A Surface-Tension-Driven Propulsion and Rotation Principle for Water-Floating Mini/Micro Robots

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This paper describes development and experimental verifications of a novel propulsion and rotation technique of water-floating objects. As opposed to mechanical paddling, this technique electrically controls surface tension forces acting on water-floating objects without any moving parts (so-called electrowetting-on-dielectric, EWOD), possibly providing a new simple and efficient method to propel and maneuver water-floating mini/micro robots and boats.

The present technique bio-mimics the propelling skill of some insects (e.g., *Pyrrhalta* larva[1]). When the larva bends its back (Fig.1b), the symmetry of surface tension forces acting on its head and tail breaks, resulting in producing a net horizontal static force and thus generating static capillary thrust.

Figure 2 illustrates the concept of bio-mimicked propulsion in a simplified rectangle mini-boat. Unlike the bending mechanism of the larva, the boat has an EWOD electrode on the left side to break force symmetry. Initially, the surface tension forces (F_L and F_R) on the boat are symmetric (Fig.2a): the boat is stationary. To generate asymmetric force configurations and thus horizontal net force, EWOD is applied to the left side of the boat (Fig.2b). Since the contact angle on the electrode is reduced by EWOD, F_L becomes pointing downward while F_R does not change significantly: the resultant of horizontal forces would direct right, and the boat would move right.

The microfabrication process of flexible EWOD electrodes to be attached on the boat surface consists of (i) patterning the Cu layer (2-μm-thick) on the polyimide film using standard lithography (Fig.3a); (ii) depositing a 3-μm thick photoresist layer serving as dielectric layer for EWOD operation (Fig.3b); (iii) depositing a hydrophobic Teflon layer (2000Å-thick) (Fig.3c).

Figure 4 shows sequential snapshots of mini-boat propelling in a water chamber. A box-type mini-boat with top open ($2.5\times1\times1$ cm^3) is made of a polymer film. The microfabricated flexible EWOD electrodes are glued on the front and rear faces of the boat and connected to an external, controllable voltage source via a thin copper wire. The wire is chosen as thin (75-μm-diameter) as possible to minimize any effects of wire bending elasticity on propelling. When 160 V (1-kHz) is applied to the rear EWOD electrode (broken circle), the boat is propelled forward and moved at ~4 mm/s.

Figure 5 shows high-speed snapshots of water meniscus (white broken lines) around the EWOD electrode when the boat is stationary (Fig.5a) and on EWOD motion (Fig.5b). When the voltage is applied to the electrode, the water meniscus is moved up due to reduced contact angle. The direction of surface tension force is changed from nearly horizontal to downward (yellow arrows), confirming the force configuration in Fig. 2.

Figure 6 shows sequential snapshots of boat rotation. To generate a torque on the boat, one electrode is attached to one of the side faces while the other to the opposite face. They are diagonally aligned to each other (broken circles). When 140 V is applied to both electrodes, the boat rotates at ~20 rpm in a clockwise direction.

Figure 7 shows the quantitative results of transportation and rotation speeds vs. applied voltage. Above the threshold voltages (100 and 80 V for transportation and rotation, respectively), the transportation and rotation speeds are increased in proportion to the applied voltage and afterwards saturated.

To generate curved motions (Fig.8), one electrode covers the front corner of the boat (blue-broken circle) while the other is attached to the rear face (red-broken circle). Upon EWOD voltage application, the forward and side resultant forces (red arrows) are produced, leading to clockwisely curved motion in the boat. The result demonstrates the capability of the present technique for steering and maneuvering water-floating objects.

Word count: 600

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References

[1] D. L. Hu and J. W. Bush, *Nature, 2005*, Vol. 437, pp. 733-736.

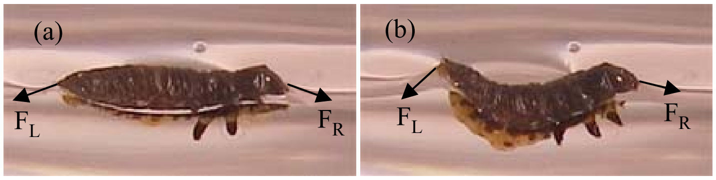

Figure 1. The larva of Pyrrhalta is able to ascend the inclined meniscus. The larva deforms the water surface by arching its back, thus generate asymmetric forces between on its head and tail that generate the desired capillary thrust to move [1].

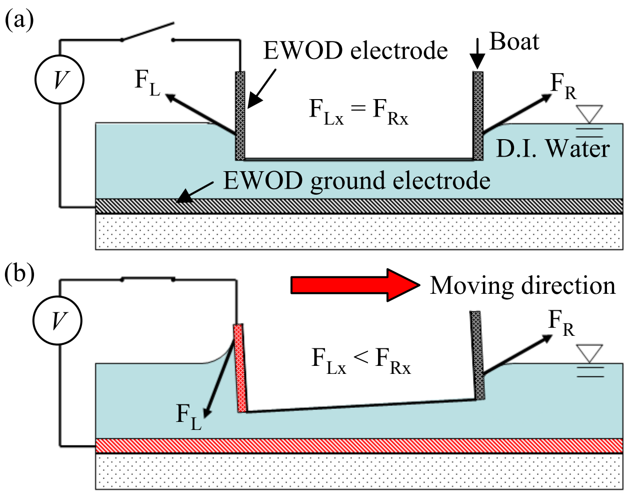

Figure 2. EWOD (electrowetting on dielectrics) propulsion scheme in a mini-boat: (a) Initial state: horizontal force components of surface tension in the left and right are equal to each other ($F_{Lx} = F_{Rx}$). (b) Under voltage application to the left electrode, the contact line rises and the contact angle is decreased (EWOD actuation). That is, $F_{Lx} < F_{Rx}$. The boat would move from left to right.

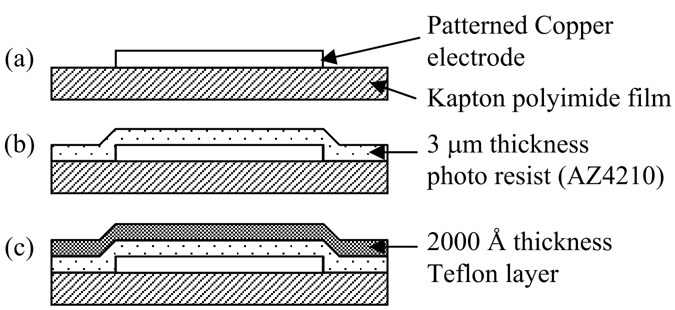

Figure 3. Microfabrication process of flexible EWOD electrodes to be attached onto the boat surfaces: (a) patterning of EWOD electrodes; (b) deposition of dielectric layer (photoresist); (c) deposition of hydrophobic Teflon layer.

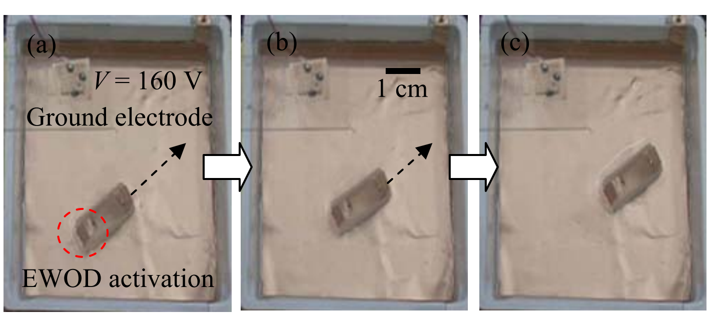

Figure 4. Sequential snapshots of mini-boat propulsion: (a-c) while a voltage of 160 V is applied to the rear electrode (broken circle), the boat is moving forward as indicated by a dotted arrow. The moving speed is at ~4 mm/s.

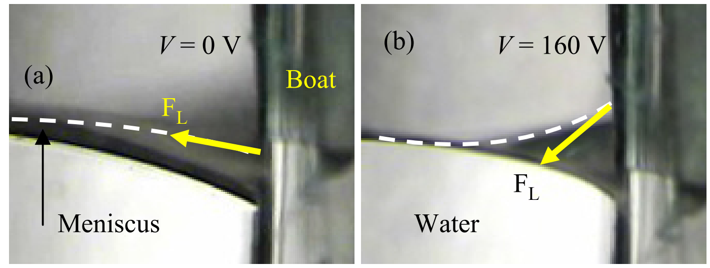

Figure 5. Side view snapshots of the water meniscus on the EWOD electrode before (a) and after (b) applying the voltage. The surface tension force points downward after voltage application, resulting in reduction in the horizontal force component. The broken lines and the arrows denote water menisci near the EWOD electrode of the boat and surface tension force, respectively.

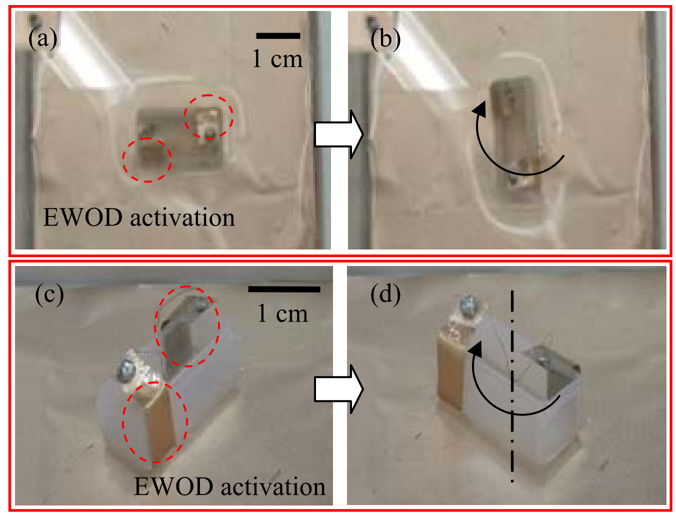

Figure 6. Sequential snapshots of mini-boat rotation: two EWOD electrodes (broken circles) are attached on the side faces to generate a torque. When a voltage (140 V) is applied to the two EWOD electrodes, the boat is rotated at 20 rpm: top view (a) and (b); perspective view (c) and (d).

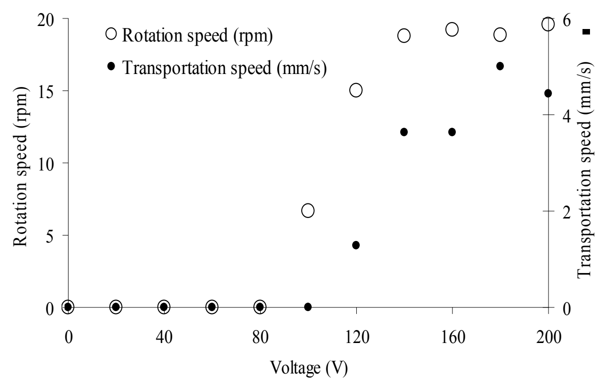

Figure 7. Quantifications of propulsion and rotation speeds vs. applied voltage. Note that there are thresholds to initiate motions.

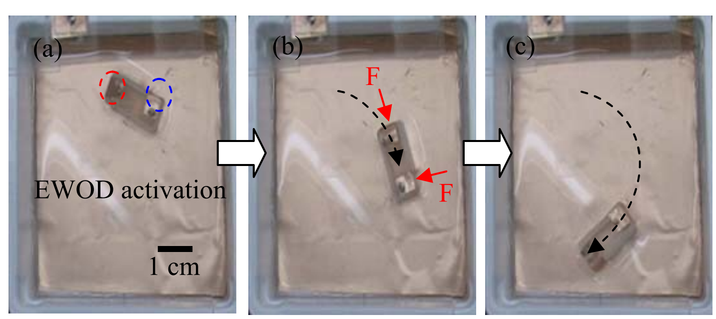

Figure 8. Sequential snapshots of steered propulsion: the boat is driven in a curved path. Note that the front electrode (blue broken circle) covers the front corner of the boat while the rear electrode covers only the rear face (red broken circle).