

# “Cheap” Underwater Locomotion: Roles of Morphological Properties and Behavioural Diversity

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*Abstract*— Toward adaptive underwater locomotion, this paper presents the experimental results of fish-like swimming robots that we have newly developed. By using motor control with only one degree of freedom, these robots exhibit surprisingly rich behavioural diversity in three dimensional underwater environment. This paper focuses on some of the behavior variations, 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 these robots exploit the unique interaction with the environment derived from the morphological properties. For better understanding how the material influences the swimming behaviour, a second robot with bending sensors implemented in its tail-fin measures the deflection during swimming. Moreover, some of the behaviors demonstrated by these robots 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.

*Keywords*— cheap design, morphological computation, 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 optimised 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 behavioural 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 biologically inspired robot research, the proper exploitation of morphological properties significantly contributes 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 into 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], [19]. 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 controls such as maintaining the stability of attitude, forward, turning, backward movement, and more generally navigation, most of these functions cannot be independently discussed, but we have to investigate functions in relation to the others. Therefore, the investigation of a minimalist design strategy is of particular interest for adaptive underwater locomotion.

In order to achieve rich behavioural repertoire with minimal actuation, the robot has to exploit the morphological properties and the interaction with the environment. With notable exceptions [20], [21], [22], 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. Morphological properties are often not explicitly considered.

There have been a number of studies on dynamic system-environment interactions in animals and robots to understand the nature of locomotion behaviours. In particular, the role of dynamic morphological properties (e.g. elasticity and rigidity of body structure, and weight distribution) have been regarded as a central issue to achieve real-time adaptability, energy and computational efficiency and rich behavioural diversity [25], [26]. The common ground for legged or swimming locomotion are the environmental conditions forming a frame of external boundaries for the system and the undulatory of motion [27]. In general, there are three important design principles required for underwater locomotion: First, a system has to maintain the stability of buoyancy. Second, propulsion force has to be considered. For fish-like swimming, it is of particular importance to consider how vortices can be created and exploited for locomotion. And third, locomotion direction needs to be controlled.

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], [23], [24]. 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 configuration and material properties. 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 two experimental robots is shown in Figure 1 (a) and (b). The front part is made of hard acryl plastic and fixed to the servo motor together with buoyant material ( $\underline{b}$ ) such as cork, foam or little balloons filled with air in order to compensate the weight ( $\underline{w}$ ) and keep the floating balance of the entire body stable. The crank arm of the servo motor consists of a plate with holes that allows to change between different types of tail-fins. The actual dimensions of the robots are approximately: 330mm length, 105mm high, and 44mm width.

In the three experiments on forward, turning and vertical movement, the robot shown in Figure 1 (b) was used. The difference to (a) is in its higher density than water, i.e. this robot sinks at 50mm/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. In contrast, the robot shown in Figure 1 (a) which is used in the experiment in section IV has a slightly lower density than water, i.e. it stays on the surface and has to actively overcome its buoyant force in order to get deeper. The morphology is therefore such that the light material is centralized and the heavier material in front and back of the robot. Both robots follow the same principle: bending movement of its own body induces not only to steer in a new direction like a ruder on a boat, but also makes them roll and pointing upwards, or for the second robot downwards respectively.

Another significant morphological property for the swimming performance of the robot is the material of the tail-fin. 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. Furthermore, bending sensors are implemented in one tail-fin to give a spacio-temporal feedback of its deformation. For the bending sensor, the bending angle is proportional to

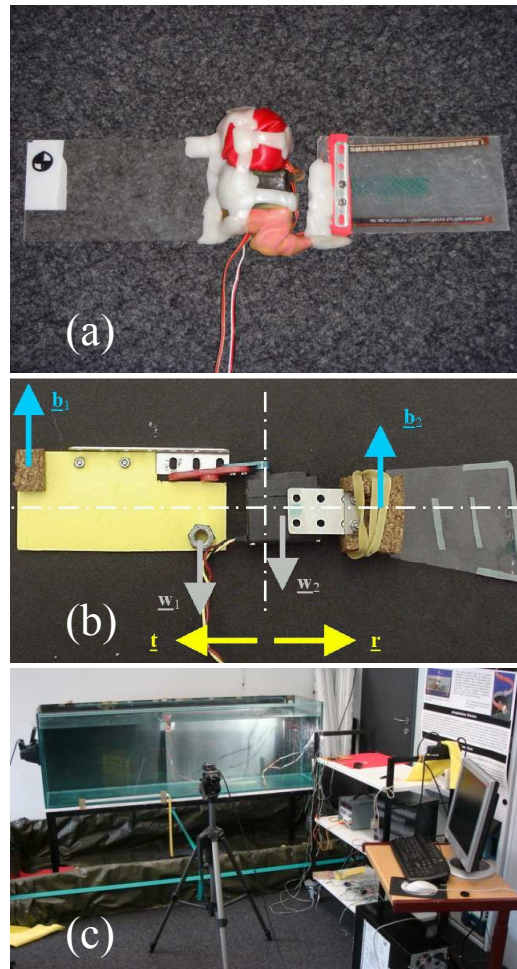


Fig. 1. The two fish robots, (a) with the bending sensors in the tail-fin used for the experiments on sensory feedback (section IV) and (b) the one used for behavioural performance test (section III). The primary forces induced in the body are illustrated by arrows. (c) The experimental setup consisting of a water tank, lighting devices and a high-speed camera.

its resistance and responds to a physical range between straight and a 90 degree bend.

For actuation, we employed commercially available servomotors Hitec HS5945MG and Kondo KRS786ICS. The limit of the rotation angle of this motor is approximately  $85^\circ$  to both right and left sides. Sensory data from the bending sensors, 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:

$$P(t) = A \sin(\omega t) + B \quad (1)$$

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  $\omega$ . In the rest of this paper, we will explore the robot’s behavioural diversity by varying these three parameters. It is important to note that, although sensors are implemented in this robot (bending sensors and the internal feedback loop of the servomotor), the control is kept fully open-loop.

### III. EXPERIMENT

By using the robotic platform described above, we analysed 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 conducted in a water tank, in 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 greyscale, IEEE 1394 interface). The image sequences were registered in a PC and analysed 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 the analysis method is the error rate of 0.56% for the measurement of time while recording at exactly 100 frames per second, an error rate of 1.09% for the measurement of the geometry, caused by slight shifts in distances between the camera and the robot and 9% for the bending sensors because of noise.

#### B. Forward Movement

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

Here we analysed the effect of three different materials of the tail-fin with respect to the control parameters of frequency  $\omega$  and amplitude  $A$ . These three variations of tail-fins have the same shape but the different elasticity and weight. The first material, labelled “Soft”, is a very soft foam plastic, which requires almost no force to be bent. The second material, labelled “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 labelled “Flex” is a flexible

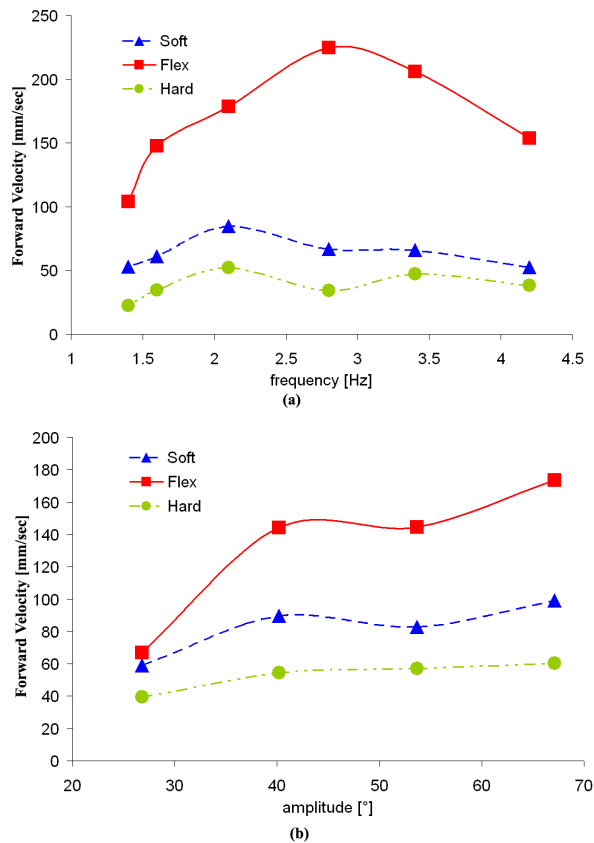


Fig. 2. Forward velocity of three different material properties. The difference of velocity with respect to the control parameters of frequency (a) and amplitude (b).

plastic foil. Its characteristic lies in between the other two materials, thus 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 constant velocity.

First, 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 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 is 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 observed in the experiments with the frequency parameter, Flex mate-

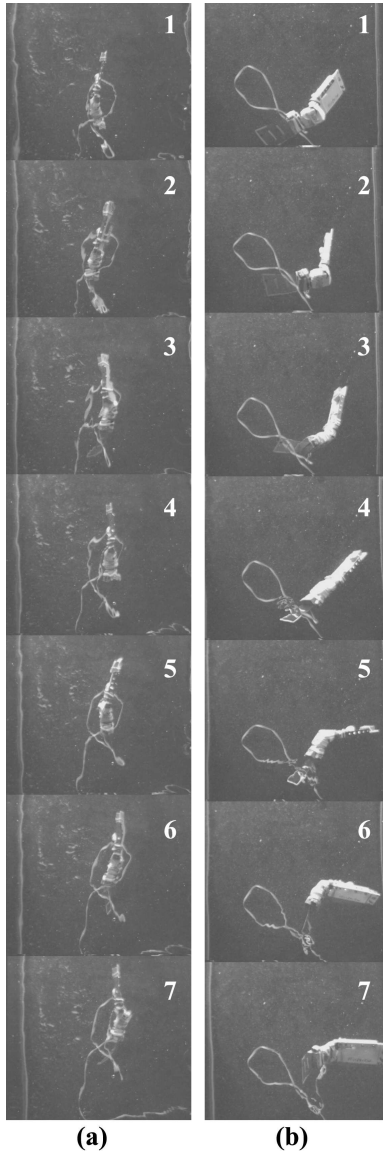


Fig. 3. Two different swimming gaits observed during the forward movement experiments.

rial shows the best performance. An interesting characteristic is that the peak forward velocity was achieved at the same amplitude of  $40^\circ$  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 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)).

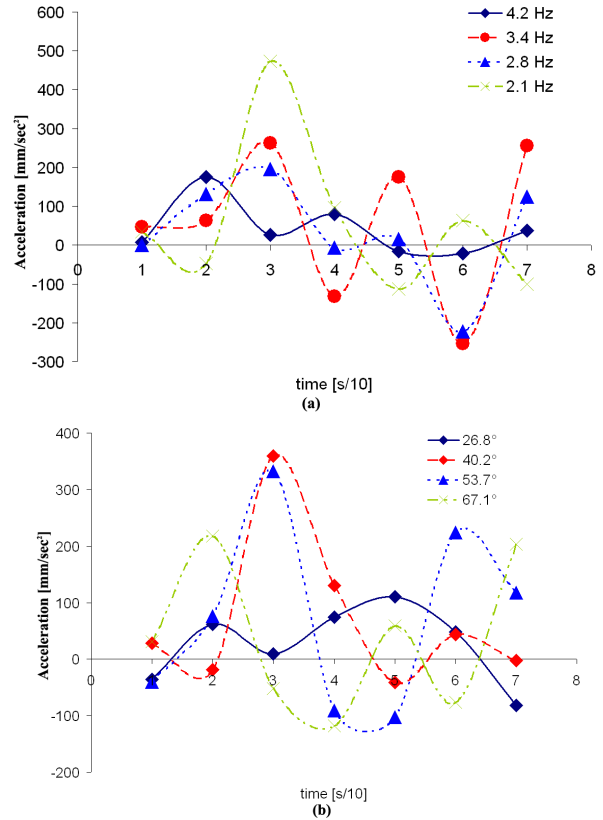


Fig. 4. Time-series changes of acceleration with respect to the control parameters of frequency (a) and amplitude(b).

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 [28]. 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 then analysed 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.

Figure 4 shows the results of the analysis, and the curves show a significant oscillating character, which is because of the wagging 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  $40^\circ$  or  $54^\circ$ . 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

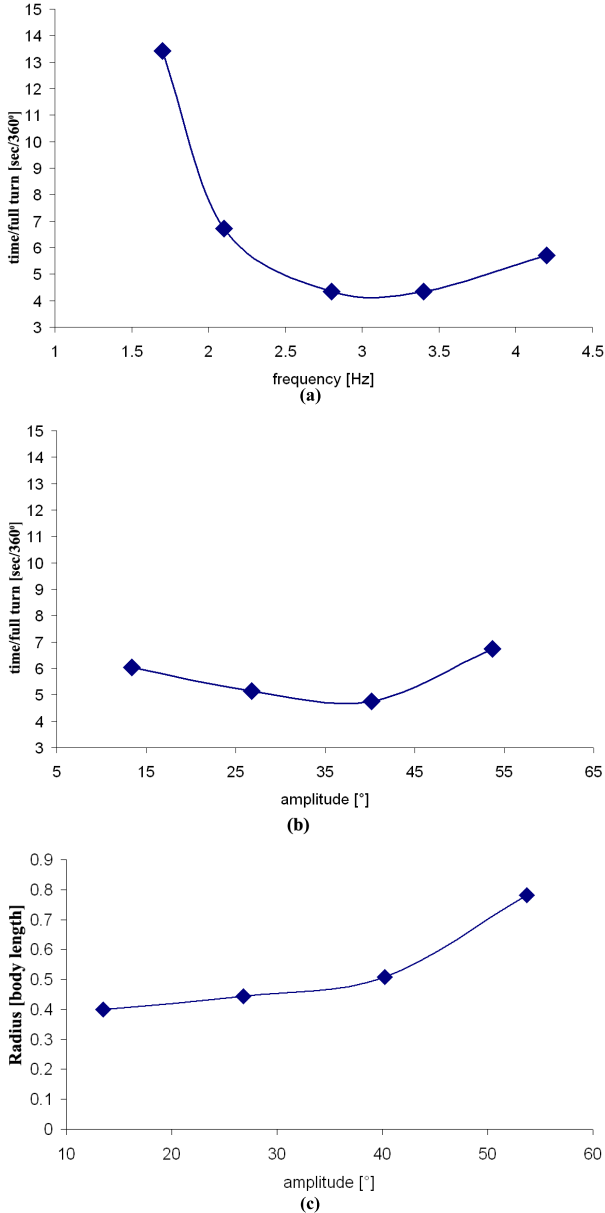


Fig. 5. Performance of turning movement. The durations of full turn with the control parameter of frequency (a) and amplitude (b). (c) The turning radius with respect to the amplitude control parameter.

that the initialisation 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 investigated how the fish robot exhibits fast turning movement with a small turning 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  $40^\circ$ , 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

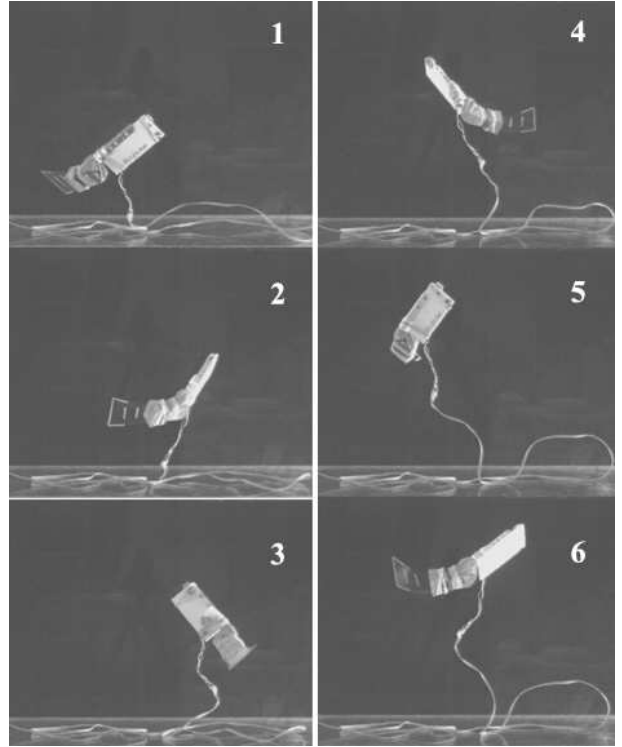


Fig. 6. A sequence of typical upward movement.

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 2.8 Hz as is also the case with the maximum forward velocity.

A complicated characteristic 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 characteristic of the 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  $54^\circ$ , but rapidly in a big circle at  $42^\circ$ .

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.

For the vertical movement, there have been several different approaches explored in the past; by adding

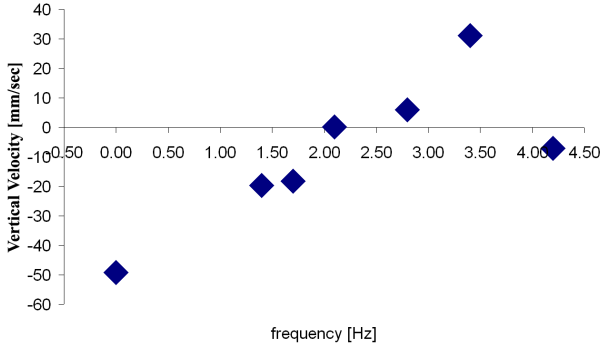


Fig. 7. The velocity of vertical movement with respect to the frequency parameter. The plot at 0.0 Hz indicates the natural sinking rate without actuation.

buoyancy by means of airbladder; by adding extra fins; by bending the whole body upward or downward; by changing the centre of mass. Whereas most of these approaches require additional actuation and control, here we again attempt to employ a minimalist 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  $\underline{w}$ ), and the light part at both ends of the body (the buoyancy vectors  $\underline{b}$ ).

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  $45^\circ$  and the amplitude parameter at  $27^\circ$ . 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 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 hydrodynamic friction for the forward movement.

#### IV. SENSORY SIGNALS INFLUENCED BY MATERIAL PROPERTY

So far, we have shown that the material properties of the tail-fin play an important role in creating vortices for forward propulsion. What we investigate in this section is how the material properties could be exploited for the measurement of physical system-environment interaction. Namely, considering the fact that the forward velocity is significantly influencing the water-fin interaction, the dynamic movement of the fin should be potentially used for estimating the behaviour of the robot. In this section, we attempt to measure the forward velocity by using a pair of bending sensors in the fin.

Along the central body axis, two bending sensors are implemented into the tail-fin made out of silicon. To increase the spring like property, a flexible plastic stripe parallel to the bending sensors is also inserted. If the tail-fin bends on one side, the resistance of one of the sensors changes accordingly to the deformation off the centre line along the body-axis. When the tail-fin bends to the other side, the second sensor indicates the deformation accordingly, because one sensor cannot measure its “negative” bending. The acquired bending sensor information is recorded together with the corresponding control signal of the servo motor. Behaviours generated by four different frequencies (from 0.7 Hz to 2.3 Hz) and six motor amplitudes (from  $20^\circ$  to  $120^\circ$ ) were analysed with the highspeed camera, and the velocity of the robot’s forward movement is extracted.

In Figure 8 the horizontal axis indicates the amplitude of deformation measured at the tail-fin, and the vertical axis indicates speed in millimetre per second. We plotted the experimental results obtained from every combination of motor frequency and amplitude. The deformation information represents relative sensory signal of the tail-fin with respect to the signals of the rest position, thus there is no unit in the horizontal axis. The deformation plots are the mean amplitude of bending sensor signal during 10 periods of oscillation.

This figure shows that, along with an increase of fin deformation, the forward velocity more or less linearly increases. Except for the lowest frequency of 0.7 Hz and large motor amplitude (i.e. above  $60^\circ$ ), the sensory information of fin deformation can be used for estimating the relative forward velocity. Moreover, when the robot takes the motor signals of frequency and amplitude into account, it is also possible to estimate the relative forward velocity more accurately: knowing the motor oscillation frequency of 0.7 Hz, the forward velocity of 80 mm/s can be estimated from the deformation of 23, for example.

The fin-water interaction at large frequency and amplitude still needs to be investigated further in the future: with the large frequency and amplitude, the forward velocity does not increase as the deformation does (see the plateau in the frequency of 2.3 Hz, Figure 8, for example). Although we do not know the underlying mechanisms of this behaviour, it can be said that information acquired from the bending sensor could po-

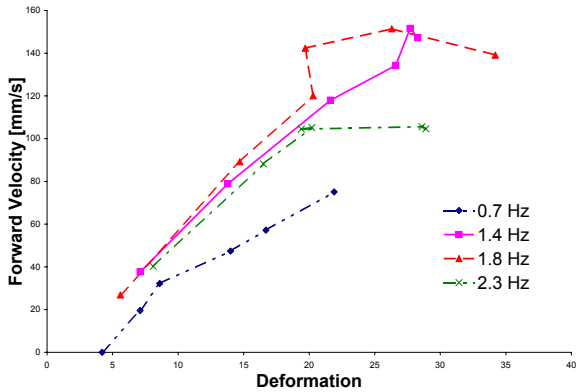


Fig. 8. The velocity of forward movement with respect to the relative deformation of the tail-fin.

tentially indicate the state of the fin-water interaction. Another kind of information about fin-water interaction can be acquired by processing temporal information. Figure 9 shows the time series deformation sensor information with respect to the corresponding motor position. In this figure, we could see that the peak of the tail-fin deformation in (a) is about 0.11 sec behind the peak of motor oscillation, while in (b), the delay is as small as 0.01 sec. In general, from our observation, the delay of the fin bending becomes shorter when the motor frequency and amplitude are larger. Such information can potentially be used to estimate the fin-water interaction, and eventually the relative forward velocity.

## V. DISCUSSION AND CONCLUSIONS

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 behavioural 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 manoeuvrability, whereas the thunniform swimmers (somewhat similar to the behavioural pattern shown in Figure 3(a)) are ca-

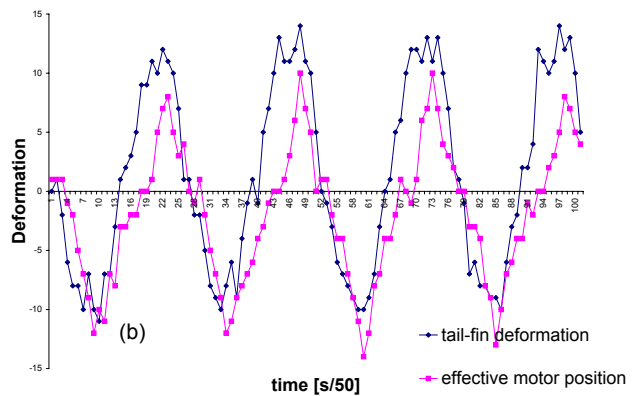
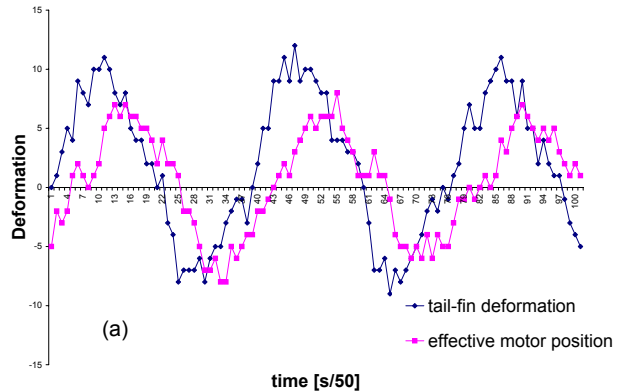


Fig. 9. Time plot of the tail-fin deformation and the motor position at a frequency of 1.4 Hz and an amplitude of  $60^\circ$  for (a) and 1.8 Hz and  $80^\circ$  for (b).

pable 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 analysed 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. [20], [21], [22]) which have been only partially investigated so far.

In addition, the optimisation process should also be considered further; There are generally two (or more)

different time-scale optimisation 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 optimised in evolutionary scale), and control (which can be learned in a relatively short time scale). The optimisation of more sophisticated sensory motor system is one of the most significant step for future work. We have shown so far that, by using morphological sensory information (i.e. measuring how the environment influences the agent and vice versa) allow two conclusions on behaviour and controller optimisation. One is a representation of the relative forward velocity based on the deformation of the tail-fin. The other is the mechanical limitation of the actuator. 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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