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Multimodal liquid transport enabled by *crassula muscosa* shoot inspired ratchet-shaped leaves channel

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Abstract

Despite significant advances in bioinspired liquid transport systems, existing surfaces relying on static wettability gradients or asymmetric structures remain limited to single-mode transport, while achieving multimodal transport in a single channel has been overlooked. Here, inspired by the *Crassula muscosa* shoots, a multimodal directional ratchet channel (MDRC) is proposed, which integrates asymmetric curvature and tilt features to enable on-demand switching among four liquid transport modes: unidirectional transport in channel, bidirectional transport in channel, unidirectional transport on channel, and transport failure. The underlying mechanism of surface-tension responsiveness is revealed, where the synergy between curvature-induced Laplace pressure asymmetry and tilt-driven meniscus dynamics enables liquids (with surface tensions of 22.8 ~ 72.8 mN/m) to dictate transport modes. Crucially, by strategically leveraging the tunable flow direction and liquid height difference characteristics between transport modes, we developed a real-time surface tension sensor capable of identifying liquid surface tension across three distinct ranges: 22.8 ~ 31.5 mN/m, 35 ~ 42.5 mN/m, and approximately 55 mN/m. And the assembled MDRCs further serve as a multiphase droplet separator achieving > 95% efficiency in both oil-water and oil-oil separations. This work establishes new strategies of liquid manipulation for adaptive microfluidics, smart diagnostics, and precise separations.

Key words: multimodal liquid transport, surface tension responsiveness, liquid-flow height control, surface tension identification, multi-phase separation

Introduction

Directional liquid transport is ubiquitous in nature, with organisms evolving sophisticated structural adaptations to manipulate fluids for survival¹⁻⁵. From cactus spines that harvest fog through multi-scale conical structures to desert beetles utilizing heterogeneous wettability for water capture^{6,7}, these biological systems demonstrate exquisite control over liquid movement^{8,9}. Inspired by such natural designs, researchers have developed functional surfaces capable of directional transport liquid for applications ranging from fog collection to oil-water separation¹⁰⁻¹³. However, a critical limitation persists: current bioinspired surfaces rely on fixed structural gradients or asymmetric wettability¹⁴⁻¹⁶, restricting them to single-mode, unidirectional transport regardless of liquid properties.

To date, some efforts have been made to achieve direction-tunable liquid manipulation by the combination of structural design and liquid properties (such as surface tension). For instance, *Araucaria* leaf inspired liquid channels capable of steering liquid spreading direction by using the difference in liquid surface tension and mechanical strain^{17,18}. Triggered by this observation, there are many direction-tunable liquid manipulation surfaces have been reported based on various precise manufacturing technologies¹⁹⁻²¹. Although these structured surfaces achieve programmable transport of liquids, such as directional selectivity^{22,23}, editable paths²⁴⁻²⁶, and diversity of transport modes²⁷. There is scant attention paid to achieving multiple transport modes and dynamic transitions within a single channel, despite its essential importance for practical applications including microfluidics, fluid sensing, and liquid phase separation. Regarding the direction-tunable liquid manipulation, the latest research shows that the asymmetric meniscus produced by the ratchet-shaped leaves of *Crassula muscosa* shoots can achieve the selection of a specific liquid transport direction²⁸. Here, transport behavior of liquids with different surface tensions are further investigated. It is worth noting that these leaves exhibit four distinct transport modes: unidirectional transport in leaves, bidirectional transport in leaves, unidirectional transport with liquid film protruding from leaves, and transport failure, which dynamically adapt to liquid surface tension, offering new ideas for controlling the multimodal fluid behavior.

In this work, inspired by the multimodal liquid transport modes on *Crassula muscosa* shoots, a multimodal directional ratchet channel (MDRC) is proposed by a simple 3D printing technology. The millimeter-scale MDRC demonstrates excellent liquid transport capabilities, and

leverages its asymmetric ratchet configuration to enabling multimodal liquid transport similar to *Crassula muscosa* shoots, named as: unidirectional transport in channel, bidirectional transport in channel, unidirectional transport on channel, and transport failure. The transport mode changes as the surface tension of the liquid changes. And the mechanism of how curvature-induced Laplace pressure asymmetry and tilt-driven meniscus dynamics synergistically govern transport mode transitions is further revealed. Based on the assemblability of the MDRCs, the spontaneous unidirectional transport behavior of the liquid on the two-dimensional curved S-shaped path, the three-dimensional helical trajectories, and the secondary assembly pathway is realized, demonstrating the customizable liquid transport paths of MDRCs. In the proof-of-concept applications, the liquid surface tensions sensor and mixed liquid separator are developed. Utilizing the flow directions and liquid flow heights differences between transport modes on MDRC, the sensor can identify the surface tension of liquids within the ranges of 22.8 ~ 31.5 mN/m, 35 ~ 42.5 mN/m and ~ 55 mN/m. The assembled liquid separator exploiting "velocity differences" based on the liquid multimodal transport behaviors, achieving a separation efficiency of > 95% for oil/water and oil/oil mixed liquids. This study provides valuable inspiration for designing advanced liquid manipulation functional surfaces toward a wide range of applications, such as microfluidic devices ^{29,30}, fog collection ^{31,32}, medical testing ³³, and multiphase liquid separation ^{34,35}.

Results and discussion

Structural design and fabrication

Crassula muscosa features centimeter-long shoots covered with asymmetrical, ratchet-shaped leaves. As depicted in Fig. 1a, these leaves exhibit a longitudinal curvature radius of R_1 and transverse curvature radii of R_2 and R_3 , tilting from the root toward the tip. Previous study has demonstrated that changes in structural parameters enable these leaves to exhibit selective directional liquid transport. To further investigate the spreading behavior of liquids with different surface tensions on the ratchet-shaped leaves surface, ethanol-water binary mixtures with ethanol volume fractions (c) ranging from 0% to 100% are injected onto the shoots surface of *Crassula muscosa* at a flow rate of 0.5 $\mu\text{L/s}$. It is noteworthy that liquids with different surface tensions exhibit different transport behaviors on the shoots, as shown in Fig. 1b. When $c = 100\%$, liquid exhibits unidirectional transport towards the leaf inclination direction without liquid surface

protrusion, i.e., a thin liquid film conforms to the leaves surface while being pinned in the opposite direction. When $c = 70\%$, liquid exhibits bidirectional transport without liquid surface protrusion. When $c = 50\%$, liquid exhibits unidirectional transport towards the leaf inclination direction, accompanied by a thick liquid film protrudes from the surface. Finally, when $c = 0\%$ (i.e., pure water), droplets aggregate and fall off. Four liquid transport modes are defined corresponding to the four different spreading behaviors. Mode I: unidirectional transport in channel; Mode II: bidirectional transport in channel; Mode III: unidirectional transport on channel; And Mode IV: transport failure (Movie S1).

Inspired by this observation, MDRC is fabricated using 3D printing technology. As shown in Fig. 1c, MDRC is assembled with a cylindrical substrate and ratchet-shaped leaves with an inclination angle $\alpha = 50^\circ$, $\beta = 60^\circ$ and a spacing $p = 1.4$ mm. The artificial ratchets show topographic parameters similar to those of the *Crassula muscosa* leaves, with radii $R_1 = 1.27$ mm, $R_2 = 0.77$ mm, and $R_3 = 0.52$ mm (Fig. S1). In order to optimize the parameters of the ratchet row in MDRC, ethanol droplets are deposited on horizontal MDRC with 0, 1, 2, and 3 ratchet rows. The results indicate that a MDRC with two ratchet rows achieves the highest liquid transport velocity and the best liquid-carrying capacity (Fig. S2). This phenomenon is attributed to the fact that ethanol transport along the ratchet channels requires the complete filling of each ratchet unit before moving to the next, thus increasing the number of ratchet rows actually slows down the liquid transport. Furthermore, binary ethanol-water mixtures with different c values are sequentially deposited on MDRC to investigate its transport performance for liquids with varying surface tensions. As shown in Fig. 1d, as the ethanol volume fraction c decreases (i.e., as the liquid surface tension increases), the liquid exhibits multimodal transport behavior similar to that observed on *Crassula muscosa* shoots, the corresponding transport modes can also be seen in the schematic diagram of Fig. 1d and Movie S2. The liquid transport direction along the ratchet inclination is defined as X^+ , while the opposite direction is defined as X^- . The contact angles and corresponding transport modes of ethanol-water mixtures with c values varying from 0% to 100% are further investigated. As shown in Fig. 1e, when the contact angle on MDRC ranges from 0° to 22.5° , 41.1° to 57° , 63.9° to 72.9° , and 77.6° to 81.8° , the liquid transport behavior exhibits Mode I, Mode II, Mode III, and Mode IV, respectively.

Mechanism analysis of multimodal transport behavior

To gain a deeper understanding of the multimodal liquid behaviors, the transport mechanisms are

elucidated from the perspectives of transport modes transition. For the upright ratchet structure without tilting, the asymmetric curvature of the ratchet exhibits different manipulation capabilities for liquids with different surface tensions^{17,19,36}. As shown in Fig. 2a and S3, the low surface tension liquid readily conforms to the ratchets profiles, creating distinct liquid–air interfaces on the high and low curvature sides. The liquid curvature radius in X -direction (R_{c1-}) becomes smaller than that in X^+ direction (R_{c1+}), leading to a Laplace pressure difference along the X^+ direction:

$$P_{c1-} = \frac{\gamma}{R_{c1-}} > P_{c1+} = \frac{\gamma}{R_{c1+}}$$

where γ is the surface tension of liquid. When the high surface tension liquid is injected, the asymmetry curvature leads to distinct liquid–air interface characteristics at a stable contact angle θ . The liquid curvature radius in X^- direction (R_{c2-}) is greater than that in the X^+ direction (R_{c2+}), resulting in a Laplace pressure gradient along the negative X^- direction, described by:

$$P_{c2-} = \frac{\gamma}{R_{c2-}} < P_{c2+} = \frac{\gamma}{R_{c2+}}$$

Then considering the inclination feature of ratchet, as shown in Fig. 2b. Liquid forms menisci with radii R_r and R_d on the left and right sides of the ratchet base, respectively^{19,37,38}. Therefore, liquid suffer asymmetric additional Laplace pressures P_d and P_r . The Laplace pressure difference ΔP can be described as follows:

$$\Delta P = P_d - P_r = \gamma \left(\frac{1}{R_d} - \frac{1}{R_r} \right)$$

The curvature radius difference of the menisci on both sides is formed $R_r > R_d$, so $\Delta P > 0$ points to the ratchet inclination direction. For the low surface tension liquid, the synergistic driving of asymmetric curvature and tilt features enables the liquid quickly spread along the ratchet inclination direction in Mode I (Fig. 2c). To further explore Mode I, phase diagram of correlation between ratchets structure and liquid transport behavior is shown in Fig. 2d. The gray, orange and blue region represent bidirectional, unidirectional and dropped liquid spreading behaviors, respectively. When the spacing p is too small, the minimum length of the meniscus bottom on the left side, formed by adjusting the inclination angle α exceeds p , resulting in the bidirectional transport of the liquid on MDRC. As for the larger spacing p , the meniscus on the right cannot reach the bottom of the next ratchet, causing the liquid to accumulate and eventually drip from the MDRC. It can be concluded that the Mode I unidirectional transport is determined by the combined effect of the size of the meniscus on both sides of the ratchet and the ratchet spacing (Fig. S4).

As the liquid surface tension increases, the inclination feature plays a dominant role resulting liquid transport in X^+ direction, the countering effect of the curvature feature causes the liquid to expand bidirectionally in Mode II (Fig. 2e). When the liquid surface tension increases further (Mode III), under the action of gravity and the inclined ratchet structure, the droplet first wraps the ratchet from top to bottom to form a raised thick liquid film, and then is transported unidirectionally driven by the Laplace pressure difference induced by the inclined structure (Fig. 2f). Fig. 2g shows the microscopic images of liquid spreading process of Mode III, and the movement of the three-phase contact line during liquid transport is shown in Fig. 2h. As the liquid surface tension further increases (such as water), the injected liquid repels the surface and exhibits hydrophobic state. In this case, the liquid is no longer influenced by asymmetry of ratchet structure. And affected by the tilt feature, the liquid spreads as a droplet slightly in X^+ direction and falls in Mode IV (Fig. 2i), due to contact angle hysteresis. As shown in Fig. 2j, MDRC possesses insufficient manipulation capability for high surface tension liquid in Mode IV, which characterizes the low surface free energy that struggles to exert control over liquids. It includes the full Cassie–Baxter state and transitions to the Wenzel state under gravity. Based on the above analysis of transport modes, the time-dependent variation of transport distance (number of units) is plotted in Fig. 2k for different water-ethanol mixtures. For $c = 100\%$ and 20% , the liquid propagates only in X^+ direction in Mode I and Mode III, respectively. For $c = 40\%$, the liquid transport is bidirectional (Mode II). For $c = 0\%$, water can only spread unidirectionally within a short distance and eventually falls from MDRC in Mode IV (Movie S2). It can be concluded that the transport mode of liquids depends on their surface tension, which provides new guidance for fluid manipulation and its applications.

Multi-dimensional unidirectional liquid transport

For the unidirectional transport of liquid, millimeter-scale structures exhibit significantly enhanced mechanical stability over micro/nanostructures. However, the existing millimeter-scale structures, characterized by high rigidity, exhibit limited adaptability for liquid transportation along complex paths. Herein, the MDRCs, fabricated via photopolymerization 3D printing technology, exhibit the advantages of excellent bending capabilities upon heating and rapid processing according to the predesigned pathways. As depicted in Fig. 3a, the S-shaped MDRC exhibits excellent bending performance, achieving a two-dimensional curved liquid pathway. The continuously injected liquid (take ethanol as an example) can be spontaneously transported

unidirectionally along the S-shaped trajectory. The initial release time of the droplet is set to 0 s, the liquid unidirectionally passes through 27 rows of ratchet units within 38.2 s (Movie S3). In addition, a three-dimensional helical liquid path is also designed and fabricated upon the customized processing, and the unidirectional transport of liquid along the three-dimensional channel is also recorded (Fig. 3b and Movie S4). These results confirm that the reconfigurable ratchet structures in MDRC enable on-demand liquid manipulation and transport through customizable geometric rearrangement.

A three-way valve device is assembled to further demonstrate the scalability of MDRC. Unlike conventional microfluidic channels, which have a fixed fluid transport path after fabrication, MDRC offers assembly-based reconfigurability, enabling on-demand design of flow pathways. As shown in Fig. 3c, a fluid three-way valve can be constructed by connecting three MDRC modules into a T-shaped structure. Specifically, when liquid (taking ethanol as an example) is continuously injected into inlet I and inlet III, the fluid can be transported unidirectionally along a predetermined path and selectively flow out from outlet II within 101.9 s and 96.6 s, respectively. However, when liquid is injected from inlet II, it will be blocked (Movie S5). The results demonstrate the flexibility of MDRC module assembly and the diversity of fluid delivery paths after assembly. In addition, a liquid surface tension sensor device is illustrated, as shown in Fig. 3d. By exploiting the different flow directions and liquid flow heights caused by different transport modes of conductive liquids (solutions of water, ethanol, and NaCl) along the MDRC, the corresponding LED bulbs can be selectively activated to indicate the range of surface tension values of the liquids. Specifically, the ethanol-water mixture with $c = 90\%$ transport to position x_1 within 37.6 s. In this case, only the blue LED bulb lights up, indicating that the liquid surface tension range of $22.8 \sim 31.5$ mN/m (from $c = 60\%$ to $c = 100\%$ in Mode I). When $c = 50\%$, the liquid bidirectionally reaches position x_2 at 27.9 s and x_1 at 43.4 s. Both the white and blue LED bulbs light up, indicating that the liquid surface tension ranges of $35 \sim 42.5$ mN/m (from $c = 30\%$ to $c = 50\%$ in Mode II). Similarly, when $c = 20\%$, the liquid reaches position x_3 in 27.9 s in Mode III and uses the liquid film height to connect the contacts and light up the green LED bulb. The surface tension of the liquid that only lights the green LED bulb is ~ 55 mN/m (Movie S6).

Mixed liquid phase separation application

To further demonstrate the universality of the different transport modes of MDRC for various

liquids, the contact angles and transport modes of nine liquids (A: n-pentane, B: isopropanol, C: n-octane, D: ethanol, E: methanol, F: cyclohexane, G: 1,2-dichloroethane, H: ethylene glycol, and I: water) on the MDRC surface are systematically investigated. As shown in Fig. 4a, liquids A to G with contact angles ranging from 0° to 22.4° , liquid H with a contact angle range of 67.5° to 72.9° , liquid I with a contact angle range of 77.6° to 80.8° , corresponding to the transport Mode I, Mode III and Mode IV, respectively. Taking the liquid forward transport through 10 rows of ratchet units as an example, Fig. 4b illustrates the liquid transport process at the second, sixth, and tenth ratchet units for the two typical unidirectional transport modes. For Mode I, n-octane and 1,2-dichloroethane passed through the second, sixth, and tenth units at 4.7 s, 13.9 s, 23.8 s and 5.3 s, 15.2 s, and 27.5 s, respectively. And for Mode III, ethylene glycol passed through the three units at 6.5 s, 24.8 s, and 43.5 s. Based on the above observations, the transport speeds of the nine liquids transport through 10 ratchet units are statistically analyzed. As shown in Fig. 4c, the average time required for liquids A to G (Mode I) to pass through one unit is 2.53 s, 2.51 s, 2.39 s, 2.52 s, 2.91 s, and 2.77 s, respectively. Liquid H, correspond to Mode III, required 4.24 s. And the liquid I (Mode IV) exhibit a droplet accumulation and detachment behavior. The results conclude that liquids within the same transport mode range exhibit similar transport speeds on MDRC, while liquids in different transport modes show significant differences in transport speeds.

While the separation of high-throughput mixed liquids has been extensively studied, the purification of microvolume mixed droplets remains an equally important yet underexplored area^{39,40}. Precise manipulation and separation of microdroplet systems are particularly critical for applications requiring minimal sample volumes, such as single-cell analysis or microfluidic diagnostics⁴¹⁻⁴⁵. According to the different transport speeds of liquids under the above-mentioned different transport modes, a "speed difference" separation strategy for multiphase mixed droplet separation is proposed here. As shown in Fig. 4d, based on the different transport modes of MDRC for liquids with varying surface tensions, the separation processes of n-octane and water are investigated. During continuous liquid injection, n-octane is transported to the end of the channel and collected at 21.4 s, while water detached at 89.9 s, achieving separation of light oil–water mixtures. Similarly, 1,2-dichloroethane is transported and collected at 27.7 s, while water detached at 86.0 s, achieving separation of heavy oil–water mixtures. In addition to the oil–water mixture, separation of oil–oil mixture is also demonstrated. Taking the separation of n-octane

(Mode I) and ethylene glycol (Mode III) mixture as an example, n-octane is delivered and collected at 19.0 s, and then ethylene glycol is delivered to the end of the channel after a certain distance at 81.4 s, showing the separation strategy based on speeds difference.

In a proof-of-concept application, an assembled liquid separator with a double-bent MDRC is proposed to achieve continuous separation of immiscible liquid mixtures. The upper MDRC of the separator is modified with a hydrophilic solution to facilitate rapid transport of the separated water. After modification, the MDRC with water contact angle of $\sim 18^\circ$ also exhibit an anti-gravity unidirectionally transport water capability (Fig. S5). As shown in Fig. 4e, the assembled separator combining the rapid transport of liquids in Mode I and the liquid height protrusion behavior in Modes III and IV. When the oil-water mixture is injected into the separator, the oil is preferentially transported to the unmodified MDRC channel on the left, and the water accumulates to a certain height at the injected liquid and then transported to the hydrophilic MDRC on the right. Fig. 4f demonstrates the 1,2-dichloroethane and water mixtures (heavy oil–water mixtures) added at a rate of 1 $\mu\text{L/s}$. Since 1,2-dichloroethane and water exhibit transport Modes I and IV, respectively, 1,2-dichloroethane is rapidly delivered to the left MDRC end in the direction of the ratchet inclination, while water accumulates on the MDRC surface and transport to the other end upon contact with the hydrophilic MDRC. Fig. 4g illustrates the close-up time lapse separation process of 1,2-dichloroethane–water mixtures, where a single oil–water separation process is completed within 0.41 s upon contact of water with the hydrophilic MDRC. In addition to heavy oil–water mixtures, separation of light oil–water mixtures (n-octane–water mixtures) and oil–oil mixtures (ethylene glycol–n-octane mixtures) is also demonstrated, achieving a separation efficiency of 95% (Movie S7). We anticipate that this MDRC separator not only demonstrates universal applicability for separating oil–water and oil–oil mixtures, but also expands the range of bioinspired functional structures available for practical applications.

Conclusion

Inspired by the multimodal liquid transport behavior of *Crassula muscosa* shoots, this work presents a multimodal directional ratchet channel that enables surface tension-dependent autonomous selection among four distinct transport modes through synergistic curvature-induced Laplace pressure asymmetry and tilt-driven meniscus dynamics. The structural design of MDRC not only facilitates customizable liquid pathways including complex 2D/3D trajectories and modular microfluidic devices, but also demonstrates practical utility in multiphase separation

with > 95% efficiency and real-time liquid surface tension sensing. We envision that the presented bioinspired functional channel establishes a universal paradigm for adaptive liquid manipulation, offering new possibilities for developing intelligent, energy-efficient systems in microfluidics, multiphase separation and purification, and smart diagnostic applications while overcoming the limitations of conventional unidirectional transport surfaces.

Methods

Materials

The methanol, ethanol, ethylene glycol, glycerol, n-pentane, n-octane, 1,2 dichloroethane, and sodium hydroxide particles used in this study are purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. The nano-hydrophilic coating is purchased from Shanghai Huaxia Jiahe New Materials Technology Co., Ltd.

Fabrication

A 3D printing technology based on cured photosensitive resin (Bene-4, Shenzhen Nova Robotics Co., Ltd.) is used for MDRCs fabrication. The designed 3D models are sliced using NovaMaker software, the printing parameters are set as follows: single printing layer thickness of 0.05 mm, single exposure time of 2.3 s, bottom layer number of 5 layers, bottom layer exposure time of 25 s, rising speed of 120 mm/min, and descending speed of 120 mm/min. After that, the obtained samples are placed in an ultrasonic cleaner (GS-010A, China) and cleaned with ethanol and deionized water for 5 minutes for subsequent testing.

Characterizations

Optical images of the samples and the transport process of the liquids are taken using a digital camera (iPhone 12). All contact angle measurements are conducted using a machine (SDC-350, Shengding Precision Instrument Co., Ltd., China) at ambient temperature. The CA value is obtained by averaging at least three measurements performed at different positions on the same sample.

Mixed liquid separation test

Two containers are placed at the bottom of the MDRC separator to collect the separated liquid. Sudan III is used to dye 1,2-dichloroethane and n-octane red, and methylene blue is used to dye water and ethylene glycol blue for better observation during the separation process. Two syringes are used to absorb 1,2-chloroethane and water and inject on MDRC surface. 1,2-chloroethane and

water transport to the bottom of MDRC along the hydrophobic/hydrophilic surfaces and collected into the containers. An electronic balance (FA1004N, Jinghai, China) is used to measure the weight of water on the hydrophilic MDRC and the container after separation. The separation efficiency can be calculated as $\omega = w_1/w_2 \times 100\%$, where w_1 and w_2 are the weights of water or oil that are collected and deposited.

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Author contributions

Competing interests

The authors declare no competing interests.

Figure legends

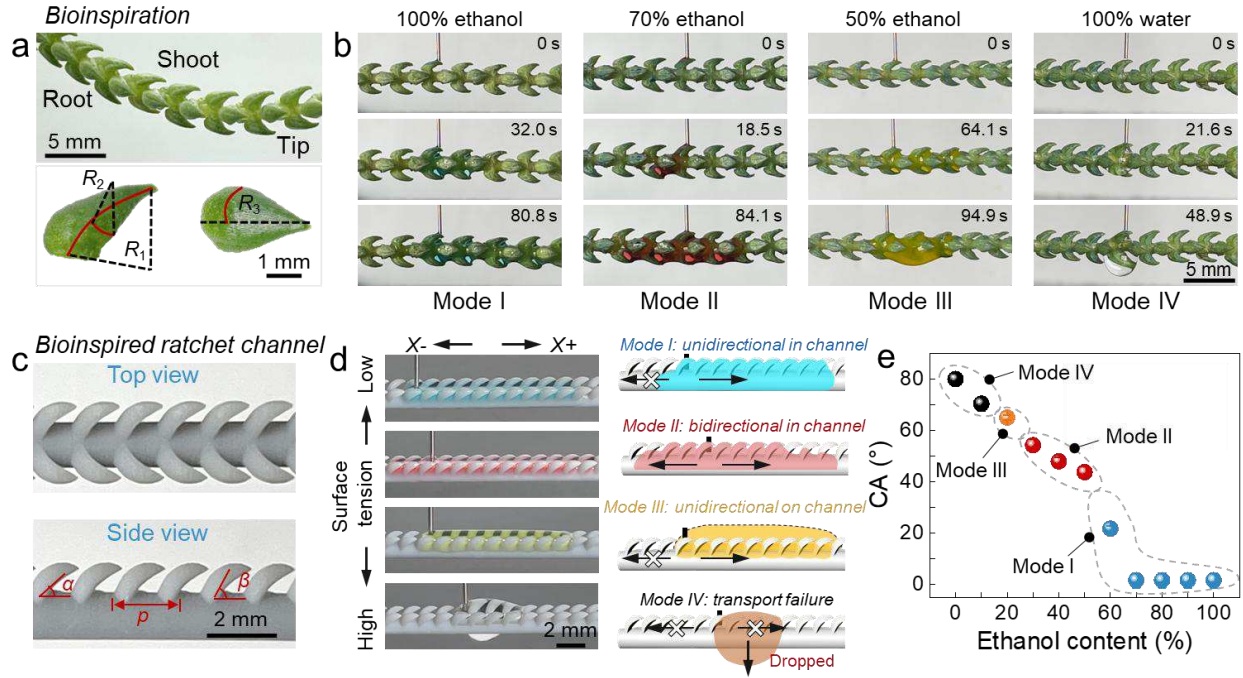


Fig. 1 Design and fabrication of the multimodal directional ratchet channels. **a** Optical images of one *Crassula muscosa* shoot and structural characteristics of its ratchet-shaped leaves. **b** Experimental images of multimodal liquid transport on *Crassula muscosa* shoots. **c** Optical images of structural characteristics the MDRC. **d** Experimental images and schematic of the four transport modes of liquids with different surface tensions. **e** Variation of the liquid contact angle and the corresponding transport mode on MDRC surface with volume fractions of ethanol in ethanol-water binary mixtures.

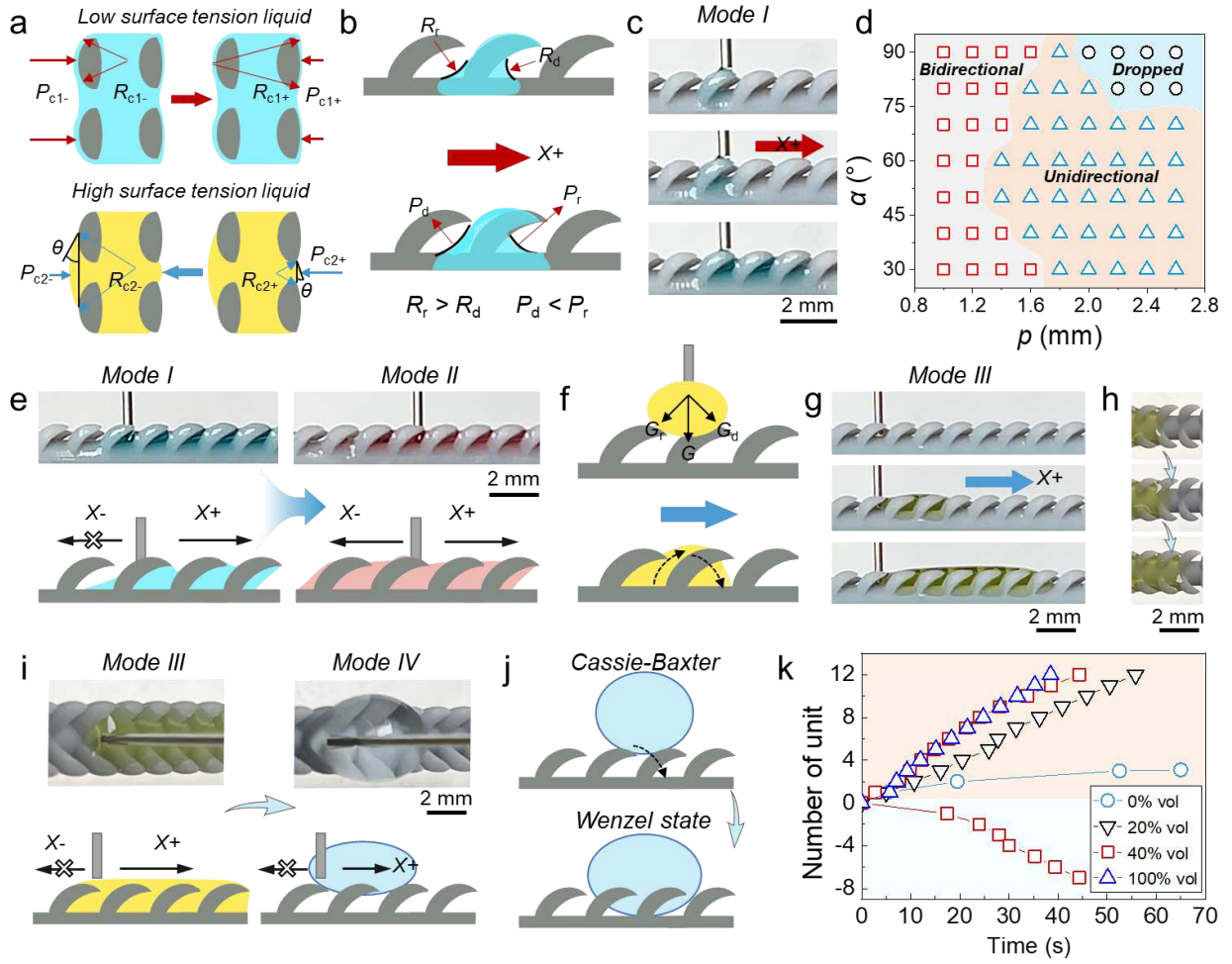


Fig. 2 Mechanism analysis of multimodal transport behavior. **a** Asymmetric ratchet structure of MDRC mediated Laplace pressure asymmetry for high surface tension liquids and low surface tension liquids. **b** Laplace pressure induced by the inclination of ratchet structure. **c** Directional spreading of low surface tension liquid ($c = 0\%$) in Mode I. **d** Illustration of the effect of MDRC structural parameters of inclination angle α and spacing p on the ethanol spreading modes. **e** Experimental and schematic diagram of the transition from Mode I to Mode II. **f** Gravity-driven asymmetric collapse of high surface tension liquid in the early stage of Mode III. **g** Directional spreading of high surface tension liquid ($c = 20\%$) in Mode III and **h** the close-up images of the solid-liquid contact line extending along $X+$ direction. **i** Experimental and schematic diagram of the transition from Mode III to Mode IV. **j** The wettability mechanism of the droplet falling in Mode IV. **k** The diffusion ratchet unit of water-ethanol mixtures with different ethanol volume fractions on MDRC changes with time. The transport distance is positive for forward transport (orange region) and negative for backward transport (blue region).

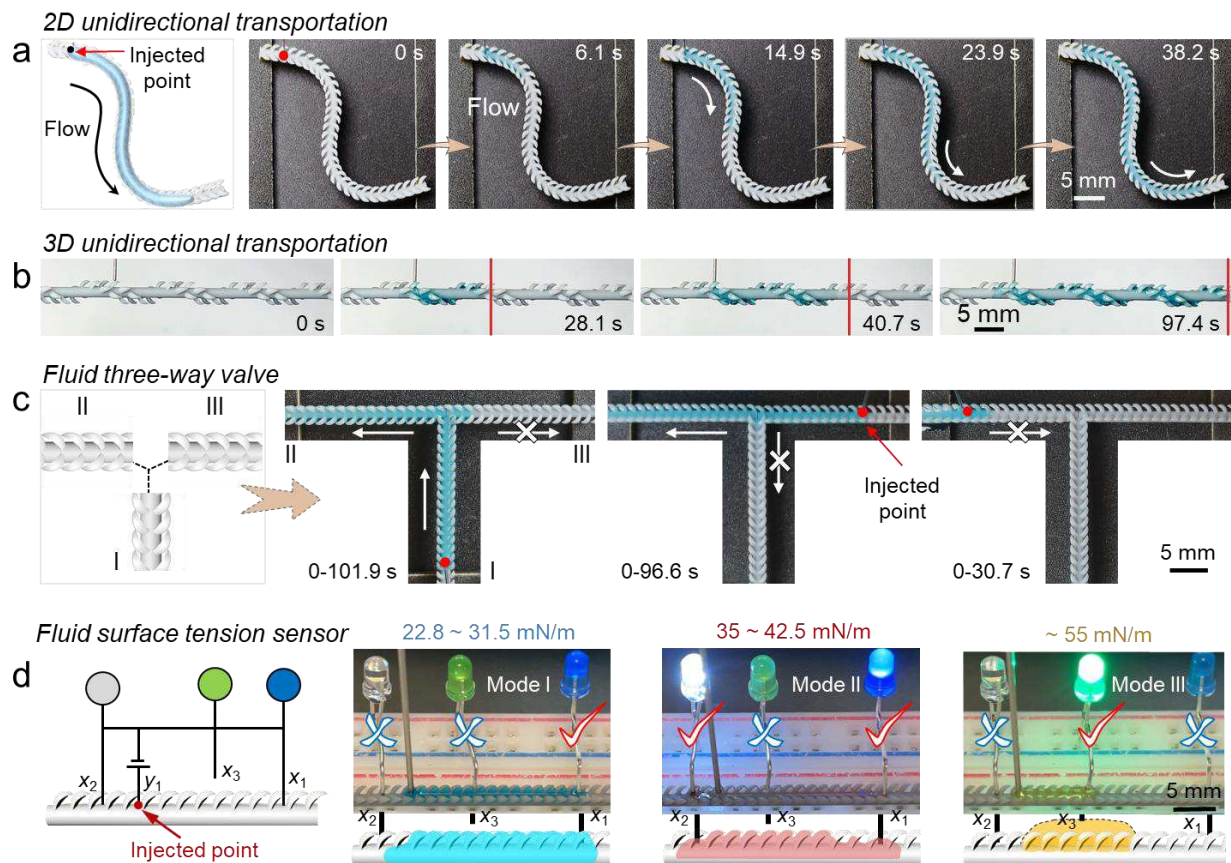


Fig. 3 Multi-dimensional unidirectional liquid transport of MDRC. **a** 2D liquid unidirectional transport on a curved MDRC. **b** 3D liquid transport behavior along a helical trajectory on deformed MDRC. **c** Schematic and experimental images of assembled MDRC serves as a functional fluid three-way valve. **d** Schematic and experimental images of fluid surface tension sensor based on the LED bulbs' selectively lighting. The conductive liquid is a mixture of water, ethanol, and NaCl, the brightness of the blue LED in the first column appears weaker due to the liquid's concentration.

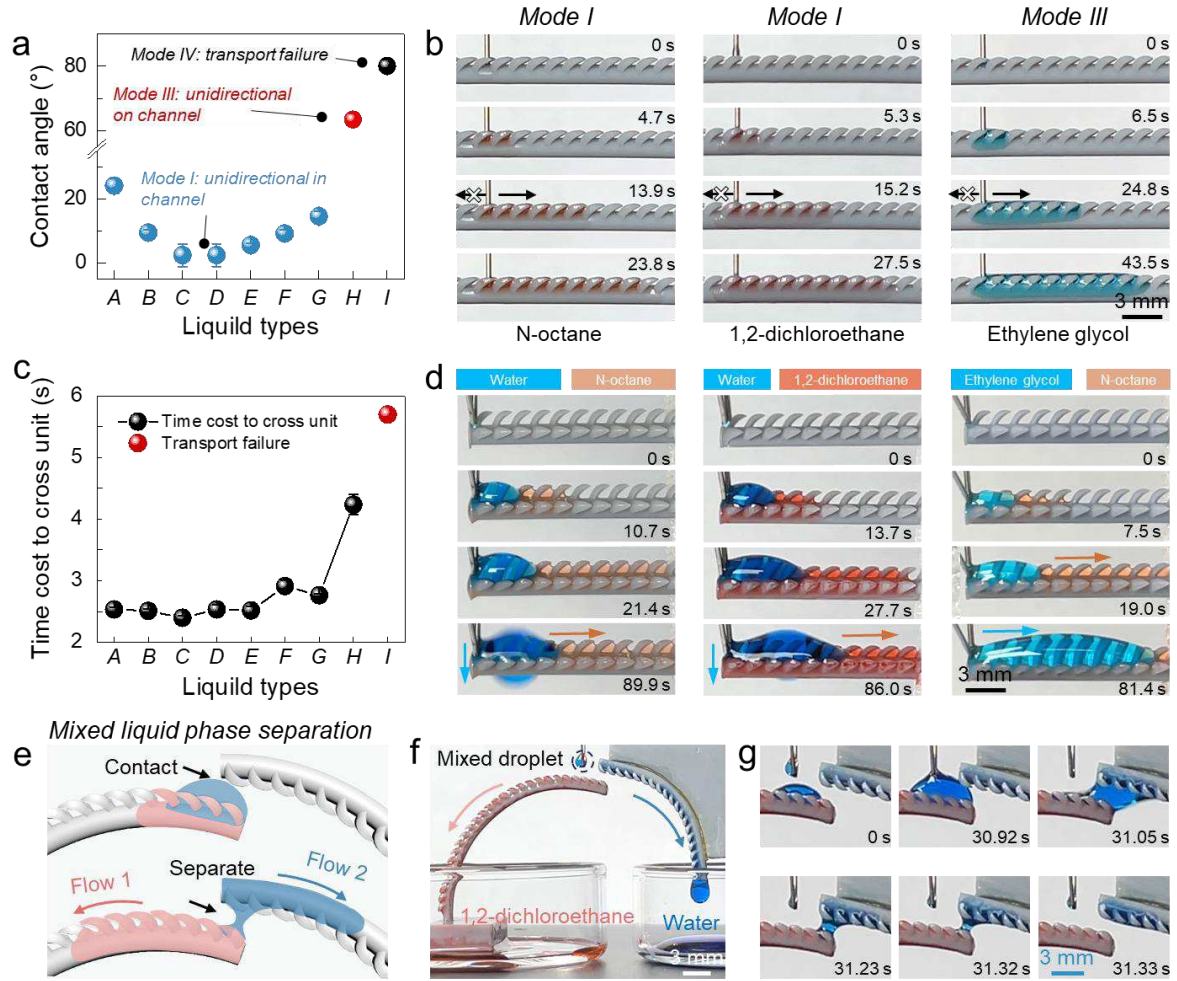


Fig. 4 Proof-of-concept mixed liquid phase separation application. **a** Variations of liquids contact angles on MDRC surface with liquid types. **b** Representative unidirectional transport processes of n-octane, 1,2-dichloroethane and ethylene glycol in Mode I and Mode III. **c** The time change for a liquid to pass through a single ratchet unit varies with liquid types. **d** Experimental images sequence of the “speed difference” separation processes of water-n-octane, water-1,2-dichloroethane and ethylene glycol-n-octane. **e** Schematic illustration of the assembled MDRCs separator for mixed liquid phase separation. **f** Optical image of the separator for the separation of continuously injected water-1,2-dichloroethane mixture. **g** Close-up time lapse images showing the process of mixed microdroplet separating.

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