Nano World Journal

https://doi.org/10.17756/nwj.2020-083

Editorial

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# Smooth Fluidic Way with Multi-Scale Roughness

**Xin Tang[1,2] and Liqiu Wang[1,2*]**

[1]*Department of Mechanical Engineering, The University of Hong Kong, Hong Kong*
[2]*HKU-Zhejiang Institute of Research and Innovation (HKU-ZIRI), Hang Zhou, Zhejiang, China*

***Correspondence to:**
Prof. Liqiu Wang
Department of Mechanical Engineering
The University of Hong Kong
Hong Kong
**E-mail:** lqwang@hku.hk

**Received:** December 31, 2020
**Accepted:** January 04, 2021
**Published:** January 04, 2021

**Citation:** Tang X, Wang L. 2020. Smooth Fluidic Way with Multi-Scale Roughness. *NanoWorld J* 6(4): 70-72.



Published by United Scientific Group

Skillful manipulation of tools and materials is fundamental to scientific research, engineering, and manufacturing. Being a precondition to unlock industrial advancement, different facilities are developed to boost the efficiency or break the limitation of our delicate hands. In warehouse of Amazon, robots transport cargos across floor for efficient storage and retrieval; inside factory of Tesla, mechanical arms grip and place heavy car parts for effortless assembling. Compared with the advanced solid processing, our manipulation towards fluids lags far behind, owing to the complicated liquid/solid interactions.

As tea or coffee droplets fall on table, they rapidly spread and stick on surface, making the intact removal a difficult task. The daily hiccup becomes huge headache in industry as retention on solid biases the transferred fluid mass and exposes sample to cross-contamination. To bypass any impurity, plastic disposables worth billions of dollars are consumed annually for liquid handling. The huge demand backfires on us as the used disposables are frequently contaminated with fluids containing infectious waste, toxic chemicals, heavy metals, or even genotoxic or radioactive substances. Mismanagement of those wastes may cause the spread of disease, potential injury, and serious pollution to the environment [1].

To tackle the "sticky" issue, nature provides potential solution. Some species have evolved retention-proof interfaces. For example, lotus leaf contains micro-papillae overlaid with nano-textured wax to repel fouling water. The hierarchical hydrophobic textures allow water resides atop the textures, forming the superhydrophobic state which is featured by high water contact angle (≥150°) and low roll-off angle (<10°) [2]. *Nepenthes* plant caps its surface within a lubricant layer to capture prey through slip. The lubricant eliminates direct contact with underlying solid, allowing ready liquid sliding [3]. The two retention-proof surfaces interface fluid in a non-sticky and frictionless manner. Assisted by them, different physical/chemical designs and engineering methods can be developed to enable unconventional fluids manipulation [4].

## Liquid Gripper

Reported in Nature Communications, mechano-regulated surfaces are designed by integrating a microfibre array of high liquid affinity with liquid repellent mesh [5]. The microfibres' size is commensurate with the mesh pores, thereby, the surface can rapidly change its state by protruding or retracting fibre array through mesh within 1 s. The mesh maintains its non-wetting feature for both states. By controlling the presence of microfibre, the liquid/solid adhesion can be reversibly switched between 100.2 and 8.9 μN, two extrema allow the capture and release of fluids droplets with volume ranges from 0.02 to 11.8 μl. The liquid loss is roughly 0.7% of that associated with the conventional pipette. The surface shows precise and rapid manipulation towards multiscale liquids. The surface functions as a gripper that can manipulate fluids in a way similar to handling of solids.

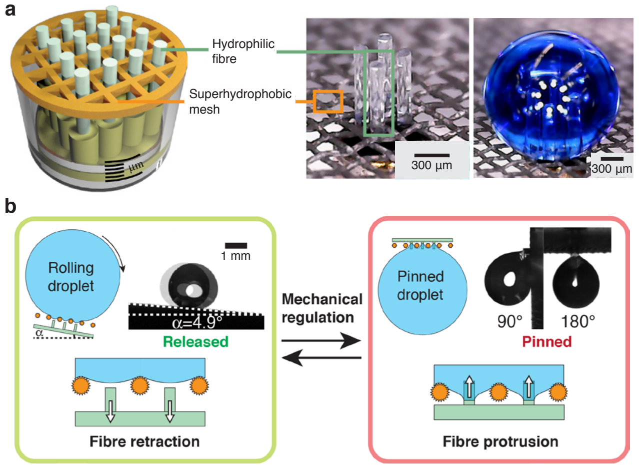


**Figure 1: Design and mechanism of mechano-regulated surfaces.** (a) Mechano-regulated surface consists of a superhydrophobic mesh and a micro-fibre array of contrasting wettability. (b) Liquid/solid adhesion is switched by controlling the presence of the microfibres. (This figure is reprinted with permission from Nature Publishing Group [5]).

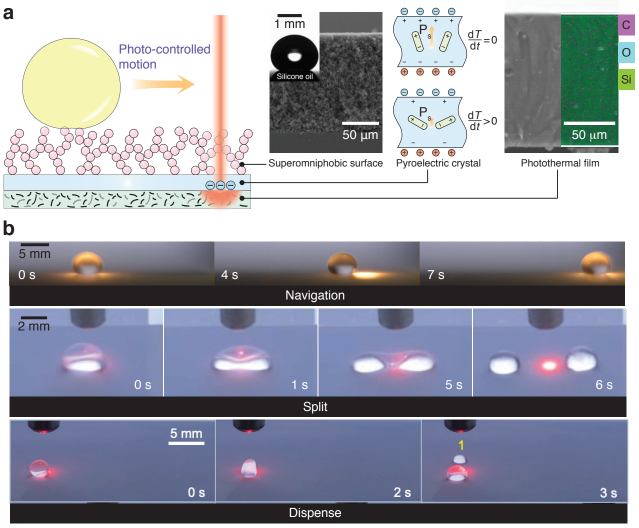


**Figure 2: Design and demonstration of photopyroelectric microfluidics.** (a) The trilayered platform consists of the superomniphobic surface, pyroelectric crystal, and photothermal film. (b) Droplets atop the platform can be navigated, split, and dispensed. (This figure is reprinted with permission from American Association for the Advancement of Science [6]).

# Liquid Processor

Reported in Science Advances, a platform termed "photopyroelectric microfluidics" is developed to move, integrate and cut fluids using just a single beam of light in a lossfree manner [6]. By stacking three homogeneous layers - a photothermal film, a pyroelectric crystal, and a superomniphobic surface - the researchers demonstrate how a ray of light generates a wavy dielectrophoretic force profile through consecutive energy conversions. Droplets atop the platform can be moved or split without physical touch, a scenario reminiscent of fantasy films where wizards levitate and move object around by raising their wands. The superomniphobic surface sustains wide range of liquids (surface tension from 18.9 to 98.0 mN $m^{-1}$) atop nano-textures. As a result, aqueous solutions, alkanes, alcohols, and even silicone oils can be transported on the platform in lossfree manner (liquid or reagent loss being only 0.5% of that with conventional techniques). The three layers work in concert to enable residue-free fluidic operations.

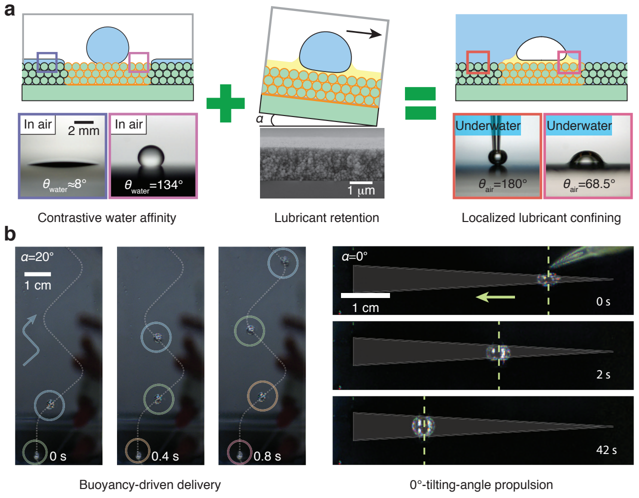


**Figure 3: Fabrication and demonstration of spatially-lubricated surfaces.** (a) Spatially-lubricated surfaces automatically form by immersing lubricated surfaces with patterned wettability underwater. (b) Bubbles can be rapidly transported in organized manner. (This figure is reprinted with permission from American Chemical Society [7])

# Gas Conveyor

Reported in ACS Applied Materials & Interfaces, underwater lubricant path is automatically formed by integrating two disconnected strategies adopted by desert beetle and *Nepenthes* plant [7]. Similar to the beetle's back of mixed hydrophobic and hydrophilic regions, a surface of nanoscale porosity is chemically modified with different liquid affinity. Then the substrate is infused with lubricant. Once immersed underwater, water automatically displaces the lubricant in regions of low oil affinity, whereas in hydrophobic regions, the lubricant retains, forming spatially-lubricated surfaces depicted by precise lubricant paths. Bubbles on the lubricant are out-of-plane fixed but in-plane mobile. Bubbles can be delivered along paths in organized manner with a velocity as high as 10 cm $s^{-1}$. Interestingly, such strategy is applied to fabricate a gas-collecting electrode in water electrolysis. Evolved and growing hydrogen bubbles can be timely removed from exposed electrodes, giving rise to gas self-collection and maximized effective electrode area.

The loss-free and precise manipulation expects to curb the plastic addiction and ease environmental strain. Apart from that, no hazardous fluid retention also upgrades personal safety for operators, particularly medical staff who are constantly exposed to infectious fluids. For example, to test the infectious virus/bacteria is highly risky, sometimes even fatal. A blood droplet from Ebola patient can break into skin and infect the medical workers. An exact diagnosis requires medical staff to break the sampled cells, filter, and purify the virus's genetic materials, series of operations done in fluidic medium. Reported by World Health Organization (WHO), the healthcare workers are between 21 and 32 times more likely to be infected with Ebola and nearly 14% of COVID-19 reported cases are among healthcare workers [8, 9]. A retention-proof handling technique will minimize the production of hazardous wastes and decrease the operational risk. Additional features such as remote and contactless control from the photopyroelectric microfluidics platform can further reduce potential contact with the testing sample. However, those demonstrations are just proof of principle. More work needs to be done before the techniques can be widely adopted. One obvious challenge is that the liquid repellent textures are mechanical fragile and liquid infused surfaces are susceptible to lubricant depletion. Approach to delay performance weathering after repeated usage is still required.

In light of recent studies, the lossfree fluids manipulation has great potential in applied perspectives. The development of superior liquid repellent materials that can accommodate for wide variety of application scenarios remains to be the key issue. Some highly valued features include mechanical durable, chemical inert, resistant to ultraviolet radiation and high temperature, low cost, and ready to fabricate. Interdisciplinary collaboration among materials science, chemistry, and especially engineering will be important for the successful application of unconventional fluids manipulation, which could be a game changer in various industries, including medical diagnosis, drug discovery, fine chemistry, and fluid-based manufacturing and engineering, to name a few.

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