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# A reciprocating linear actuator driven by anti-phototaxis of plankton

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ABSTRACT

This study focuses on the development of a reciprocating linear actuator driven by plankton. The actuator consists of a straight channel groove in a base plate and a small float with a fin for channel separation. On both sides of the separated channel, plankton freely swims. When the channel is alternatively illuminated by light sources installed at both ends, the plankton escape from the light because of their anti-phototaxis and collide against the fin, resulting in actuation of the float. As an experimental example of plankton, matured *Artemia sallina* (brine shrimp) was used because of its anti-phototaxis nature, as well as its suitable physical size and the breeding convenience. Because of the small driving capacity of the float, two types of reciprocating mechanisms without mechanical load were designed and examined. One type has an optical switching system that is a combination of the shade on the float and optical fibers arranged along the channel. This system drives the float according to the switching of the light; however, a dead point exists where the brightness of the illumination becomes equal. The other type is based on an electronic switching system using photo-interrupters and a flip-flop, enabling continuous reciprocation. An average float speed of 0.21 mm/s and a driving force of 0.537 mN per plankton were obtained in an experiment using 15 Artemia adults. An average round-trip travel time of 69.3 s was obtained for the linear reciprocation. Thus, the possibility of a plankton-driven mechanism is demonstrated, although further research on fatigue and habituation of the plankton is required.



## 1. Introduction

Actuators driven by microorganisms have excellent possibilities of non-battery, self-maintained micro-mechanisms, provided the ecological system is properly maintained. Bacteria motors using mycoplasma has been reported and confirmed to be capable of rotating a $SiO_2$ rotor at a speed of 0.5 rpm [1]. A motor driven by *Escherichia coli* successfully rotated a PMMA (Poly Methyl Methacrylate) ratchet wheel at 1 rpm despite of the random movement of the micro-germs [2]. Gears with asymmetrical teeth were developed for rotation by the random movement of bacteria [3]. However, the small movement in these mechanisms cannot be applied directly to millimeter-order actuation.

Another approach for the construction of bio-mechanisms is based on the application of molecular motors [4], and kinesin-driven system [5]; however, these have no self-maintenance ability and have difficulties in being assembled in micro-mechanisms.

A novel concept for a bio-mechanical-driven mechanism is proposed in Fig. 1. As an example, the closed ecosystem of a bottle aquarium, consisting of a water plant, fish, and bacteria, is presented. The energy flow cycle from the growth of the water plant to live fish, including decomposition and fertilization, is ensured by solar energy, which is the ultimate power source. By adding a small mechanism that is driven by the movement of the fish – a water-wheel for example, kinetic energy can be extracted directly from the ecosystem without conversion into electric power by the artificial photosynthesis [6] or chemical component produced by an alga [7], which are typical energy applications of microorganisms. In the case of microorganisms given the nature of photosynthesis and phototaxis, the system will be simpler and can be regarded as a quasi-perpetual mobile provided the ecosystem is maintained.

As the first step to realize the ecosystem-driven mechanism, a plankton-driven mechanism is designed and manufactured for the examination of the novel continuous drive mechanisms.

## 2. Actuation principle

Fig. 2 shows a schematic of the actuation principle. A float with a fin can freely travel along a straight channel, which is filled with a medium suitable for microorganism culture. The fin separates the channel into two parts, and also serves as a driving force generator. Stimulation sources for the microorganisms are placed at both ends of the channel. The stimulation may be phototaxis, chemotaxis, or

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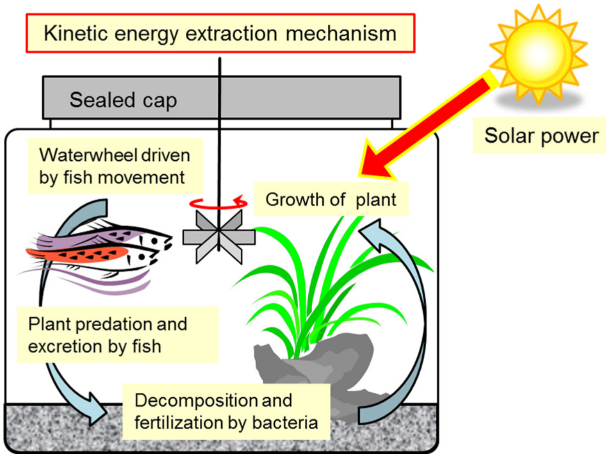


**Fig. 1.** Example of solar-powered closed ecosystem loop. (1) Sunlight natures water plant, which acts as the food for the fish. (2) The excreted matter of the fish is decomposed to nitrogenous fertilizer by bacteria. (3) Some of the solar power is converted to the kinetic energy of the fish.

whatever is available, provided it drives the microorganisms in a uniform direction. Practically, phototaxis is the most convenient because of the simplicity of switching compared to chemotaxis, that has the difficulty of controlling the concentration in a liquid.

Thus, for phototaxis stimulation, light sources are fixed at both ends of the channel and illuminate the channel alternatively. When phototaxis microorganisms are cultured in the channel, they attempt to approach the illuminated end, and the group in the non-illuminated side collides against the float fin, resulting in float actuation. By switching the illumination at the end of the channel, a reciprocating linear movement is realized. Thus, a small amount of mechanical driving force can be obtained by the accumulation of the collision force of microorganisms, although they are individually very small and have random directions originally.

One of the important points in realizing the mechanism, is the switching of the light source, which is operated by a small amount of force obtained from the mechanism or a non of force-driven method. The fluid resistance, typically viscous drag and the friction force between the float and channel walls must be minimized.

## 3. Experimental preparations

### 3.1. Preparation of Artemia

*A. sallina*, known as brine shrimps, were selected for the experimental use because of their phototaxis, suitable physical size and ease of breeding. They can be obtained in the state of dormant dried eggs, which can be hatched in a couple of days by immersing in salt water ranging from 3 to 30 wt%. During the first two weeks after hatching, they remain in a nauplii larva stage and show phototaxis, while their nature changes to anti-phototaxis when they become mature to a size of several millimeters. The adults live for several

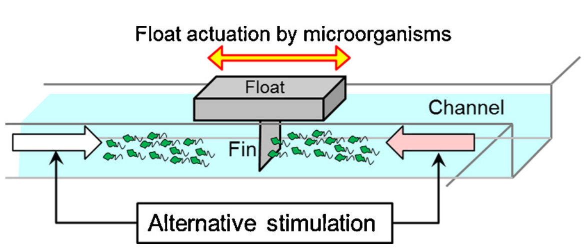


**Fig. 2.** Float actuation principle by microorganisms with alternatively switched stimulation.

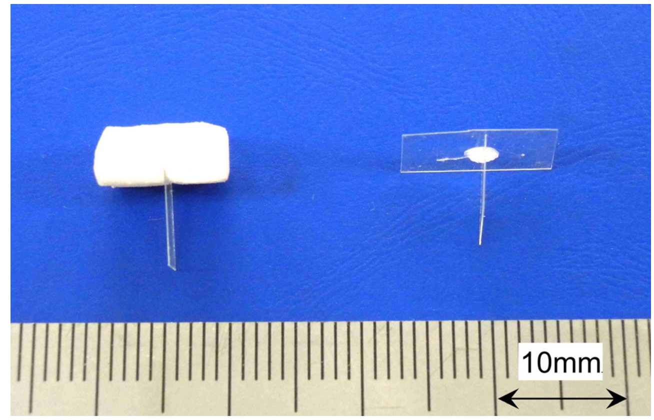


**Fig. 3.** Two types of floats, left; styrene foam with a PET fin, and right; T-shaped PET float.

months feeding on dehydrated powder algae, which allows an easy maintenance of the ecosystem.

For the experiments, Artemias were bred in a 4 wt% salt water maintained at 26 °C. Adults measuring from 2 to 6 mm were selected from the matured group by a plastic syringe, and counted up the number for each channel.

### 3.2. Estimation of float speed and driving force

Estimation of the speed and driving force of Artemia is important for the design of the illumination switching mechanism. An experimental channel with a width of 10 mm and a depth of 7 mm was constructed in an acrylic plate. Two types of floats, shown in Fig. 3, were tested to compare the driving characteristics. A styrene foam block measuring 9 mm × 10 mm × 10 mm with a 6 mm PET(Poly-Ethylene Terephthalate) fin 0.2 mm thick was used owing to its high buoyancy; however, it showed a stick-slip tendency because of the large friction force against the acryl channel wall. As an alternative, a T-shaped PET float was tested to reduce friction, and it successfully traveled in the channel.

The traveling speed of the T- float driven by 16 Artemia adults for crossing 20 mm in the channel was measured using a video camera. The results are presented in Table 1, showing an average speed of 0.21 ± 0.29 mm/s. A large variation in the speed was observed because of the variation in impulse by individual Artemia, which was attributed to the variety in the size and collision angles of the adults.

Because the driving force is expected to be too small in order to carry out the measurement directly using force sensors, the hydrodynamic measurement setup shown in Fig. 4 was used. A sail blown by a motor fan was erected on the float. The driving force $F_A$ generated by Artemia was balanced to the wind force $F_W$ at the sail when the float was stationary. No viscous drag around the bottom fin was generated because there was no movement of the float.

Therefore, $F_A$ can be obtained by the following equation,

$$F_A = F_W = C_d \frac{\rho V_W^2 S}{2}, \qquad (3\text{-}1)$$

where $C_d$ is the sail drag coefficient, $\rho$ is the density of the air, $V_W$ is the wind speed, and $S$ is the area of the sail.

**Table 1**
Results of float speed of 20 mm in the channel.

| Direction | Speed (mm/s) | | | |
|---|---|---|---|---|
| Leftward | 0.40 | 0.08 | 0.10 | 0.11 |
| Rightward | 0.14 | 0.59 | 0.08 | 0.19 |