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Micro-rotary ratchets driven by migratory phytoplankton with phototactic stimulus

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ABSTRACT

This study proposes micro-rotary ratchets driven by a migratory phytoplankton–*Volvox*, exhibiting a positive phototaxis. Two types of micro-discs, i.e., ratchet- and starfish-like ratchets are fabricated using conventional photolithography. The ratchet is floated in the center of a Petri dish filled with *Volvox* suspension under an optical microscope with halogen lamp illumination and is covered by a mask with a small hole so that the microorganisms are concentrated around the micro-ratchets by the phototaxis. Rotations of the ratchets with the same diameter of 0.567 mm were observed through a biological microscope; a rotation speed of 0.86 rpm for the micro-ratchet and 2.01 rpm for the starfish ratchet were obtained for a *Volvox* density of 1000–3000/mL under an illumination intensity of 0.18 W/cm^2. As the driving mechanism of the ratchet is based on the microorganisms adhesion to the ratchets surface rather than collision impacts, a gelatin coating on the ratchet was used to enhance the adhered number of *Volvox*. Although the drag force was increased owing to the larger ratchet diameter, a rotation speed of 0.16 rpm was observed. A particle tracking velocimetry measurement using polystyrene beads was performed to study the fluid flow around the micro-ratchet. A vortex generation by the micro-ratchets was confirmed; this effect may work as a micro-mechanical power booster for microorganisms. This drive system may open the possibility of a solar-power-driven and sustainable micro-mechanism using phytoplankton.

1. Introduction

Various driving methods regarding micromechanisms have been studied using a microorganism as a kinetic driving source because they do not depend on electrical or chemical sources just like regular machines. Several mechanisms such as bacterial motors [1], micro-objects driven by *Escherichia coli* [2], *Bacillus subtilis* [3], and *Serratia marcescens* [4], micro-bead transportation by *Escherichia coli* [5] and *Chlamydomonas* [6], reciprocating linear actuators [7], and micro-ratchet gears [8] driven by *Artemia* among others have been reported to date. In these mechanisms, the moving vector of each microorganism is random and should be aligned along an uniform direction. To achieve this, the asymmetric shape of micro-objects such as lead-in entrance [1], ratchet gears [2]. Also, a mass- microorganism drive is important for the application of the rotary actuator power source, although a linear beads driven system has been realized for small numbers of migratory phytoplankton(6)so far. To gather microorganisms around micro-ratchets, stimulation to microorganisms [6] are typical solutions. Among various types of stimulation, phototaxis is one of the most convenient because of the simplicity of control outside of the breeding environment. We have reported two types of micro-actuators driven by oceanic zooplankton [7,8]; however, they have some difficulties, such as low growth yield to become adults, short lifetime of larva, and the requirement of salt water for breeding.

To solve those difficulties, an alternative approach using migratory phytoplankton with phototaxis was proposed, fabricated and evaluated in order to actuate micro-rotary ratchets floating on the water, as well as a surface treatment for the torque enhancement and an image analysis for the application. Compared to zooplankton, phytoplankton has a long driving possibility because of its photosynthesis and lack of feeding requirement, except for a small amount of fertilizer and solar power. Moreover, existence and reproduction can be maintained sustainably as along as the environmental condition is secured, which may lead to a bio-solar power driven micro mechanical system without parts maintenance.

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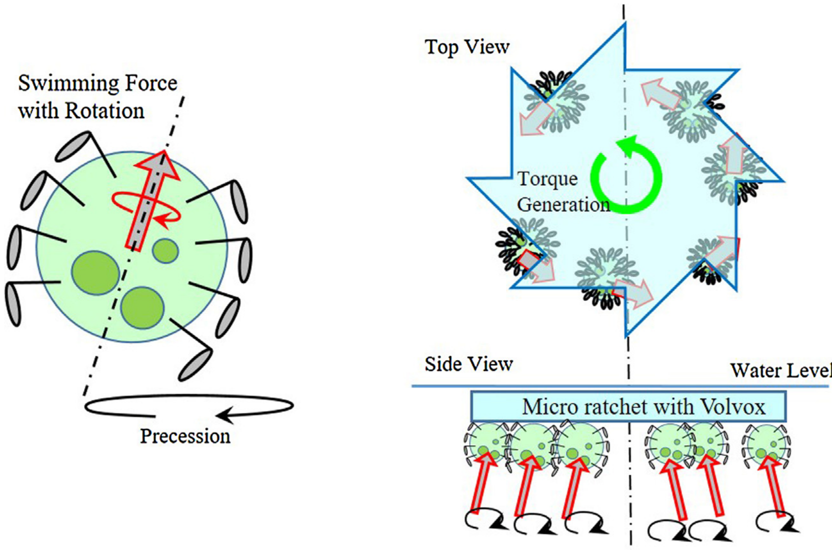

Fig. 1. Swimming force of *Volvox* and principle of micro-ratchet drive by multi-*Volvox*.

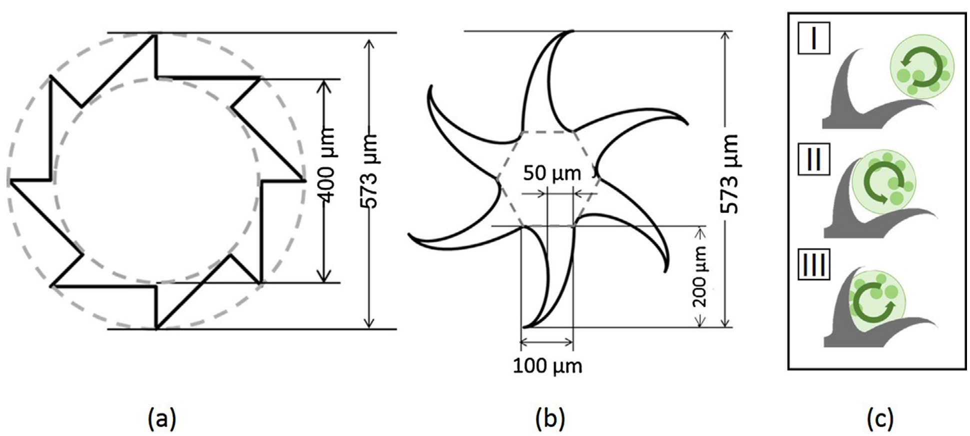

Fig. 2. Design of the micro-ratchets; (a) 8-tooth ratchet gear, (b) starfish-like micro-disk, and (c) principle of roll-in clip action.

In the experiment, two types of micro-rotary ratchets, i.e., ratchet gear and starfish, were fabricated via conventional photolithography on a silicon substrate and *Volvox* was selected as the driving plankton after testing three species. A gelatin coating on the micro-ratchets was also examined to increase *Volvox* engagement, resulting in the ratchet rotation for large diameters. Finaly for the application purposes, a particle tracking velocimetry (PTV) measurement using polystyrene beads was performed for investigating fluid movement around the micro-ratchets; the PTV measurement confirmed that the fluid was driven by the micro-rotary ratchets.

2. Driving principle and ratchet design and phytoplankton selection

The swimming behavior of *Volvox* is based on the rising force with rotation by the flagellum movement due to the nature of phototaxis [10], which is shown in Fig. 1. When the *Volvox* reaches the lower face of the ratchet, a precession is expected by the composition of rising force and revolution, because the top of *Volvox* is fixed on the back surface, resulting in components of horizontal force. Originally, the direction of precession force is random, however, the asymmetry of the ratchet makes the torque in unique direction according to the teeth orientation illustrated in Fig. 1. One directional rotation by the ratchet is common in micro-ratchet motors [2,3], and pawl is attributed to the difference of fluid resistance by the ratchet asymmetry. An analysis of rotation drag force around a ratchet is performed in the previous study [8], directional difference of the drag force seems to be very small due to slow rotation speed and small radius.

Base on the principle, two types of micro-ratchets designed for phytoplankton actuation are shown in Fig. 2. The first one (a) is based on the 8-teeth ratchet gear configuration used in the previous study for the *Artemia* actuation [7] to confirm the usefulness of the ratchet shape; however, its diameter is reduced to 1/10 because of the size difference between the two planktons. Three types of migratory phytoplankton, i.e., *Chlamydomonas sp.*, *Euglena proxima*, and *Volvox aureus*, with diameters of 10–30 µm, 20–50 µm, and 200–500 µm, respectively, and almost the same swimming velocity of 100 µm/s, were considered in a preliminary driving experiment under a microscope. The micro-ratchet can be rotated only in the case of *Volvox*, while the others have no driving power to rotate the ratchet owing to their small sizes. Thus, the superiority of *Volvox* as a micro actuator has been confirmed. During the experiments, *Volvox* tends to roll along the edge of micro-ratchet because its rotation originated from the swim action. Incorporating this movement as a roll-in clip between two carving teeth shown in Fig. 2(c),

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