Supplementary Information for

Adjustable objects floating states based on three-segment three-phase contact line evolution

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This PDF file includes:

Supplementary text
Figures S1 to S12
Legends for Movies S1 to S9

Other supplementary materials for this manuscript include the following:

Movies S1 to S9
Supplementary Information Text

Analysis of objects falling on the water surface

The process of the cuboid box falling in water can be divided into two stages: (1) from initial releasing to reaching the maximum immersion depth (Supplementary Text Fig. 1A); (2) from the maximum immersion depth to the stable floating (Supplementary Text Fig. 1B). The box falls at a height of $H$ between the top of the box and the water surface. It sinks and firstly reaches a force balance position with an immersion depth of $D_e$, which can be obtained by the force balance of gravity, surface tension, and buoyancy:

$$D_e = \frac{mg + 4\gamma a \cos \theta_{adv}}{\rho g a^2}$$  \hspace{0.5cm} (1)

where $\rho$ and $\gamma$ are the density and surface tension coefficient of water, $g$ is the gravitational acceleration, $a$ is the side length of the box cross-section, and $\theta_{adv}$ is the advancing contact angle of the box, which is considered as constant in this speed range. Here and in the following text, the surface tension represents the upward component of the solid-liquid interfacial tension. The box continuously descends due to the inertia, until reaching the maximum immersion depth. The distance between the maximum immersion depth and the equilibrium immersion depth is termed as the offset distance $\Delta D$.

During the box descending, the box is subjected to four forces: the gravity, the buoyancy, the surface tension, and the drag force. The gravity and the surface tension are constant in this process, and the buoyancy increases with the descending. The drag force that resists the box falling can be ignored in this process, as analyzed below.

When the box falls into water, the Reynolds number is $Re = \frac{\rho a U}{\eta}$, where $U$ is the falling speed of the box. Bring typical values: $\eta = 10^{-3}$ Pa s, $\gamma = 7.2 \times 10^{-2}$ N m$^{-1}$, $\rho = 10^3$ kg m$^{-3}$, $a = 10^{-2}$ m, we find $Re$ at scale of $10^2$. Therefore, the drag force originates from the skin drag of a boundary layer around the box. The characteristic thickness of the boundary layer is $\delta \sim \sqrt{\nu t}$. Here $\nu$ is the kinematic viscosity of water and $t$ is the time for the development of the boundary layer. For the box, $\delta \sim \sqrt{\eta b / \rho U}$, where $b$ is the box height. The stress is $\sigma \sim \eta U / \delta$, and the drag force is $F_d \sim \sqrt{\eta \rho (RU)^{3/2}}$. The force is at the scale of $10^{-6}$ N, much smaller than other forces (typically at the scale of $10^{-3}$ N). Therefore, the drag force can be ignored during the box falling.

The work of the buoyancy during the box descending is:

$$W_b = \int_0^{D_m} \rho g a^2 D_0 \cdot dx + \int_0^{D_m} \rho g a^2 \cdot d^2 x$$  \hspace{0.5cm} (2)

where $D_0$ is the initial immersion depth, and $D_m$ is the maximum movement distance, as shown in Supplementary Text Fig. 2.
According to the kinetic energy theorem, the relationship between the maximum movement distance \( D_m \) and the falling height \( H \) is:
\[
mgD_m + 4\gamma aD_m \cos \theta_{\text{adv}} - W_b = 0 \tag{3}
\]

Note that \( D_e + \Delta D = D_0 + D_m \) and \( D_0 + H = b \), where \( b \) is the height of the box. We get the relationship between the offset distance \( \Delta D \) and the falling height \( H \):
\[
\Delta D = \frac{2mg + 4\gamma a \cos \theta_{\text{adv}}}{\rho g a^2} - D_e - b + H \tag{4}
\]

Equation (4) suggests \( \Delta D \) be linear with \( H \), with a proportionality coefficient of unity (Supplementary Text Fig. 3, the dashed line).

We drop the box from different heights, and plot \( \Delta D \) versus \( H \) in Supplementary Text Fig. 3 and the inset of Fig. 2 (blue circles). The well-fitted results suggest the validity of the model. A deviation occurs when \( H \) is greater than 10 mm is because the solid-liquid adhesion force cannot grasp the box in the floating stage, resulting in the slip of the three-phase contact line.

Supplementary Text Fig. 3. Relationship between the offset distance \( \Delta D \) and the falling height \( H \).

Afterward, we will discuss the relationship between the final buoyancy \( F_b \) and the falling height \( H \). When the box reaches the maximum immersion depth, the buoyancy is larger than the sum of the surface tension and the gravity:
\[
\rho g a^2(D_e + \Delta D) > mg + 4\gamma a \cos \theta_{\text{adv}} \tag{5}
\]

The unbalanced force makes the box float up. The forces rebalance when the box rises to a certain height \( \Delta H \) (Supplementary Text Fig. 4). However, the inertia of the box makes the box continuously move upward and then vibrate on the water surface.

Supplementary Text Fig. 4. Schematic of the box vibration on water.

In the vibration process, the three-phase contact line (TCL) is pinned, as shown in Supplementary Text Fig. 5. Finally, the box stabilizes at the force-balance position with an immersion depth of \( D \):
\[
D = D_e + \Delta D - \Delta H \tag{6}
\]

The forces balance as shown in Supplementary Text Fig. 4 is:
\[
\rho g a^2 D = mg + 4\gamma l \cos \theta \tag{7}
\]
In the box vibration process, the shape of the meniscus changes since the pinning of the TCL. We consider this process as quasi-static, the shape of the meniscus is determined by the gravity and the surface tension (Supplementary Text Fig. 6):

\[ \gamma \sin \theta + \frac{1}{2} \rho g z^2 = \gamma \]  

Solving for \( \theta \), we get:

\[ \cos \theta = \frac{1}{2} \left( \frac{1}{1 - \frac{z^2}{4l_c^2}} \right) \]  

Where \( l_c = \left( \frac{\gamma}{\rho g} \right)^{1/2} \) is the capillary length (about 2.7 mm for water at 20°C).

Since \( z \) may be considered much smaller than \( 2l_c \), equations (10) and (11) can be written as:

\[ \cos \theta \approx -\frac{z_1}{l_c} \]  

\[ \cos \theta \approx \frac{z_2}{l_c} \]  

Note that \( z_1 + z_2 = \Delta H \), \( \cos \theta \) and \( \Delta H \) have a simple relationship:

\[ \cos \theta - \cos \theta_{adv} \approx \frac{\Delta H}{l_c} \]  

Combining equations (4), (6), (7), and (14), we get the equation about the final immersion depth \( D \), that is:

\[ D \sim \frac{4\gamma a}{l_c} - \frac{\rho g a^2 z H}{4l_c} \]  

And, the final buoyancy is:

\[ F_b \sim \frac{4\gamma a}{l_c} - \frac{\rho g a^2 z H}{4l_c} \]  

Equation (16) suggests the final buoyancy \( F_b \) to be linear in \( H \), with a proportionality coefficient of 0.52. We measured the final immersion depths of the box falls from different heights and calculated the corresponding buoyancies, the results are plotted in Supplementary Text Fig. 7. The black dashed line is the theoretical prediction based on equation (16). The experimental results are well fitted with the theoretical prediction. The error bars in Supplementary Text Figs. 3
and 7 are obtained by repeatedly releasing the box from the same height. The number of tests for each data point is five. The error is mainly because of the difference in falling height. Since the box needs to be clamped on the moving stage, the installation process may cause a difference.

**Supplementary Text Fig. 7.** Relationship between the final buoyancy $F_b$ and the falling height $H$. The final buoyancy increases as the falling height. The slope of the black dashed line, based on the theoretical.
Detailed analysis of the buoyancy hysteresis loop

As shown in the Supplementary Text Fig. 8A, a cuboid box is fixed under a platform, which can exert force to move the box up and down. The box is pre-immersed in water with an immersion depth of 8 mm, and the contact angle is the advancing contact angle (about 115°). During the loading-unloading cycle, the box is subjected to four forces: the gravity, the buoyancy, the surface tension, and the external force. The force balance of the box is:

\[ mg + F = F_b + F_s \] (17)

where \( F \) is the applied force, \( F_s \) is the surface tension.

Supplementary Text Fig. 8. Buoyancy hysteresis loop. (A) Schematic of the apparatus. The cuboid box is fixed under a platform, which can exert force to move the box up and down. (B) Dependence of the buoyancy on the applied force during the loading-unloading (i to ii to iii) and unloading-loading (iii to iv to i) cycles.

Supplementary Text Fig. 8B is the change of the buoyancy \( F_b \) with the applied force \( F \). The loading-unloading (i to ii to iii) and the unloading-loading (iii to iv to i) cycles result in a rhombic loop. For the loading-unloading cycle, point i is the start of the loading, point ii is the start of the unloading, and point iii is the end of the unloading. In the loading stage, \( F_b \) enlarges as \( F \) increases, and the slope is unity. However, in the unloading stage, the decrease of \( F_b \) lags behind the decrease of \( F \), forming a curve with a slope of 0.48. For the unloading-loading cycle, the decrease of \( F_b \) equals the decrease of \( F \) in the unloading stage, but the increase of \( F_b \) lags behind the increase of \( F \) in the loading stage.

To explain the loop, we measure the change of the contact angle in the loading-unloading and unloading-loading cycles. The contact angles range between the advancing angle and the receding contact angle, and form a loop, as shown in Supplementary Text Fig. 9.

Supplementary Text Fig. 9. Variation of the contact angle in the loading-unloading and unloading-loading cycles. The red arrows indicate the direction of the loop.
For the loading-unloading cycle (i to ii to iii): In the loading stage (i to ii), the contact angle remains fixed at the advancing contact angle with the enlarge of the load, leading to a constant surface tension of $F_s = 4\gamma \cos \theta_{adv}$. Therefore, only the buoyancy increases (Supplementary Text Fig. 10). The slope of the curve in the loading stage is:

$$k_1 = \frac{dF_0}{dF} = \frac{d(mg+F_s)}{dF} = 1$$

Taking the values of $\rho = 10^3 \text{ kg} \cdot \text{m}^3$, $g = 9.8 \text{ N} \cdot \text{kg}^{-1}$ $a = 10^{-2} \text{ m}$, we get $k_1 = 1$.

Supplementary Text Fig. 10. Variations of the contact angle and the immersion depth at the loading stage from i to ii. The blue arrows indicate the direction of the box moving.

During the unloading stage (ii to iii), the TCL is pinned and the contact angle gradually decreases from the advancing contact angle to the receding contact angle (as shown in Supplementary Text Fig. 11). Taking into account the surface tension, according to equations (13) and (17), the slope of the curve at the unloading stage is:

$$k_2 = \frac{d(mg+F_s)}{dF} = \frac{1}{\frac{1}{\rho g a^2} + l_c}$$

Taking the typical values of $l_c = 2.7 \text{ mm}$, we get $k_2 = 0.48$, which well agrees with the experimental data shown in Supplementary Text Fig. 8B.

Supplementary Text Fig. 11. Variations of the contact angle and the immersion depth at the unloading stage from ii to iii.

For the unloading-loading cycle (iii to iv to i): In the unloading stage (iii to iv), the contact angle remains fixed at the minimum receding contact angle (Supplementary Text Fig. 12), resulting in the slope of the curve at this stage as:

$$k_3 = \frac{d(mg+F_s)}{dF} = 1$$

Supplementary Text Fig. 12. Variations of the contact angle and the immersion depth at the unloading stage from iii to iv.
In the loading stage (iv to i), the contact angle increases from the minimum receding contact angle to the advancing contact angle (Supplementary Text Fig. 13). The slope of the curve at this stage is:

\[ k_4 = \frac{1}{\eta \cdot \rho \cdot g \cdot b \cdot l_c} \]  

(21)

Taking the typical values, we get \( k_4 = 0.48 \) (Supplementary Text Fig. 8).

Supplementary Text Fig. 13. Variations of the contact angle and the immersion depth at the loading stage from iv to i.

In addition, we repeatedly load and unload the box. The results are displayed in Supplementary Text Fig. 14A. The overlapped loops indicate that the buoyancy lagging behind the loading/unloading is an intrinsic property of the floating objects. However, this phenomenon can be minimized using objects with ignorable contact angle hysteresis. Supplementary Text Fig. 14B shows the buoyancy hysteresis loops of a superhydrophobic box (with a contact angle hysteresis of 3°) and a superhydrophilic box. During the loading-unloading and unloading-loading cycles, the variation in buoyancy \( F_b \) equals the loading and unloading, and no obvious loop appears.

Supplementary Text Fig. 14. (A) Buoyancy hysteresis loops of repeated loading-unloading cycles. (B) Buoyancy hysteresis loop of the box with superhydrophobic surface. (C) Buoyancy hysteresis loop of the box with superhydrophilic surface.
Influencing factors of the buoyancy hysteresis loop

The buoyancy hysteresis loop is caused by the variable surface tension, and is greatly affected by the contact angle hysteresis. As shown in Supplementary Text Fig. 8, the upright distance between lines of i-ii and iii-iv corresponds to the maximal variation in the surface tension:

$$\Delta F_s = 4\alpha (\cos \theta_{rec} - \cos \theta_{adv})$$

(22)

For the cuboid box, $a = 10$ mm, $\theta_{adv} = 115^\circ$, and $\theta_{rec} = 33^\circ$. Considering that the variation in surface tension induces the mutable buoyancy, we get $\Delta F_b = \Delta F_s = 3.3$ mN, which well-fits the data in Supplementary Text Fig. 8B. Reducing the contact angle hysteresis can minimize the upright distance between lines of i-ii and iii-iv in the loop, as shown in Supplementary Text Fig. 14B and C.

In addition to the contact angle hysteresis, the buoyancy hysteresis loop is also affected by the size of the floating object. We measure the loops of cuboid boxes with side-lengths of cross-section ranging from 4 mm to 30 mm. As shown in Supplementary Text Fig. 15, the small box displays a wider loop than the big box, which means the influence of the contact angle hysteresis on the buoyancy reduces with the enlargement of the object size.

Supplementary Text Fig. 15. Buoyancy hysteresis loops of cuboid boxes with different side-lengths.

Then, we investigate the mechanism for the shape change of the loop. As shown in Supplementary Text Fig. 16A, the typical loop consists of four curves. Since the slopes of the curves i-ii and iii-iv are constant at unity, the shape of the loop is determined by the slopes of the curves ii-iii and iv-i. According to equation (19), the slope of the curves is

$$k = \frac{1}{l_c}$$

(23)

For the cuboid box, the perimeter $c = 4a$, the cross-section area $s = a^2$. The equation above can be written as:

$$k = \frac{1}{1 + \frac{g l_c}{\rho a^2}}$$

Considering that the water density $\rho$, the surface tension coefficient $\gamma$, the gravitational acceleration $g$, and the capillary length $l_c$ are fixed in these cases, the shape of the loop is determined by the perimeter/cross-sectional area ratio $\varepsilon = c/s$. The perimeter/cross-sectional area ratios are 1 mm$^{-1}$, 0.8 mm$^{-1}$, 0.57 mm$^{-1}$, 0.4 mm$^{-1}$, and 0.2 mm$^{-1}$ for the boxes of 4 mm, 5 mm, 7 mm, 10 mm, and 20 mm in side-lengths, respectively. The smaller the perimeter/cross-sectional area ratio, the narrower the loop. According to equation (23), the relationship between $1/k$ and $\varepsilon$ is:

$$\frac{1}{k} \sim \frac{\rho g l_c}{\gamma} \varepsilon$$

(24)
The theoretically-calculated dependence of $1/k$ on the perimeter/cross-section area ratio $\varepsilon$ is displayed in Supplementary Text Fig. 16B (the black dashed line), which agrees well with the experimental data (red dots) obtained from Supplementary Text Fig. 15.

**Supplementary Text Fig. 16.** (A) Typical buoyancy hysteresis loops. (B) $1/k$ versus cross-section area ratio $\varepsilon$. 

![Supplementary Text Fig. 16](image-url)
Figures S1 to S12

**Fig. S1. Parameters of the hollow cuboid box.** (A) Skeleton of the cuboid box. The length, the width, and the height of the box are 10 mm, 10 mm, and 20 mm, respectively. (B) Scanning electron micrograph (SEM) of the box surface. Scale bar is 1 μm. (C) Static contact angle of the box surface.
Fig. S2. Evolutions of the objects at different floating states. (A-B) Box floating on the water with different floating states. Scale bars, 5 mm. (C-D) Floating-adjustable robot floating on the water with different floating states. Scale bars, 4 mm.
Fig. S3. Different buoyancies of various objects floating on water. (A) Peanut; (B) Shell; (C) PP sphere. The weights of the peanut, the shell, and the PP sphere are 995.1 mg, 987.5 mg, and 330.5 mg, respectively. All scale bars are 5 mm.
Fig. S4. Different TCL dynamics of the falling different boxes. (A) Box with an obvious contact angle hysteresis. The contact angle hysteresis is 82°. (B) Superhydrophobic box with a negligible contact angle hysteresis. The contact angle hysteresis is less than 3°.
Fig. S5. Box with superhydrophobic surface falling on water from different heights. Scale bars are 10 mm.
Fig. S6. Fruits falling on water from different heights. (A and B) The same fruit of *Ardisia crenata* falling on water from different heights. Scale bars, 5 mm. (C and D) The same fruit of *Raspberry* falling on water from different heights. Scale bars, 10 mm.
Fig. S7. Variation of the contact angle $\theta$ versus the immersion depth $D$. The contact angles form a loop during the loading-unloading (blue dots) and unloading-loading (red dots) cycles. The red arrows indicate the direction of processes.
Fig. S8. Buoyancy hysteresis loops of boxes with different size. (A to E), Buoyancy hysteresis loops of cuboid boxes with cross-section widths of 4 mm, 5 mm, 7 mm, 10 mm, and 20 mm, respectively. The perimeter/cross-sectional area ratios $\epsilon$ are 1 mm$^{-1}$, 0.8 mm$^{-1}$, 0.57 mm$^{-1}$, 0.4 mm$^{-1}$, and 0.2 mm$^{-1}$ for the boxes.
Fig. S9. Buoyancy hysteresis loops of boxes with different surfaces. (A) The buoyancy hysteresis loop of the superhydrophobic box. The slopes of the four curves are fixed at unity, and no obvious loop is formed. (B) SEM image and contact angle characterization of the superhydrophobic box. (C) The buoyancy hysteresis loop of the superhydrophilic box. The slopes of the four curves are unity, and no obvious loop is formed. (D) SEM image and dynamic contact angle characterization of the superhydrophilic box. The advancing and receding contact angles are 158° and 155°, respectively. The scale bars in SEM images and contact angle images are 1 μm and 500 μm.
Fig. S10. Illustration of the floating state transformation of the floating-adjustable robot.
Fig. S11. Applications of the floating-adjustable robot. (A) Spontaneous approaching and leaving the shore by adjusting the robot buoyancy. A capillary pull generates between the dive state robot and the shore, while transforming the robot to surface state can form a capillary thrust. The red arrows indicate the moving directions. Scale bar, 10 mm. (B) Spontaneous release and collection of micro floaters. The micro floaters attach to the surface-state robot by the capillary force. The robot at dive state will release the micro floaters, while spontaneously collection of the floaters can be realized by changing the robot from dive state to surface state. The blue dashed lines indicate the water surfaces. The red arrows indicate the impulses. Scale bar, 10 mm.
Fig. S12. Demonstration of controllable drug release. (A) Evolution of the capsule at dive state. (B) Evolution of the capsule at surface state. Scale bars, 3 mm.
Legends for Movies S1 to S9

Movie S1. *Ardisia crenata* fruit falling into water from different heights.
We drop *Ardisia crenata* fruit from different heights. The fruit that falls from a small height displays a small buoyancy state, while the fruit that falls from a large height displays a large buoyancy state.

Movie S2. Different floating states of the cuboid box falling from different heights.
When the box is dropped from a small height (the left one), the box eventually displays a small immersion depth. However, the box falling from a large height (the right one) displays a large immersion depth. The distances between the top of the box and the water surface are 5 mm and 9 mm, respectively. The movie is played at 1/10 times of the real speed.

Movie S3. Box falling on the water surface.
When releasing the box on the water surface, the box first falls into the water and then floats up repeatedly. The vibration process before the stable floating lasts about 30 seconds and the amplitudes decrease continuously with time. The movie is played at 1/10 times of the real speed.

Movie S4. Three-phase contact line dynamics during the falling of the cuboid box.
During the falling of the box, the three-phase contact line (TCL) pins on the box surface until the contact angle reaches the advancing contact angle (115°). When the box floats up, the contact angle begins to decrease and does not reach the receding contact angle, leading to the pinning of the TCL on the box surface. The movie is played at 1/20 times of the real speed.

Movie S5. Buoyancy hysteresis loop.
The box is pre-immersed in water. The immersion depth is 8 mm, and the contact angle is the advancing contact angle. The buoyancy $F_b$ changes when the external force $F$ is applied. Periodical loading/unloading and unloading/loading cycles result in a rhombic loop. The loading and unloading stages correspond to curves with different slopes. The movie is played at 5 times of the real speed.

Movie S6. Two states of floating-adjustable robot.
We gently place the robot on water and make it at the surface state. The contact angle is 115°, which is the advancing contact angle of the robot surface. A downward impulse sinks the robot and transforms it to the dive state. Then an upward impulse floats up the robot and transforms it to the surface state. The movie is played at 2 times of the real speed.

Movie S7. Spontaneous approaching and leaving the shore of floating-adjustable robot.
A convex meniscus is formed around the robot when transforming the robot from surface state to dive state, thus creating a capillary pull with the shore. After the robot lands, a capillary thrust can generate to push the robot away from the shore only need to transform the robot from dive state to surface state.

Movie S8. Micro floaters release and collection of the floating-adjustable robot.
The micro floaters are initially attracted around the robot when the robot is at the surface state. The transformation from the surface state to the dive state will release the micro floaters, enabled by the "cheerios effect". The released detectors can be collected when transforming the robot back to the surface state. The movie is played at 5 times of the real speed.

Movie S9. Interface catalysis demonstration of floater with different states.
The controllable interface catalysis is demonstrated by using a platinum metal coated-polypropylene bead to catalyze the decomposition of hydrogen peroxide. Different floating state of the bead contributes to different contact areas between platinum and hydrogen peroxide, which results in diverse catalytic efficiencies. The catalytic efficiency of the dive state bead is about three times higher than that in the surface state, by calculating the number and volume of the generated bubbles. The movie is played at 2 times of the real speed.