illustrated in Figure 1(b), the robot has a heavy part concentrated at the middle body (as shown by two force vectors of w), and the light part at both ends of the body (the buoyancy vectors b).

This body weight distribution induces a roll movement when the offset of the oscillation is biased to one side. The more it bends, the more it rolls. Once this roll is set properly, the vertical movement can now be controlled by the swimming speed, i.e. by the amplitude and frequency parameters. A typical upward swimming is shown in Figure 6.

The vertical movement was measured quantitatively with respect to the frequency parameter. In this experiment, we set the offset parameter at 45° and the amplitude parameter at 27°. Figure 7 shows the vertical velocity, in which the value is positive when the robot fish moves upward and negative when it sinks. As soon as the fish robot starts wiggling, the sinking speed decreases. By increasing frequency, the robot maintains the horizontal movement, and then it swims upward at the peak velocity around 3.5Hz. After the peak, as the swimming velocity becomes slower, it slowly start sinking again. Therefore, the maximum downward velocity occurs when there is no actuation which is shown in the left most plot in the figure. Note that the vertical speed can also be varied by the offset or amplitude parameters, but it also changes the turning radius as was demonstrated in the previous subsection.

The advantage of this vertical movement method is the simplicity of control. Although it is not able to swim up or downward independently from turning, it does not require any additional morphological changes such as adding motors nor fins. Thus it does not cause energy loss by hydrodynamical friction for the forward movement.

IV. Discussion and Conclusion

This paper presents preliminary experimental results on fish-like swimming with the simplest kind of control architecture, i.e. open-loop position control of sinusoidal trajectories. The demonstration of fish-like swimming and steering itself in three dimensions was possible because the fish robot exploits the unique interaction with the environment derived from the morphological properties. Although we have explored only some parts on the possible morphological variations, i.e. elasticity of the tail-fin and weight distribution, the experimental results provided significant insights toward a comprehensive understanding of adaptive underwater locomotion.

As shown in the forward velocity, an interesting behavioral pattern with a large swing of the frontal part (Figure 3(b)) was observed when the material properties and weight distribution are properly taken into account. This swimming gait is very similar to the so-called "carangiform" observed in nature. In general, the carangiform swimmers have a good balance between speed, acceleration, and maneuverability, whereas the thuniform swimmers (somewhat similar to the behavioral pattern shown in Figure 3(a)) are capable of faster cruising speed (see e.g. [9]). It would be interesting to investigate further how the morphological properties are related to the forms of swimming, which is highly related to the issue of adaptability as observed in nature.

Although we have not yet analyzed the hydrodynamics, we believe that the findings shown in this paper provide a significant contribution to research on adaptive underwater locomotion. It is quite often the case that we do not know how to design morphology and controller even though we know that the inverted-Karman vortices [6], [9] are necessary for efficient forward swimming, for example. Particularly, the inter-relation between morphology, control, and the swimming behavior would be a highly challenging topic for the studies of underwater actuation and material properties (e.g. [19], [20], [21]) which have been only partially investigated so far. Along the similar line, the sensory feedback should also be considered. For example, by measuring flexion of the passive tailfin, it would be possible to estimate the interaction between the body and vorteces. It would be a particularly interesting issue how much the robot is able to identify the whole body dynamics such as optimal thrust, forward velocity, and maneuverability.

In addition, the optimization process should also be considered further; There are generally two (or more) different time-scale optimization processes, i.e. evolution and learning, in order to deal with highly complicated non-linear interaction in underwater biological systems. The significance of the preliminary results presented in this paper lies in the fact that, by using the simplest form of control, we tested morphology (which is generally optimized in evolutionary scale), and control (which can be learned in a relatively short time scale). From this perspective, whereas we have only explored the optimization of morphology in this paper, the optimization of more sophisticated sensory motor system would be a significant future work. However, it has to be emphasized that, even with the sophisticated sensory motor control, exploitation of morphological properties have to be always carefully considered.

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