2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

WeC9.3

Design and Control of a Fish-like Robot Using an Electrostatic Motor

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Abstract— **This paper presents a project that aims at constructing a biologically inspired fish-like robot. The robot is designed to be capable of propelling itself through oscillations of a flexible caudal fin, like a real underwater fish. In particular, the caudal fin is driven by a mechanism actuated by a unique actuator called electrostatic film motor. In this paper, the dynamics of the electrostatic film motor are briefly introduced so as to well understand its characteristics and behavior. Based on the theoretical analysis and several design considerations inspired by biological concepts, we realize the fish-like robot actuated by an electrostatic film motor and propose swimming control methods for it. Experiments are carried out to confirm the validity of the original design and control. The current robot achieves fish-like maneuvering and approximate velocity of $0.018\ \mathrm{m/s}$ in dielectric liquid.**

I. INTRODUCTION

Many previous studies of submersible vehicles have been performed, including studies on conventional autonomous underwater vehicles relying on small screw propellers and on fish-like robots relying on fin-based motion for the forward thrust. Since fish are highly maneuverable and power-efficient endurance swimmers, the better route toward designing submersible vehicles with similar capabilities is to understand fish physiological design and control strategies. Then, more researches have been devoted to the hydrodynamics mechanism of fish-like swimming [1], the different maneuverable swimming modes [2] and the mechanical structure of fish-like robot models [3]. However, studies of actuation with high efficiency and energy density have been started by only a few research groups. One example is the recent achievement of applications of new style actuators, as artificial muscles [3]–[5]. The purpose of our study is to realize fish-like mobility using oscillation of a flexible caudal fin to provide propulsion. In particular, the actuator of the fish-like robot is a unique synchronous motor referred to as "electrostatic film motor".

In fact, the electrostatic motor has been originally developed as a MEMS (Micro Electro-Mechanical Systems) actuator because of its planar structure and high power density at micro scale. As some further studies have progressed in recent years [6], [7], it has become generally accepted that the electrostatic motor can be applied to not only micro machines but also ordinary-sized devices such as robotic servo actuators. Inspired by these studies, we employ the electrostatic motor to actuate the propulsor of the fish-like robot. To the best of our knowledge, our designed robot is the first attempt of an electrostatic film motor as the artificial muscle in robotic fish.

In the next sections, we will first describe our design considerations for the fish-like robot. Next, we will introduce a model of the electrostatic motor to theoretically analyze its dynamics. We will then propose several swimming control methods to generate fish-like mobility. Finally, experiments are carried out to confirm the validity of the original design and control.

II. DESIGN CONSIDERATIONS FOR A FISH-LIKE ROBOT

A. Fish Locomotion

Two main different locomotion modes have been documented in fish: undulatory motion and oscillatory motion [8]. Fish principally use the two motions of body and/or fin to generate thrust. For instance, eels and lampreys take advantage of undulation of a slender and highly flexible body (i.e., passing a transverse wave from head to tail) so as to produce propulsion. In addition, some fish, including tuna and sharks, have very low-drag body shapes, narrow peduncles, and tall lunate caudal fins. They propel themselves only through oscillations of caudal fins. As a matter of fact, such caudal-fin-based swimming is considered to be the most efficient at cruising speeds [8]. Motivated by the review from biology, many researches concerning fish-like robots have focused their attention on the locomotion mode like tuna and sharks [1], [9], [10].

Even though the caudal fin is arguably the most successful aquatic propulsor, there are many types of fish that generate thrust using principally median (e.g., dorsal and anal) and paired (e.g., pectoral and ventral) fins. They principally make use of oscillations of median and paired fins, and rarely use the motion of body or caudal fin. The type of swimming is thought to be more efficient at slow speed and more maneuverable as well since the median and paired fins may be controlled independently and produce reverse thrust.

Our robot will use caudal-fin-based swimming and neglect motions of median and paired fins because our basic idea to realize the fish-like locomotion is to utilize only one actuator to generate thrust.

B. Application of Unique Actuation

It is well known that fish use muscle to actuate their propulsors. Since muscle has considerably complex constructions and performances, it is not currently an alternative for artificial systems. In general, electromagnetic motor is a normal selection as an artificial muscle for providing the

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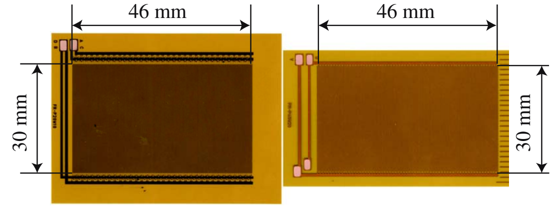

Fig. 1. An electrostatic film motor consists of two pieces of flexible printed circuit boards: stator (left) and slider (right).

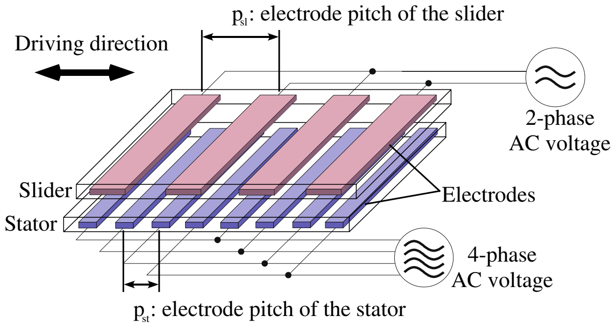

Fig. 2. An electrostatic film motor is a synchronous motor with six phases. The slider (top film) is excited by 2-phase AC voltage and the stator (bottom film) is excited by 4-phase AC voltage.

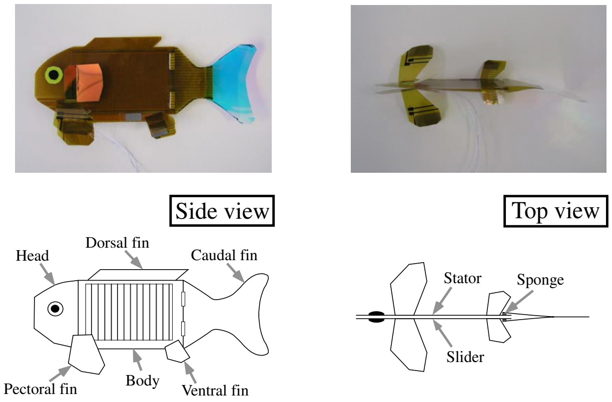

Fig. 3. The photograph (top) and schematic structure (bottom) of the designed fish-like robot. The size of the designed robot is 130 mm × 50 mm × 55 mm and its total weight is only 5 g.

propulsion while a fish-like robot is designed. However, Barrett et al. indicated that the actuation made of electromagnetic motors is noisy and requires a fairly elaborate transmission system to amplify torque [11]. Thus, many other actuators (e.g., shape memory alloy actuators, piezoelectric actuators and conducting polymer actuators) have been studied and applied to fish-like robots as artificial muscles [3]–[5].

In this paper, we do not discuss these existent artificial muscles since the subject is beyond the scope of this paper. Conversely, we focus on a unique actuator referred to as electrostatic film motor which is made of flexible printed circuit boards (see Fig. 1). As plotted in Fig. 2, the electrostatic motor is a synchronous motor with six phases and utilizes film electrodes for both stator and slider. While the slider film is placed directly on the stator film, a planar, light, flexible and high output linear motor is constructed. The slider film is driven by the electrostatic force so as to accomplish the linear motion. It is important to note that the slider is excited by 2-phase AC voltage and the stator is excited by 4-phase AC voltage, which is different from two sets of 3-phase AC voltage in [6], [7]. The configuration of electrodes has two benefits: (1) it is easy to accomplish the power supply by reversing voltage of the certain electrode since there should be the 180 deg phase difference in the case of the even numbers of electrodes; (2) it is possible to reduce the manufacturing cost of the flexible printed circuit since the two-phase electrodes of the slider can be realized by single-side board that does not need through-holes. The electrode pitches of the stator p_{st} and the slider p_{sl} are 200 μm and 400 μm, respectively. Both of their electrode areas represent 46 mm × 30 mm. In order to decrease the influence of friction between the slider and the stator, we scatter glass beads of 7 μm in diameter between the two films. The more detailed explanation and analysis in relation to the electrostatic film motor will be described in Section **III**.

C. Mechanism Synthesis

The first step in synthesizing mechanisms for a fish-like robot is to select a desired caudal fin motion. In our design, a lunate caudal fin undergoing small amplitude oscillation is chosen to mimic biological propulsion. Full and Koditschek indicated that locomotion results from complex, high-dimensional, nonlinear, dynamically coupled interactions between an organization and its environment [12]. Videler stated further that the actual swimming locomotion is caused by the interaction between the body and the surrounding water [13]. Hu and his co-workers found that their fish-like robot with a passive and flexible caudal fin is capable of generating the fish-like undulating motion to propel itself forward [14]. Motivated by above-mentioned points of view, we also use a lunate flexible caudal fin and a narrow peduncle to realize fish-like undulating motion and to output the necessary forward thrust. The schematic structure and photograph of the designed fish-like robot are shown in Fig. 3. The body of the robot consists of the stator film and the slider film. Namely, the entire fish body can be considered to be an electrostatic motor. Although the dorsal, pectoral and ventral fins are equipped, they are inactive and used to maintain balance in water. It is important to note that the lathy sponges are applied to the caudal peduncle in order to benefit the transfer from the reciprocating motion of the electrostatic linear motor to the undulating motion of the caudal fin. The designed fish-like robot is 130 mm in length, 50 mm in width, and 55 mm in height. The total weight is only 5 g. To the best of our knowledge, the robot is simplest and lightest in the fish-like robot literature.

III. ELECTROSTATIC MOTOR DYNAMICS

As described in Section *II-B*, the electrostatic motor is a synchronous motor with six phases. It is driven by a 2-phase AC voltage and a 4-phase AC voltage, which are respectively imposed upon 2-phase electrodes in the slider and 4-phase electrodes in the stator (see Fig. 2). The driving voltages can be expressed in a vector from as

$$\begin{aligned}\mathbf{v} &= [v_1, v_2, v_3, v_4, v_5, v_6]^T \\ &= \Big[v_{st}\sin(\omega_{st}t), v_{st}\sin(\omega_{st}t+\frac{\pi}{2}), \\ &\quad v_{st}\sin(\omega_{st}t+\pi), v_{st}\sin(\omega_{st}t-\frac{\pi}{2}), \\ &\quad v_{sl}\sin(\omega_{sl}t), v_{sl}\sin(\omega_{sl}t+\pi) \Big]^T \\ &= \Big[v_{st}\sin(\phi_{st}), v_{st}\cos(\phi_{st}), -v_{st}\sin(\phi_{st}), \\ &\quad -v_{st}\cos(\phi_{st}), v_{sl}\sin(\phi_{sl}), -v_{sl}\sin(\phi_{sl}) \Big]^T, \quad (1)\end{aligned}$$

where $v_1 \sim v_6$ represent the voltages applied to the corresponding six electrodes. v_{st}, v_{sl}, ω_{st}, ω_{sl} and ϕ_{st}, ϕ_{sl} respectively represent voltage amplitudes, angular frequencies and phases of the basic AC voltages applied to the stator and slider. Based on our previous studies, we have realized that the electrostatic film motor synchronizes its slider running speed with the velocity difference of the running electric potential distribution on the stator and the slider. Fig. 4 illustrates the electric potential distribution that are excited by the six-phase AC voltage on the two films. Since the electric field wave on the slider is a standing wave, it can be decomposed into two completely converse running waves (i.e., slider electric field wave 1 and slider electric field wave 2). Conversely, the electric field wave (i.e., stator electric field wave) on the stator is referred to as running electric field wave. Since the wavelengths of the waves on the stator and the slider are respectively $4p_{st}$ and $2p_{sl}$, the velocities of the waves on the stator and slider, u_{st},u_{sl1},u_{sl2}, are as follows:

$$\begin{aligned} u_{st} &= \frac{2p_{st}}{\pi}\omega_{st} \\ u_{sl1} &= -\frac{p_{sl}}{\pi}\omega_{sl} \quad (2) \\ u_{sl2} &= \frac{p_{sl}}{\pi}\omega_{sl} \end{aligned}$$

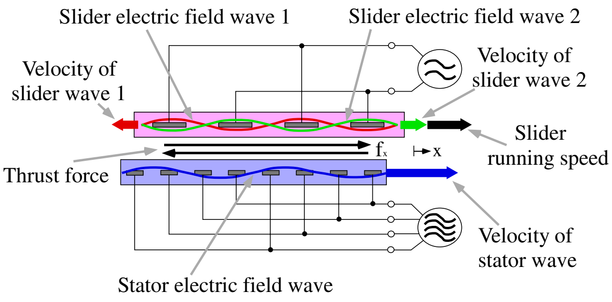

Fig. 4. The operation principle of an electrostatic film motor: the interaction between stator electric field wave and slider electric field wave generates the electrostatic force to drive the slider.

Here, p_{st} and p_{sl} represent the electrode pitches of the stator and the slider (see Fig. 2). As a matter of fact, an electrostatic film motor is driven by the electrostatic force that results from the electric field waves on the stator and the slider. In our other paper [15], we have theoretically analyzed the thrust force of the 2-4-phase electrostatic film motor by using a six-terminal capacitance network model. Then, we will not describe the detailed analysis because it is beyond the scope of this paper. As a result, the thrust force f_x in the x direction of the electrostatic film motor can be trivially computed as

$$\begin{aligned} f_x &= K v_{st} v_{sl} \sin(\phi_{sl}) \cos(\phi_{st} - \theta_x) \\ &= K v_{st} v_{sl} [\sin(\phi_{sl} + \phi_{st} - \theta_x) \\ &\quad + \sin(\phi_{sl} - \phi_{st} + \theta_x)]. \quad (3) \end{aligned}$$

Here, K is a coefficient which has relations with the capacitances among each electrodes, θ_x represent the electrical angle expression of the relative position of slider electrodes. It is clear that the thrust force is increased as the voltage amplitudes (i.e., v_{st} and v_{sl}) increase. Namely, the power output of the electrostatic film motor is decided by the AC voltages applied to the stator and the slider. In addition, Eq. (3) also shows that the thrust force contains components of the sum of frequencies (i.e., $\phi_{sl} + \phi_{st}$) and the difference of frequencies (i.e., $\phi_{sl} - \phi_{st}$). When the angular frequencies of the AC voltages are the higher values, the components of the sum will become further large. Because the mechanical parts can hardly respond to the high-frequency signal, the components of the sum of frequencies (i.e., $\sin(\phi_{sl} + \phi_{st} - \theta_x)$) can be neglected. Then, Eq. (3) can be simplified as follows:

$$f_x = K v_{st} v_{sl} \sin(\phi_{sl} - \phi_{st} + \theta_x). \quad (4)$$

Thus, the slider running speed u is decided only by the interaction between stator electric field wave and slider electric field wave 2. According to Eq. (2), the slider running speed u can be written as

$$u = u_{st} - u_{sl} = \frac{2p_{st}\omega_{st} - p_{sl}\omega_{sl}}{\pi}. \quad (5)$$

For the above equation, varying the difference of frequencies applied to the stator and slider can adjust the slider running speed. The moving distance of the slider S during the operating time T is defined as

$$S = uT = \frac{2p_{st}\omega_{st} - p_{sl}\omega_{sl}}{\pi}T. \quad (6)$$

If the frequencies are expressed as a function of time t[1], Eq. (6) can be rewritten as an integral format,

$$S = \int_0^T \left[\frac{2p_{st}}{\pi}\omega_{st}(t) - \frac{p_{sl}}{\pi}\omega_{sl}(t) \right] dt. \quad (7)$$

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[1] For instance, the frequency is continuously modulated during a constant period when we use the electrostatic motor to provide propulsion for the designed fish-like robot.

If ω_{st} is constant, then the moving distance is proportional to the change of ω_{sl} during the operating time T. For the case in which the frequency difference between the stator and slider is positive when $\omega_{sl} < \omega_{st}$, the slider is moving in order to make up for the velocity difference between the electric field waves on the stator and the slider. Conversely, for the case in which the frequency difference is negative when $\omega_{sl} > \omega_{st}$, the slider is moving towards the converse direction for the compensation of the velocity difference. Of course, the slider stops moving when the frequency difference becomes zero. As a consequence, the operation similar to a linear stepping motor is realized in the electrostatic film motor. It is important to note here that the electrostatic film motor can operate as long as the contact area between the stator and the slider are fully insulated. Thus, dielectric liquid is injected between the two films for operation in general.

IV. SWIMMING CONTROL

Control problems for a fish-like robot include various topics (e.g., trajectory planning, tracking trajectory, efficient swimming, high maneuverability and so on). This study is a challenge to an application of a unique actuator (i.e., electrostatic film motor) in fish-like robots. As the first stage of the study, we will focus on problems relating to generation of swimming and adjustments of position and posture. In this section, drawing inspiration from fish, we propose an open-loop control method to realize the fish-like motion.

A. Controller Description

As described in above-mentioned sections, the electrostatic motor essentially needs a six-phase driving AC signal for operation. Fortunately, since we engage the even electrode films, it is easy to obtain a new one-phase driving AC signal as long as we reverse a certain signal. Thus, a set of driving signals containing three AC signals can be instead of the six-phase driving AC signal. As shown in Fig. 5, we utilize two function generators (WF1946A, NF Co.) to provide the three driving AC signals. The one provides a two signals for the stator. The other provides one signal for the slider. Through a high voltage amplifier made by ourselves, the four and two high AC voltages are fed to the stator and the slider, respectively. The central component of the control circuit is a laptop computer with GPIB(IEEE 488) interface card. The computer sends out signal commands to function generators through the GPIB interface. It is important to note that using a laptop computer is useful at establishing more input/output devices and conveniently developing control program. As a matter of fact, we have effortlessly added a joystick as a hand steering through the USB interface of the computer.

All control programs are developed with a visual programming language, $LabVIEW$ (National Instruments Co.). The control program sends the control commands concerning the frequency, phase and amplitude of each driving AC signal by the GPIB interface. The function generators mainly produce 2 $\mathrm{V_{p-p}}$ sinusoidal wave signals according to the control command from the computer. Since the amplifier has a gain of 1000, the AC voltages applied to the electrostatic motor can be controlled at 2 $\mathrm{kV_{p-p}}$.

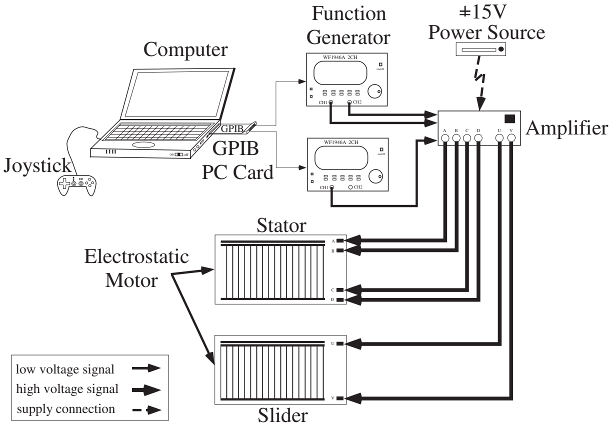

Fig. 5. The logical connection among each control component. Through a high voltage amplifier, a three-phase driving AC signal is changed as a six-phase driving AC signal.

B. Generation of Swimming Motion with Flexible Caudal Fin

In the designed fish-like robot, the thrust force of the electrostatic film motor is transformed into propulsion by an elaborate caudal peduncle mechanism. More concretely, the electrostatic film motor generates reciprocating motion in front and rear by modulating the frequencies of sine waves applied to the slider. The range of the frequency modulation is between 525 Hz and 475 Hz. The period of frequency modulation is approximately 0.6 s. But, the frequencies of sine waves applied to the stator always remain 500 Hz. As a result, the slider runs within ± 20 mm/s speed and produces oscillating motion of the caudal fin to propel the robot forward.

Fig. 6 illustrates the oscillation of the caudal peduncle and fin during one frequency modulation period. First, the caudal fin starts at the right swing limit while the frequencies of sine waves applied to the slider are the central frequency 500 Hz. Next, the caudal fin swings over to the left side as soon as the frequencies sweep up to 525 Hz. For the case in which the frequency arrives at 525 Hz, the slider running speed u is maximized since the maximum frequency difference is operating. Then, Since the frequency returns towards 500 Hz, the swing of the caudal fin is decelerated as the slider running speed decreases. For the case in which the frequency arrives at 500 Hz, the slider running speed u becomes zero and the caudal fin stops at the left swing limit. Conversely, the caudal fin swings over to the right side when the frequencies sweep down to 475 Hz. Finally, when the frequency returns to 500 Hz again, the slider running speed u is zero and the caudal fin stops at the right swing limit.

It should be mentioned here that the oscillating motion only generates a C-shape bend of the caudal fin in air, but in water, it can generate correct fish-like undulating motion.

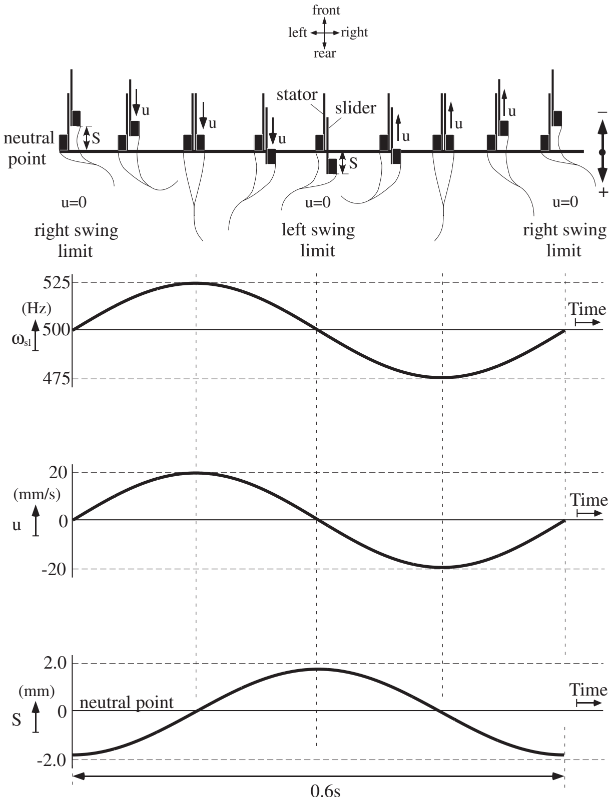

Fig. 6. Time history of the oscillation of the caudal peduncle and fin. During one frequency modulation period(i.e., 1.2 s), the caudal fin generates correct fish-like undulating motion under the operation of the electrostatic film motor.

Since the flexible caudal fin is pushed through the water, its top is inversed from the driven C-shape bend by the water resistance. This shape inversion undulates the caudal fin and provides the enough propulsion. The fact could provide a rational and possible explanation of why our fish-like robot can achieve good swimming performance only using an active joint and a very simple open-loop control method. It is in agreement with the recent research from biomechanics, which shows that, fish make use of passive mechanical properties, most notably compliance, to enhance the effectiveness of their muscles [16].

Furthermore, in order to achieve better fish-like maneuverability, we design a method which takes advantage of the characteristic of electrostatic film motor to control the left/right turning. It is clear that many fish continuously change the body shapes, especially bend the caudal fins, to accomplish the turning. In the same way, such continuously changing or bending can be achieved in the fish-like robot by adjusting the neutral point of the caudal fin. We divide the turning control method into two steps: offset and oscillate. First, the initial phases of sinusoidal waves applied to the stator are modulated so as to produce the offset between the stator and slider films. As a result, the neutral point of the caudal fin is adjusted toward left or right side as the initial phase is set at the positive or negative value. Next, based on the adjusted neutral point, the robot operates the above-mentioned frequency modulation of the stator to realize the oscillation of the caudal fin. When the two steps are simultaneously implemented, the robot accomplishes the left/right turning like a real fish.

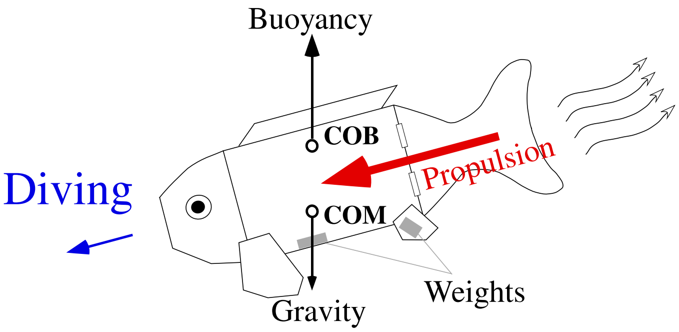

Fig. 7. Outline drawing in relation to the balance of the fish-like robot.

C. Adjustments of Posture and Position

In fact, many fish are essentially open-loop unstable. For instance, most dead fish tend to float belly-up, suggesting that the center of buoyancy lies below the center of mass. Thus, most fish can be considered to be inverted pendulums and must use feedback control to remain upright. In addition, pitch instabilities of fish are also common because the center of buoyancy is typically located fore and hind of the center of mass [17]. Since this study is an attempt on applying a unique electrostatic motor and a simple swimming control method to a fish-like robot, the complex attitude control and position control are beyond the scope of this paper.

In this study, we utilize the adjustment of centroid to remain upright posture and pitch stabilities. As shown in Fig. 7, we attach the suitable weights to the abdomen and the ventral fins so that the center of mass (COM) lies below the center of buoyancy (COB) and the gravity is somewhat less than the buoyancy. This configuration makes the fish-like robot slowly rise to the surface with the upright posture when the caudal fin stops oscillating (i.e., no propulsion is provided).

Furthermore, we incline the head of the fish-like robot down by using the adjustment of centroid (see Fig. 7). The slantwise fundamental posture in sagittal plane facilitates the realization of diving motion. In the fish-like robot, only the caudal fin can provide propulsion due to a single actuator. Using the downward propulsion makes it gradually dive down as it ceaselessly cruises in water. By providing the proper downward propulsion or not, the fish-like robot is capable of freely cruising at the optional depth of water.

V. PROTOTYPE TESTING

To validate the original designs, we use the fish-like robot presented in Section *II-C* to accomplish its cruise in an aquarium. The length, width, and depth of the aquarium

Fig. 8. Snapshots of the fish-like robot swimming in an aquarium.

are respectively $750\ \mathrm{mm}$, $350\ \mathrm{mm}$, and $450\ \mathrm{mm}$. Since water is conductor of electricity, the actuator can not work if the fish-like robot directly swims in water. Therefore, we infuse dielectric liquid, Fluorinert FC-77 (3M Co., Density: 1780 kg/m^2, Kinematic viscosity: 0.8 cSt), into the aquarium.

Fig. 8 shows snapshots of swimming locomotion of the fish-like robot with the proposed control method. When the robot swims forward at the cruising speed $0.018\ \mathrm{m/s}$, the frequency of sine waves applied to the stator are swept in the range of $50\ \mathrm{Hz}$ with $0.6\ \mathrm{s}$ sweeping period. The oscillation amplitude and speed of the caudal fin are changed as the center frequency, sweeping range and sweeping period are varied. In addition, the initial phase applied to the stator is gradually changed to $800\ \mathrm{deg}$ and $-800\ \mathrm{deg}$ for the right and left turnings while the robot implements the turning motion. Since the body of the fish-like robot is made of flexible printed circuit boards, the entire robot can be considered to be notably compliant. Under the interaction between the compliant body and the surround liquid, a C-shape sharp turning has been already realized.

VI. CONCLUSIONS AND FUTURE WORK

We have built the first fish-like robot with an electrostatic film motor, thus demonstrating that applying such a unique actuator to robotics is possible. The fish-like robot relies on the dynamics of the flexible and high-power electrostatic film motor, and passively compliant designs of body and caudal fin. We have proposed a very simple control method that relies on open-loop feedforward (i.e., no sensory feedback). The proposed control method results in not only swimming at average cruising speed approximately $0.018\ \mathrm{m/s}$ but also good fish-like maneuvering. Our robot provides an experimental instantiation of fundamental design and control principles for a new class of fish-like robots with reduced mechanical complexity and power requirements.

Current work focuses on building upon a waterproof case so that the designed fish-like robot can directly swim in water. In addition, further understanding of hydrodynamics of the fish-like robot will allow us to improve its mobility and energy efficiency. Future work will also address to the development of a self-contained robotic fish where the power source are embedded in the body of the robot.

ACKNOWLEDGMENTS

This work was supported by a grant from the Japan Science and Technology Agency. The authors thank Olympus corporation for their contributions toward the project.

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