

Supplementary Information

Asymmetric vibration pattern enables ultrafast locomotion of an insect-scale amphibious microrobot

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S1. Dynamical model of the microrobot under aquatic locomotion mode

A simplified dynamic model is developed to investigate the locomotion characteristics of the microrobot on the water surface, which consists of two rigid bodies M_f (relatively stationary parts including support frames, buoyancy tank, and rear legs) and M_{pd} (swimming paddles), a lumped mass m_e (equivalent of the permanent magnet and the simply supported beams within the electromagnetic actuator), as shown in Fig. 2d. Several simplifications are adopted to highlight the governing influence of design parameters of the swimming paddle:

(1) The actuation mechanism engages with the water surface via two components: the front legs and the swimming paddles. When the microrobot floats on the water surface, the front legs are oriented perpendicular to the water surface. Their swinging motion is theoretically symmetric, yielding zero net propulsive force. Therefore, the front legs are excluded from the dynamic model of the microrobot, with only the swimming paddles taken into account.

(2) The output parameters of the two electromagnetic actuators are the same. Therefore, two swimming paddles connected with two actuators respectively are simplified to one rigid body M_{pd} .

(3) The unidirectional passive hinge of the swimming paddle is simplified as a torsional spring (k_θ) exhibiting asymmetric elastic and damping coefficients between clockwise and counterclockwise rotations.

(4) On the water surface, the vertical degree of freedom of the microrobot was omitted in favor of its forward degree of freedom.

We utilize the Lagrangian method to establish the dynamical equations of the microrobot. Three generalized coordinates q_i ($i = 1, 2, 3$) are selected to characterize the locomotion of the microrobot: x , s , and θ_s . x is the lateral displacement along the x -axis for the COM of M_f in the inertial coordinate system (x - o - y). s is the

37 relative displacement of m_e with respect to M_f along the x -axis. θ_s is the swing angle of M_{pd} relative to M_f .

38 The Lagrange function can be given as:

$$39 \quad \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i \quad (1)$$

$$40 \quad \begin{bmatrix} 2m+M+2m_{pd} & 2m-2m_{pd}T & m_{pd}h_{pd}\cos\theta_s \\ 2m-2m_{pd}T & 2m+2m_{pd}T^2 & -m_{pd}h_{pd}T\cos\theta_s \\ m_{pd}h_{pd}\cos\theta_s & -m_{pd}h_{pd}T\cos\theta_s & 0.5m_{pd}h_{pd}^2+2J_{pd} \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{s} \\ \ddot{\theta}_s \end{bmatrix} = \begin{bmatrix} m_{pd}h_{pd}\ddot{\theta}_s^2\sin\theta_s+F_1 \\ -m_{pd}Th_{pd}\ddot{\theta}_s^2\sin\theta_s-2k_s+F_2 \\ k_\theta\theta_s+F_3 \end{bmatrix} \quad (2)$$

41 where m , M and m_{pd} are the masses of m_e , M_f and M_{pd} ; T is the displacement transmission ratio from the
 42 actuator-connected end to the paddle-attached end of the simply supported beams; J_{pd} is the moment of inertia
 43 of M_{pd} ; h_{pd} is the height of M_{pd} ; k is the elastic coefficient of the simply supported beams; k_θ is the torsional
 44 elastic coefficient of the passive hinge of the swimming paddle; F_1 , F_2 , and F_3 are the generalized forces
 45 associated with three generalized coordinates. Their explicit expressions are:

$$46 \quad \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} F_{af} + F_{wf} + F_{pd} \\ F_{EM} + F_{am} - TF_{pd} \\ T_{pd} \end{bmatrix} \quad (3)$$

47 where F_{af} and F_{wf} are the air and water damping forces applying on rigid body M_f respectively; F_{pd} and T_{pd}
 48 are the water damping force and torque applying on rigid body M_{pd} respectively; F_{EM} is the electromagnetic
 49 force applying on the lumped mass m_e ; F_{am} is the air damping force applying on the lumped mass m_e .

50 The three damping forces, F_{af} , F_{am} , and F_{wf} , in Eq. (3) exhibit similar functional form:

$$51 \quad \begin{cases} F_{af} = -0.5C_a A_{af} \rho_{air} \dot{x}^2 \text{sgn}(\dot{x}) \\ F_{am} = -0.5C_a A_m \rho_{air} \dot{x}_m^2 \text{sgn}(\dot{x}_m) \\ F_{wf} = -0.5C_{w1} A_{wf} \rho_{water} \dot{x}^2 \text{sgn}(\dot{x}) \end{cases} \quad (4)$$

52 where C_a is the air damping coefficient; ρ_{air} is the density of air; A_{af} is the cross-sectional area of the portion
 53 of the body M_f exposed to the air, perpendicular to the x -axis; A_m is the area of the surface perpendicular to
 54 the x -axis for the lumped mass m_e ; C_{w1} is the water damping coefficient of the body M_f ; ρ_{water} is the density
 55 of water; A_{wf} is the cross-sectional area of the submerged portion of the body M_f , perpendicular to the x -axis.

56 The electromagnetic force F_{EM} depends on the input current signal and the structural parameters of the
 57 electromagnetic actuator, and can be specifically expressed as:

$$58 \quad F_{EM} = \frac{B_r(B_{z1} - B_{z2})A}{\mu_0} = \frac{\pi B_r(B_{z1} - B_{z2})R^2}{\mu_0} \quad (5)$$

59 where B_r is the residual magnetization of the magnet; B_{z1} is the magnetic field strength of the lower surface
 60 of the magnet in the axial direction; B_{z2} is the magnetic field strength of the upper surface of the magnet in
 61 the axial direction; R is the radius of the magnet; μ_0 is the permeability of vacuum. B_{z1} and B_{z2} are:

$$62 \quad \begin{cases} B_{z1} = B_z(z) = \frac{\mu_0 NI}{2} \left(\frac{l-z}{\sqrt{(l-z)^2 + r^2}} + \frac{z}{\sqrt{z^2 + r^2}} \right) \\ B_{z2} = B_z(z+L) = \frac{\mu_0 NI}{2} \left(-\frac{z+L-l}{\sqrt{(z+L-l)^2 + r^2}} + \frac{z+L}{\sqrt{(z+L)^2 + r^2}} \right) \end{cases} \quad (6)$$

63 where z is the distance from the lower surface of the magnet to the lower surface of the coil; N is the number
 64 of turns of the coil; I is the current flowing through the coil; l is the axial length of the coil; r is the radius of
 65 the coil; L is the axial length of the magnet.

66 As the paddle undergoes compound rigid-body motion involving both translation and rotation, the resultant
 67 force F_{pd} and moment T_{pd} exerted on it in Equation (3) should be computed via integration:

$$68 \quad \begin{cases} F_{pd} = \frac{1}{2} \rho_{water} C_{w2} w_{pd} \int_{-h_{pd}}^0 v_{pd,n}^2 \operatorname{sgn}(-v_{pd,n}) dy_{pd} \\ T_{pd} = \frac{1}{2} \rho_{water} C_{w2} w_{pd} \int_{-h_{pd}}^0 -v_{pd,n}^2 y_{pd} \operatorname{sgn}(-v_{pd,n}) dy_{pd} \end{cases} \quad (7)$$

69 where C_{w2} is the water damping coefficient of the body M_{pd} ; w_{pd} and h_{pd} are the width and height of the
 70 swimming paddle respectively; $v_{pd,n}$ is the surface-normal velocity of a point on the paddle in the inertial
 71 coordinate system.

72 S2. Dynamical model of the microrobot under terrestrial locomotion mode

73 In order to analyze the terrestrial locomotion characteristics of the microrobot, a separate dynamic model
 74 is also established. Similar to the dynamic model for aquatic locomotion, the microrobot is simplified as a

dynamic system composed of a rigid body M_b and a lumped mass m_e , as shown in Supplementary Fig. 5.

Three simplifications are introduced to this model:

(1) The output parameters of the two electromagnetic actuators are the same. Therefore, two front legs connecting with two actuators respectively are simplified to one front leg.

(2) The simply supported beams are simplified as a massless spring with an elastic coefficient of k .

(3) The magnet is simplified as a lumped mass m_e , and the remaining components of the microrobot form the rigid body M_b , including the supporting frames, coil and legs.

(4) The action between the feet of the microrobot and the ground is simplified as a vertical spring-damper (k_y-d_y) with a normal force in the vertical direction (F_N) and a friction force in the lateral direction (F_f). Several key geometric dimensions of the microrobot are illustrated in Supplementary Fig. 5.

Two coordinate systems are developed to characterize the motion of the microrobot, including the inertial coordinate system $x-o-y$ and the body coordinate system $x'-o-y'$ with the center of mass (COM) of rigid body M_b as the origin, as shown in Supplementary Fig. 5. The Lagrangian method is used to establish the dynamic equations of the microrobot based on four generalized coordinates, including the horizontal and vertical coordinates (x, y) of the COM of the rigid body M_b , the displacement s of the lumped mass m_e relative to its initial position in the body direction, and the body tilt angle θ_b . The absolute coordinates of any point (x_p, y_p) in the system can be obtained through these generalized coordinates and the transform relation between two coordinate systems:

$$\begin{pmatrix} x_p \\ y_p \end{pmatrix} = \begin{pmatrix} \cos \theta_b & -\sin \theta_b \\ \sin \theta_b & \cos \theta_b \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix} + \begin{pmatrix} x \\ y \end{pmatrix} \quad (8)$$

The lagrangian equations of the dynamic model can be given as:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = Q_i \quad (i=1,2,3,4) \quad (9)$$

$$\begin{bmatrix} 2m+M & 0 & 2m\cos\theta_b & A \\ 0 & 2m+M & 2m\sin\theta_b & B \\ 2m\cos\theta_b & m\sin\theta_b & m & -2ml_m \\ A & B & -2ml_m & C \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{s} \\ \ddot{\theta}_b \end{bmatrix} = \begin{bmatrix} 2m\dot{s}\dot{\theta}_b\sin\theta_b + m(r_m+s)\dot{\theta}_b^2\cos\theta_b + F_1 \\ -2m\dot{s}\dot{\theta}_b\cos\theta_b + m(r_m+s)\dot{\theta}_b^2\sin\theta_b - (m+M)g + F_2 \\ m\dot{x}\dot{\theta}_b\sin\theta_b - m\dot{y}\dot{\theta}_b\cos\theta_b - ks + F_3 \\ -2m(r_m+s)\dot{s}\dot{\theta}_b - mg(r_m+s)\cos\theta_b + F_4 \end{bmatrix} \quad (10)$$

$$\begin{cases} A = -2m(r_m+s)\sin\theta_b - 2ml_m\cos\theta_b \\ B = 2m(r_m+s)\cos\theta_b - 2ml_m\sin\theta_b \\ C = 2m(r_m+s)^2 + 2ml_m^2 + J_b \end{cases} \quad (11)$$

where m and M are the masses of the lumped mass m_e and rigid body M_b ; r_m is the relative distance between m_e (at the initial position) and the COM of M_b along x' -axis; k is the elastic coefficient of the simply supported beams; l_m is the relative distance between m (at the initial position) and the COM of M_b along y' -axis; J_b is the moments of inertia of M_b ; h_b is the height of M_b ; F_1 , F_2 , F_3 and F_4 are the generalized forces associated with four generalized coordinates. Their explicit expressions are:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = \begin{bmatrix} 2F_{fr} + 2F_{ff} + F_{dx,b} \\ 2F_{Nr} + 2F_{Nf} + F_{dy,b} \\ F_{EM} + F_{dm} + 2F_{ff}(-T\cos\theta_b) + 2F_{ff}(-T\sin\theta_b) \\ 2T_{fr} + 2T_{ff} + T_d \end{bmatrix} \quad (12)$$

where F_{fr} and F_{ff} are the frictional forces applying on the rear and front legs respectively; F_{Nr} and F_{Nf} are the normal forces applying on the rear and front legs respectively; $F_{dx,b}$ and $F_{dy,b}$ are the air damping forces applying on the rigid body M_b in the x -axis and y -axis direction respectively; F_{dm} is the air damping forces applying on the lumped mass m_e in the x' -axis direction; F_{EM} is the electromagnetic force applying on the lumped mass m_e ; T is the displacement transmission ratio from the actuator-connected end to the paddle-attached end of the simply supported beams; T_{fr} and T_{ff} are the friction torques applying on the rear and front legs respectively; T_d is the damping torque from air applying on the rigid body M_b .

Based on the spring-damper model between the feet and the ground, the normal forces are given as (13) and (14) when the feet are in contact with the ground. If one foot is off the ground, the corresponding normal force and frictional force are both equal to zero.

$$\begin{cases} F_{Nr} = \text{sgn}(-y_{fr}) \times (-k_y y_{fr} - d_y \dot{y}_{fr}) \\ F_{Nf} = \text{sgn}(-y_{ff}) \times (-k_y y_{ff} - d_y \dot{y}_{ff}) \end{cases} \quad (13)$$

$$\begin{cases} F_{fr} = \text{sgn}(-\dot{x}_{fr})\mu F_{Nr} \\ F_{ff} = \text{sgn}(-\dot{x}_{ff})\mu F_{Nr} \end{cases} \quad (14)$$

where x_{fr}, y_{fr} are the coordinates of the rear foot in the inertial coordinate system; x_{ff}, y_{ff} are the coordinates of the front foot in the inertial coordinate system; k_y, d_y are the elastic coefficient and damping coefficient respectively when the feet are in contact with the ground; μ is the friction coefficient between the feet and ground.

The air damping forces in (12) are expressed as:

$$\begin{cases} F_{dx, b} = -0.5C_a A_{bx} \rho_{air} \dot{x}^2 \text{sgn}(\dot{x}) \\ F_{dy, b} = -0.5C_a A_{by} \rho_{air} \dot{y}^2 \text{sgn}(\dot{y}) \\ F_{dm} = -0.5C_a A_m \rho_{air} \dot{x}_m^2 \text{sgn}(\dot{x}_m) \end{cases} \quad (15)$$

where C_a is the air damping coefficient; ρ_{air} is the density of air; A_{bx} is the area of the surface perpendicular to the x -axis for the body M_b ; A_{by} is the area of the surface perpendicular to the y -axis for the body M_b ; A_m is the area of the surface perpendicular to the x -axis for the lumped mass m_e .

The torques in (12) are expressed as:

$$\begin{cases} T_{fr} = F_{fr}(r_{fr} \sin \theta_b + l_{fr} \cos \theta_b) - F_{Nr}(r_{fr} \cos \theta_b - l_{fr} \sin \theta_b) \\ T_{ff} = F_{ff}(r_{ff} \cos \theta_b - l_{ff} \sin \theta_b) + F_{Nr}(r_{ff} \sin \theta_b + l_{ff} \cos \theta_b) \\ T_d = -0.5C_a \rho_{air} \int_{-x_f}^{x_r} (x \dot{\theta}_b)^2 w(x) \text{sgn}(\dot{\theta}_b) dx \end{cases} \quad (16)$$

where r_{fr} is the distance between the rear feet and the COM of M_b along x' -axis; l_{fr} is the distance between the rear feet and the COM of M_b along y' -axis; r_{ff} is the distance between the front feet and the COM of M_b along x' -axis; l_{ff} is the distance between the front feet and the COM of M_b along y' -axis; x_f is the distance between the COM of M_b and the front end along x' -axis; x_r is the distance between the COM of M_b and the rear end along x' -axis; $w(x)$ is the width function of M_b with elliptical shape.

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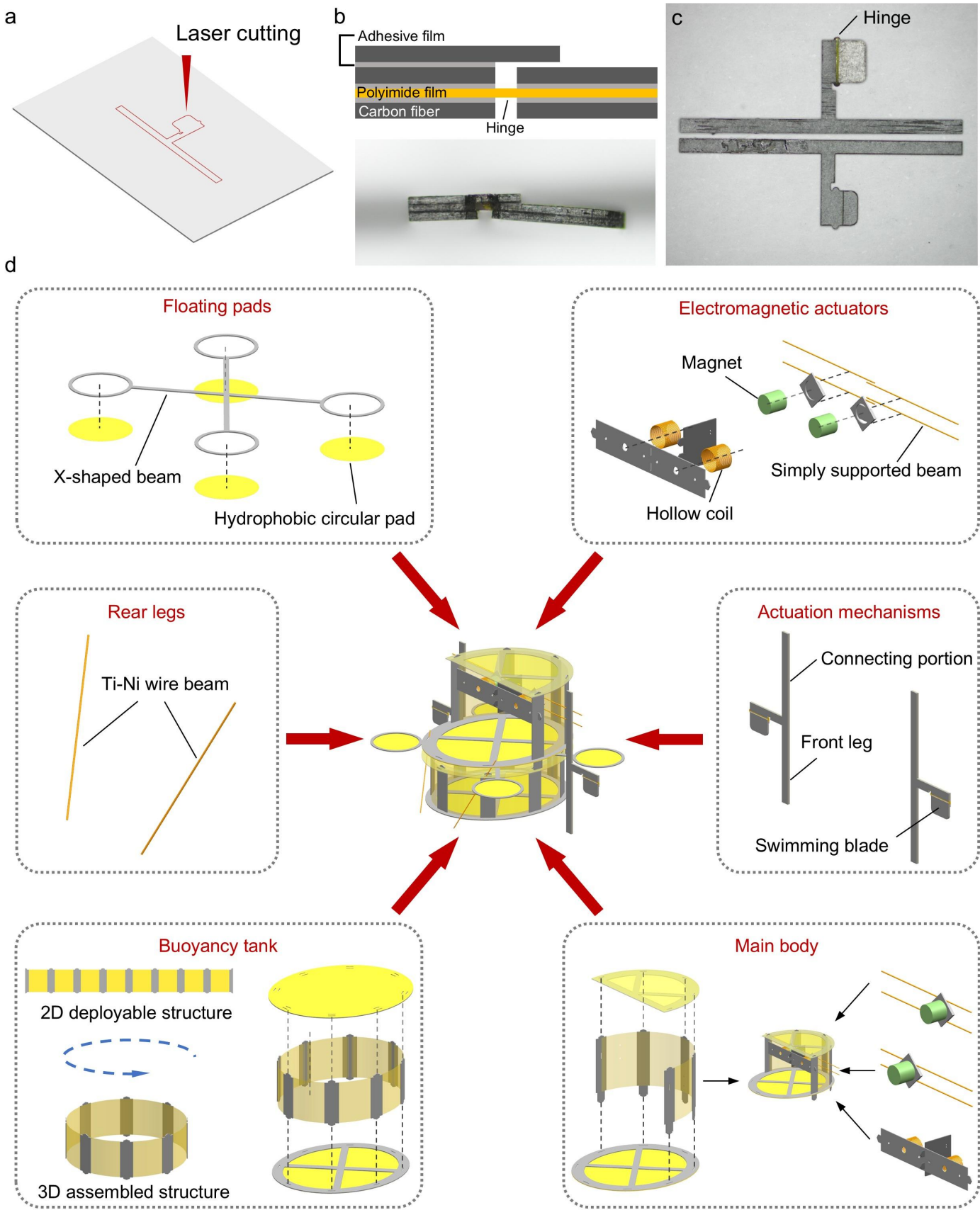
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Supplementary Figures 1-7



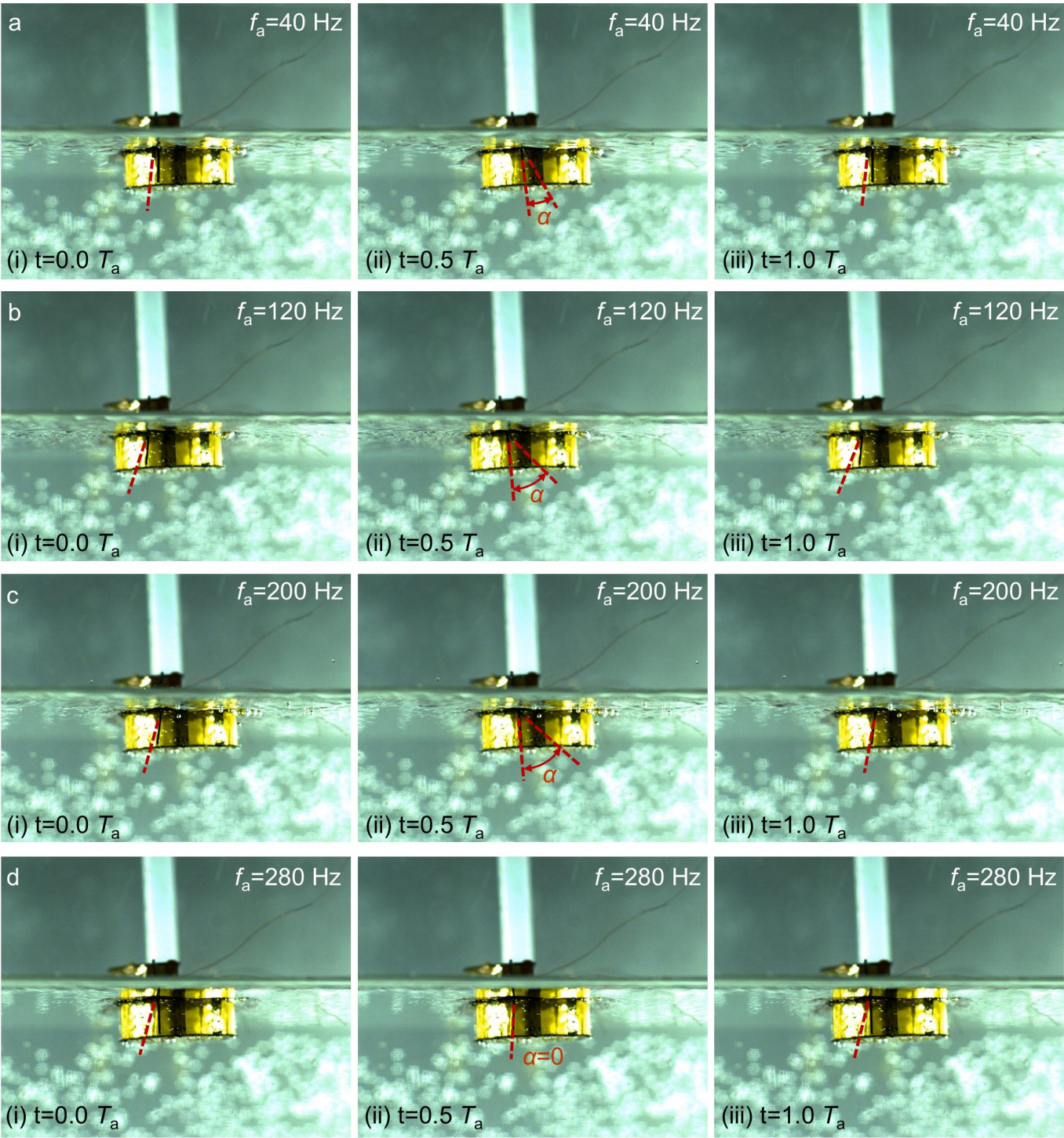
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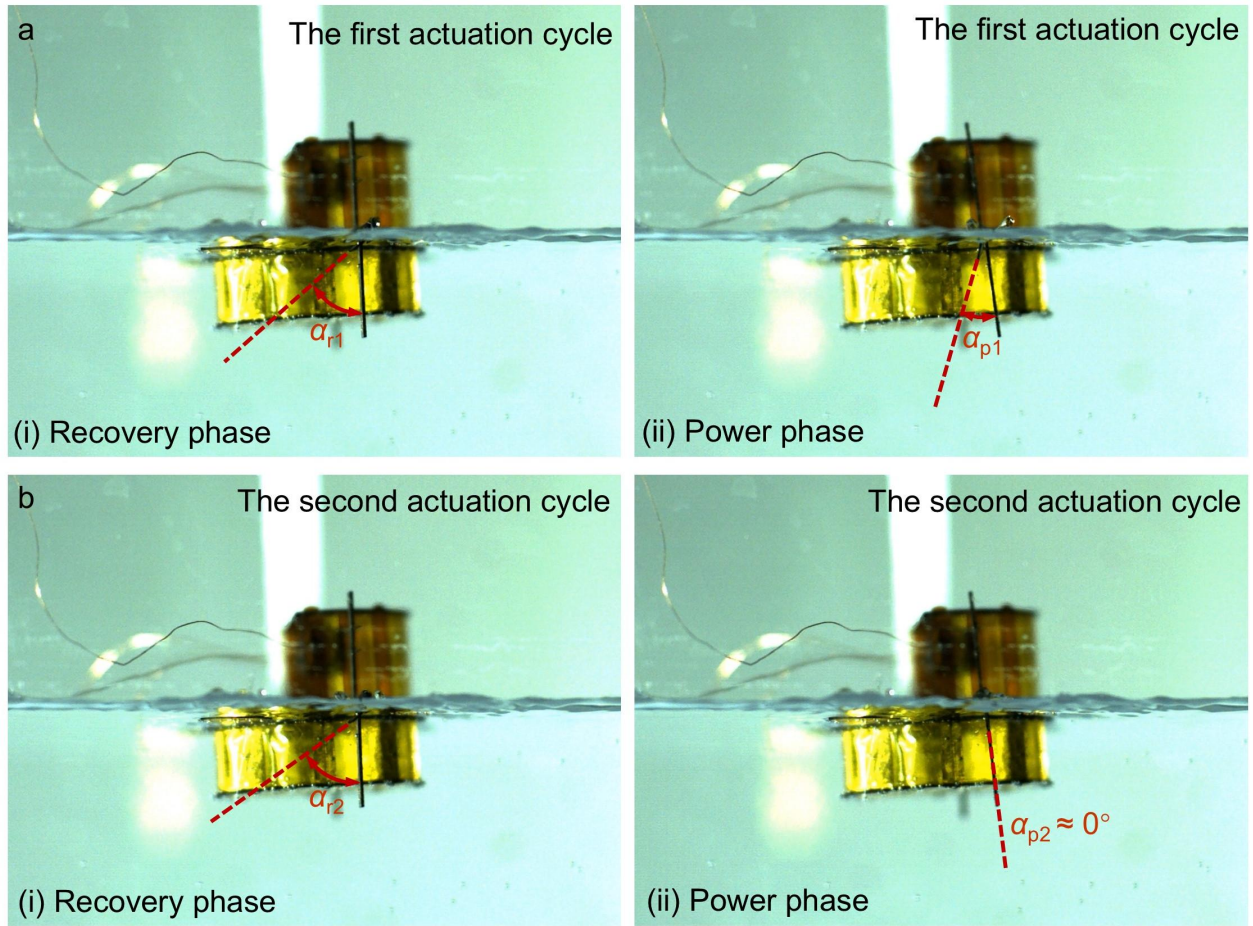
Supplementary Fig. 1. The fabrication process of the microrobot. **a**, Fabrication process of the swimming paddle via laser cutting. **b**, Diagram and optical photo showing the laminated structure of the swimming paddle. **c**, Optical photo of two swimming paddles with different dimensions. **d**, Manual assembly process of individual modules and the whole microrobot.



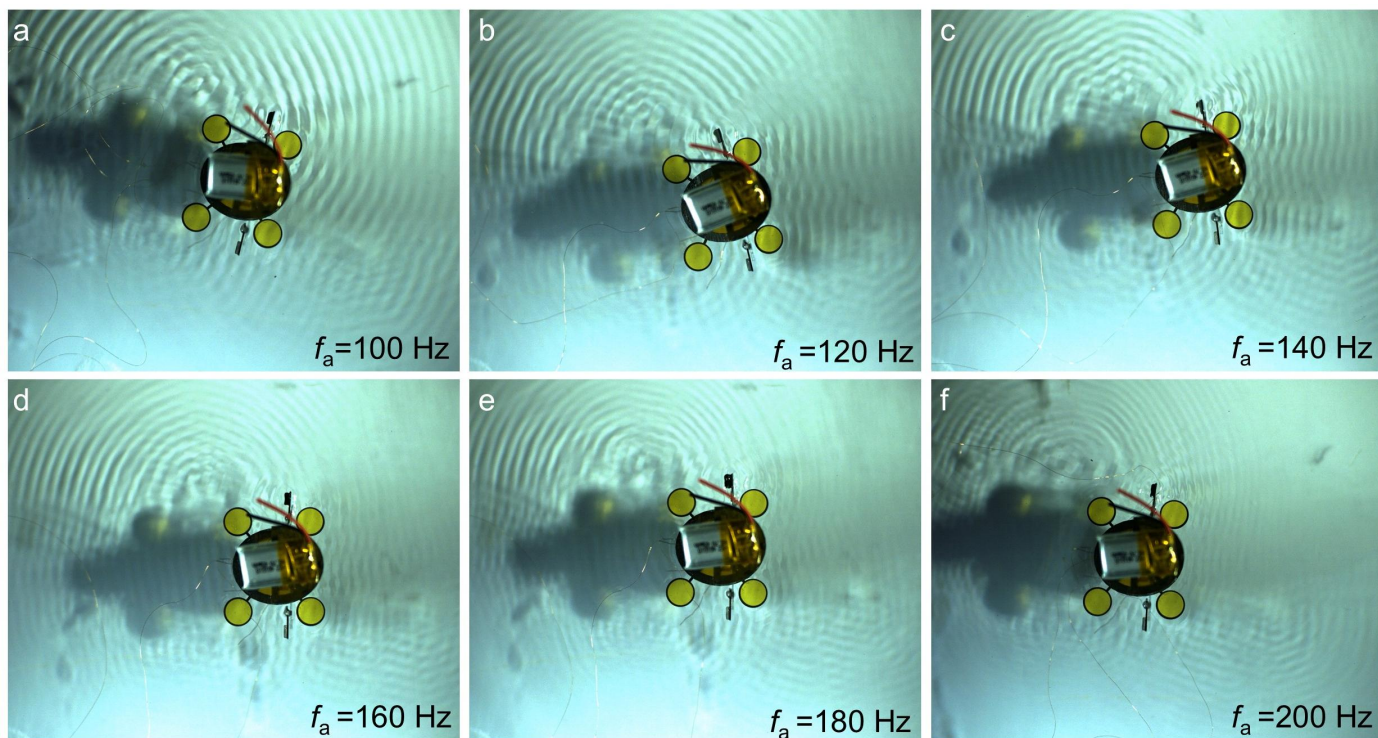
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211 **Supplementary Fig. 2.** The swing motion of the swimming paddle under different actuating frequency f_a (40, 120, 200, and
212 280 Hz). As the actuation frequency approaches the natural frequency of the microrobot, the swing angle during recovery
213 phase reaches its peak.

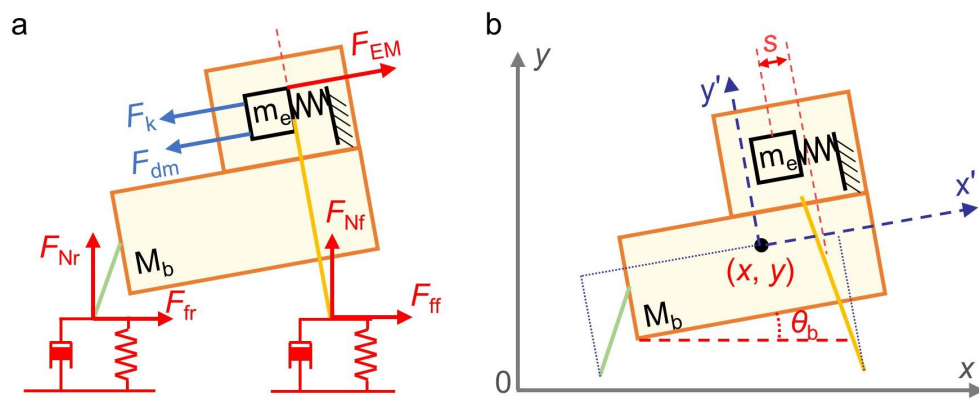
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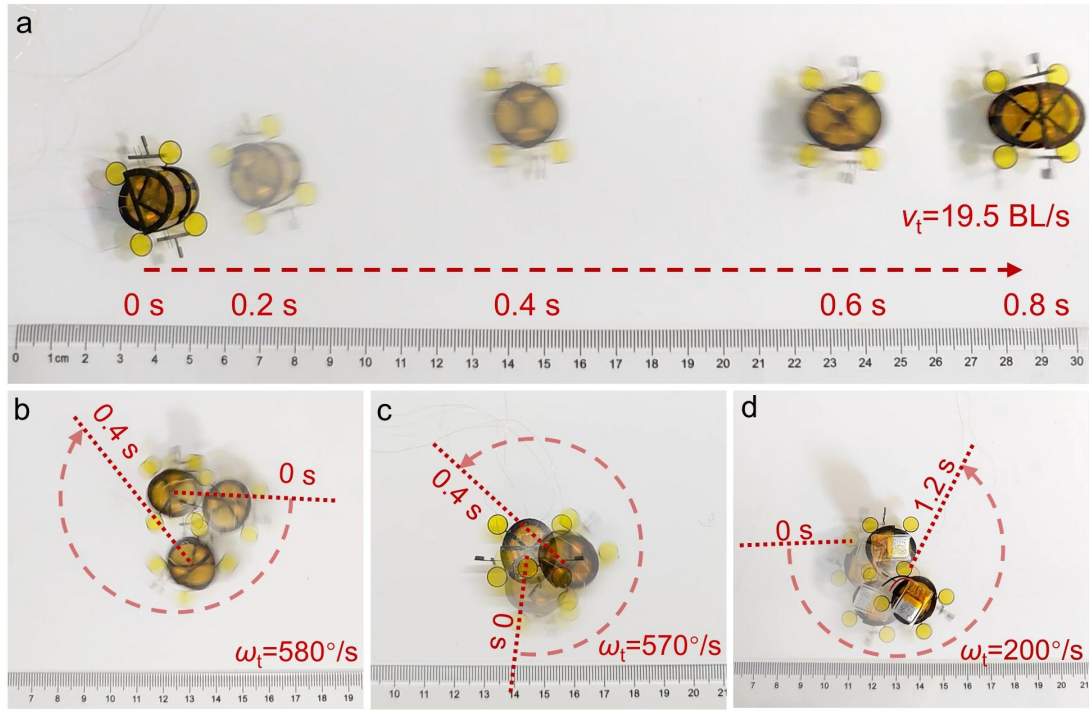
Supplementary Fig. 3. The swing motion of the swimming paddle under a small hinge thickness ($4\ \mu\text{m}$). In every other actuation cycle, it is observed that the relative rotation angle of the swimming paddle α fails to return to 0° during the power phase.



Supplementary Fig. 4. Propagation of water surface waves during the clockwise turning of the microrobot at different actuation frequencies (100, 120, 140, 160, 180, and 200 Hz).



Supplementary Fig. 5. Simplified dynamic model of the microrobot under terrestrial locomotion mode.



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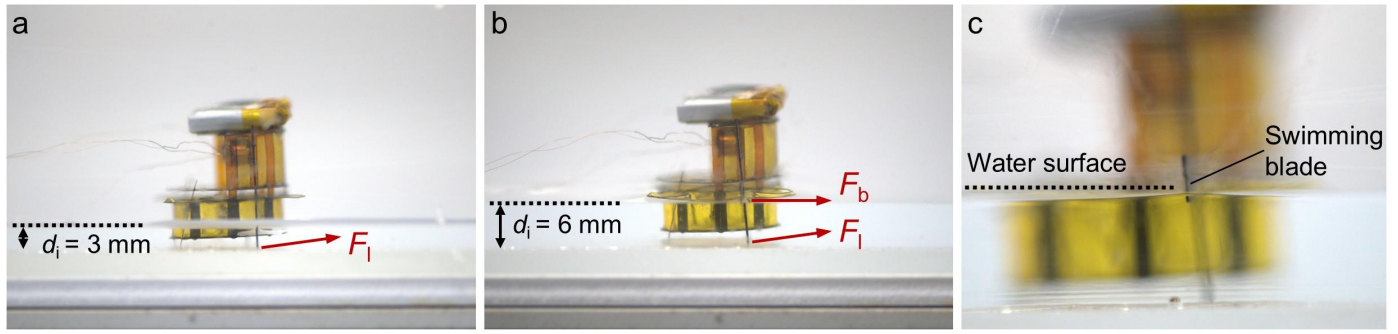
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Supplementary Fig. 6. Tethered terrestrial locomotion performance of the microrobot on the plastic board. **a**, Optical photo of the tethered microrobot moving forward at a maximum speed of 19.5 BL/s on a plastic board without payload. **b**, **c**, Optical photos of the tethered microrobot achieving a maximum turning angular speed of $580^\circ/\text{s}$ in the clockwise direction and $570^\circ/\text{s}$ in the anticlockwise direction under a payload of 0 mg. **d**, Optical photo of the tethered microrobot achieving a maximum anticlockwise turning speed of $200^\circ/\text{s}$ under a payload of 1200 mg.



Supplementary Fig. 7. Propulsion force analysis of the microrobot under varying immersion depths. **a**, At a 3 mm immersion depth, propulsion is generated exclusively by the front legs in contact with the ground. **b**, At a 6 mm immersion depth, propulsion is generated by both the front legs and the swimming paddles. **c**, Enlarged image of the paddle–water interface at a 6 mm immersion depth.

235

Supplementary Tables 1-3

236

Supplementary Table 1. The quantities and masses of individual components for the microrobot

Description	Quantity	Mass (mg)
Support frames	--	78
Simply supported beam	2	2
Permanent magnets	2	100
Hollow coils	2	102
Fixed boards for coils	1	13
Floating pads	4	29
Buoyancy tank	1	91
Front legs integrated with swimming paddles	2	30
Rear legs	2	1
Power and control electronics	1	555
Lithium battery	1	680
Wires and glue	--	≈ 9
Total		≈ 1690

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238 **Supplementary Table 2. Components of the power and control circuit board**

Description	Model	Quantity	Weight (mg)
Microcontroller	RF-BM-4044B4	1	193.1
Voltage regulator (3.3V)	SPX3819M5	1	14.8
Voltage regulator (1.2V)	TLV75709PDBVR	1	15.2
Schmitt-Trigger inverter	SN74LVC2G14DCK	1	16.4
H-Bride driver	DRV8837C	2	19.6
Sensor (a microphone)	ICS-40181	1	60.0
Capacitor	0402; 0603	11	81.9
PCB	L: 17.5 mm; W:14.5 mm; Elliptical pattern	1	129.0
Solder	--	--	~25
Total weight			~555

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240 **Supplementary Table 3. Data of moving speed with respect to the body length of amphibians and**
241 **existing amphibious robots**

Species	Body length (cm)	Terrestrial relative speed (BL/s)	Aquatic relative speed (BL/s)	Reference
Amphibians				
Green turtle	≈50	≈0.4	≈1.0	1,2
Sea snakes (Laticauda colubrina)	≈80	≈0.3	≈1.4	3
Lizard (Anolis Sagrei)	≈5	≈11.0	≈7.0	4
Untethered amphibious robots				
Leglessbot	5.5	1.4	0.61	5
Robot by Zhao et al	7.5	10.90	2.30	6
EHR	73	3.15	1.23	7
Groundbot	60	5	--	8
Amoeba-II	65.51	--	0.21	9
Salamandra Robotica I	77	0.384	0.323	10
BoxyBot	25	--	1.4	11
AmphiHex-II	51.0	0.71	0.37	12
Spherical robot by Ishihara et al	25	0.9	0.644	13
FroBot	70	1.43	0.57	14
Salamandra Robotica II	110	0.38	0.46	15
AmphiRobot-II	70	0.86	0.64	16
ASRobot	30	0.18	0.12	17
SeaDog	114.5	2.0	--	18
Crablike robot by Xie et al	53.5	--	0.37	19
Tethered amphibious robots				
AmphiHex-I	84.4	0.65	0.59	20,21
Starfish robot	20	0.35	0.33	22
Soft-Amphibious Robot by Suzumori et al	21	0.27	0.105	23
HAMR	4.0	1.75	0.7	24
Mini-robot by Yang et al	2	0.05	0.5	25
MCR	5	0.32	--	26
SAM	4.5	3.4	2.02	27
Soft microrobot by Feng et al	3	0.13	--	28
Soft robot by Chen et al	9.5	1.79	0.316	29
SEALicone	25.74	--	0.07	30
EELWORM	40	0.033	0.05	31
ACSR	17.9	0.03	--	32
BASR	168	0.97	--	33
AISR	4.4	2.44	1.2	34
This work (untethered)				
This work	2.1	15.5	5.4	--

Captions of Supplementary Movie 1 to 12

Movie S1. Swing motion of the swimming paddle for the tethered microrobot during the swimming locomotion

This high-speed movie shows the swing motion of the swimming paddle for the tethered microrobot during the swimming locomotion. It is observed that the swimming paddle rotates around the hinge asymmetrically during the swimming locomotion.

Movie S2. Straight movements of the tethered microrobot on the water surface

This movie shows straight moving performance of two tethered microrobot prototypes (the original and the optimized) on the water surface when carrying a payload mass of 1200 mg. Part 1 shows the original prototype swimming forward with a relative speed of 3.7 BL/s. Part 2 shows the optimized prototype swimming forward with a relative speed of 5.5 BL/s.

Movie S3. Turns of the tethered microrobot on the water surface

This movie shows turning performance of the tethered microrobot on the water surface when carrying a payload mass of 1200 mg. Parts 1 and 2 show the microrobot achieving clockwise and anticlockwise turns on the water surface with a maximum turning speed of $370^{\circ}/s$ and $280^{\circ}/s$ respectively.

Movie S4. Untethered locomotion performance of the microrobot on the water surface

This movie shows untethered locomotion performance of the microrobot on the water surface when driven near its natural frequency. Part 1 shows the microrobot swimming linearly on the water surface with a maximum speed of 5.4 BL/s. Part 2 shows the microrobot achieving clockwise and anticlockwise turns on the water surface with a maximum turning speed of $450^{\circ}/s$ and $360^{\circ}/s$ respectively.

Movie S5. Obstacles avoidance via remote control on the water surface for the untethered microrobot

This movie shows the obstacle avoidance process of the untethered microrobot via navigating around immovable obstacles. The demonstration scenario is a 100 cm-by-60 cm water pool scattered with simulated

266 aquatic plants and lotus leaves. The microrobot traverses from the bottom-left corner to the top-right corner
267 of the water pool, and subsequently navigates back to the bottom-left corner via an alternative route.

268 **Movie S6. Pushing aside floating obstacles on water surface for the untethered microrobot**

269 This movie shows the obstacle avoidance process of the untethered microrobot when encountering floating
270 objects. During the process, the microrobot approaches, pushes away, and detaches from floating wooden
271 blocks that are 6.6 times heavier than the microrobot itself.

272 **Movie S7. Straight movements of the tethered microrobot on the ground**

273 This movie shows straight moving performance of the tethered microrobot on the ground under different
274 payload masses. Part 1 shows the microrobot moving forward at a maximum speed of 19.5 BL/s when carrying
275 a payload of 0 mg. Part 2 shows the microrobot moving forward at a maximum speed of 11.9 BL/s when
276 carrying a payload of 1200 mg.

277 **Movie S8. Turns of the tethered microrobot on the ground**

278 This movie shows turning performance of the tethered microrobot on the ground under different payload
279 masses. Part 1 shows the microrobot achieving clockwise and anticlockwise turns on the ground with a
280 maximum turning speed of 580°/s and 570°/s respectively when carrying a payload of 0 mg. Part 2 shows the
281 microrobot achieving clockwise and anticlockwise turns on the ground with a maximum turning speed of
282 470°/s and 200°/s respectively when carrying a payload of 1200 mg.

283 **Movie S9. Untethered locomotion performance of the microrobot on the ground**

284 This movie shows the untethered locomotion performance of the microrobot on the ground when driven near
285 its natural frequency. Part 1 shows the untethered microrobot running linearly on the plastic board with a
286 maximum speed of 15.5 BL/s. Part 2 shows the untethered microrobot achieving clockwise and anticlockwise
287 turns on a plastic board with a maximum turning speed of 760°/s and 470°/s respectively.

Movie S10. Slope climbing of the untethered microrobot

This movie shows the untethered microrobot crawling on a slope of 4° via a bipedal alternating relay climbing strategy within 30 s.

Movie S11. Water-traversing locomotion of the tethered microrobot

This movie shows the water traversing locomotion of the tethered microrobot at a submersion depth of 8 mm. The microrobot moves forward at a maximum speed of 5.4 BL/s, with the front leg and swimming paddle jointly generating propulsion.

Movie S12. Bidirectional transitions between the water surface and ground of the untethered microrobot via a slope

This movie shows that the untethered microrobot achieves bidirectional transitions between the water surface and ground via a slope. Part 1 shows the side view of the microrobot traversing the water surface, transitioning onto land via a slope, reversing direction, and returning to the water surface. Part 2 shows the top view of the whole process.