

Microscopic robots that sense and reshape their environment

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In natural systems, the physical environment can alter the behaviour of organisms which, in turn, can change how the organisms actively modify their environment. Translating such behaviour to microscopic robots and creating a system that can actively reshape its surroundings through a dynamic closed-loop coupling between the behaviour and environmental cues could lead to emergent functionalities such as collective self-organization and adaptive environmental regulation. Here we report microscopic robots that integrate thermal sensing, programmable complementary metal–oxide–semiconductor logic and electrochemical actuators, and can couple robot behaviour to environmental cues. The robots drive artificial cilia to pump fluid with a direction and speed that adapt in real time to the thermal environment. We demonstrate three temperature-responsive modalities that can drive robot-to-environment coupling: binary sensing for threshold-based flow reversal, continuous sensing for smooth flow-speed modulation and gradient sensing for flow alignment along spatial temperature gradients. We show that the cilia-generated flows can regulate local thermal fields, providing a closed-loop interaction with the environment.

In nature, organisms engage with their environment through dynamic interactions that guide both their behaviour and changes to their surroundings^{1–4}. Termites construct complex nests in response to surrounding mound structures and secreted pheromones, and the resulting structural changes reshape local airflow and humidity; this, in turn, guides further collective building behaviours and can lead to self-organized, adaptive morphogenesis¹. At the microscale, *Lactobacillus* detects extracellular acidity through membrane-associated stress-response pathways

and acidifies its environment through lactic acid secretion, a process that simultaneously triggers its acid-tolerance response and suppresses competitors³. Similarly, ciliated protists such as *Paramecium* sense local chemical gradients with their cilia and, on detecting hazardous substances, alter their beating patterns to trigger an escape response and generate vortices that disperse the harmful compounds away from the cell⁴. In these systems, coupling between environmental physics and organismal behaviours forms feedback loops that support adaptation in changing environments.

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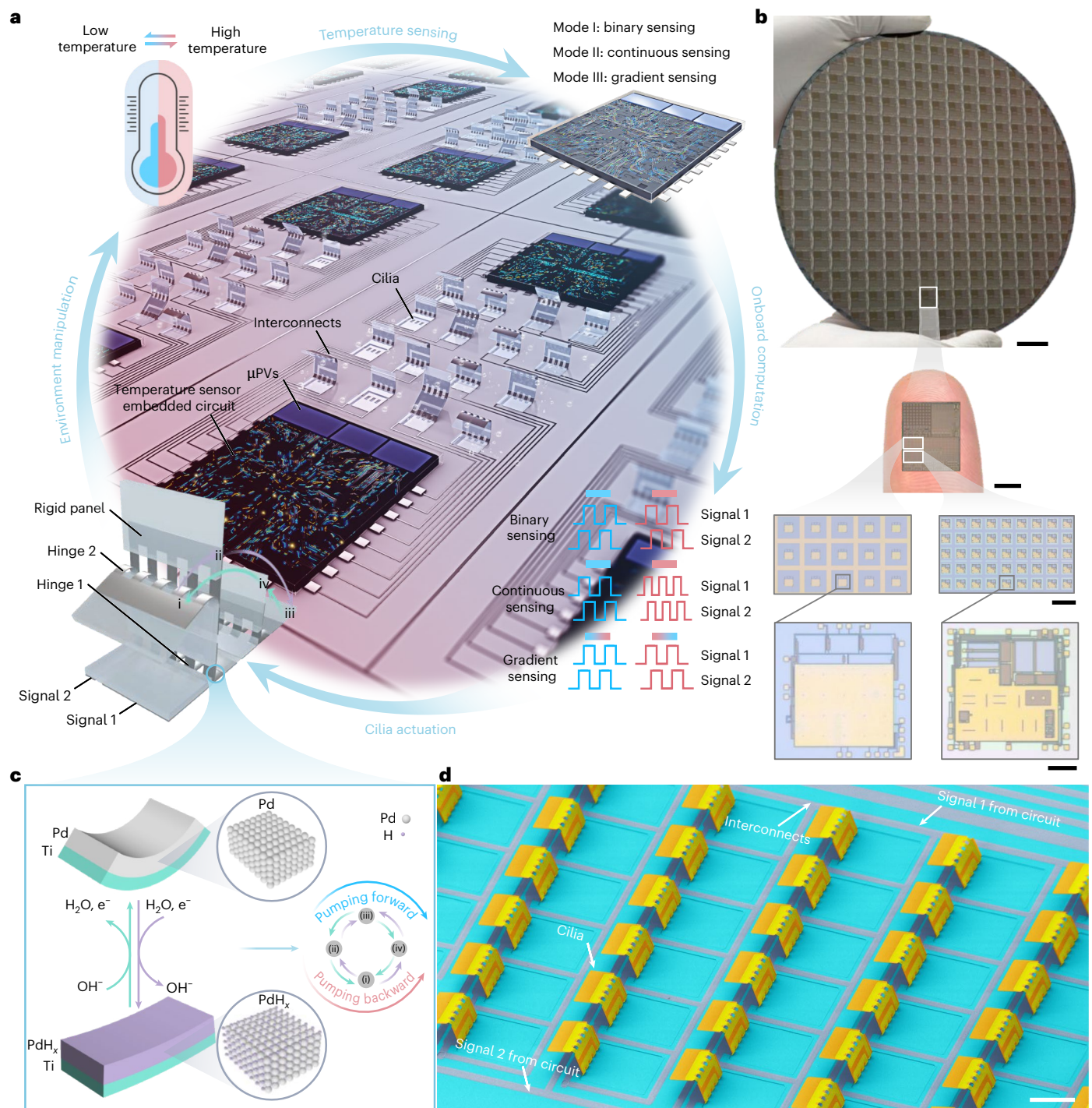


Fig. 1 | Coupling between microscopic robots and thermal environments.

a, Conceptual illustration of a microscopic robot integrating thermally responsive CMOS circuitry, μ PV cells and hinged artificial cilia. The circuits operate in three programmed modes: binary, continuous and gradient sensing (top right). Each mode produces two controllable output signals (signal 1 and signal 2) with tuneable frequency/phase delay (bottom right), used to actuate the two-hinged cilia (hinge 1 and hinge 2) for adaptive fluid control (bottom left). The relative phase of the two signals, namely, which signal leads or lags, determines the hinge actuation sequence and pumping direction, whereas their frequency determines the cilium beating frequency and pumping speed. During each actuation cycle, the cilium progresses through four configurations: (i) both hinges bent, (ii) hinge 1 bent and hinge 2 flat, (iii) both hinges flat and (iv) hinge 1 flat and hinge 2 bent. Cycling through these states in the sequence (i) $\rightarrow$ (ii) $\rightarrow$ (iii) $\rightarrow$ (iv) $\rightarrow$ (i) produces forward pumping, whereas traversing them in the opposite order produces backward pumping. In binary sensing, the phase order switches across

the temperature thresholds, reversing the pumping direction. In continuous sensing, the phase order remains unchanged, whereas the frequency increases with temperature, increasing the pumping speed. In gradient sensing, the hotter oscillator becomes the leader; reversing the thermal gradient exchanges the leader and follower, reversing the phase order and reverses pumping. **b**, Optical images of the fabricated CMOS circuits. Top: overview of an 8-inch wafer. Middle: composite image of a single die on top of a finger. Bottom: zoomed-in views of circuits for binary sensing (left) and continuous/gradient sensing (right). Scale bars, 2 cm (top), 5 mm (middle), 500 μ m (top zoomed-in views), 50 μ m (bottom zoomed-in views). **c**, Electrochemical mechanism of the Pd/Ti bimorph actuator that drives shape change in the cilium, enabling bidirectional pumping by altering hinge actuation sequences. **d**, False-colour SEM image of a released cilia array integrated with the CMOS circuits. Two routed signals from the circuits independently address the hinges and the pre-stress-induced curvature from fabrication defines the initial configuration. Scale bar, 50 μ m.

Microscopic robots^{5–16}, with sizes comparable with biological cells, can operate in microscale environments that cannot be accessed by conventional machines. Advances in electrical engineering and materials science have produced autonomous microscopic robots capable of locomotion^{17,18}, flow manipulation¹⁹ and simple onboard computation^{19,20}. Recent implementations have incorporated complementary metal–oxide–semiconductor (CMOS)-integrated sensors for detecting temperature²¹ and light^{20,22}, allowing robots to perceive and respond to environmental changes. Extending these capabilities to robots that actively reshape their surroundings through dynamic closed-loop coupling between behaviour and environmental cues could enable collective self-organization and adaptive environmental regulation. Achieving this coupling at the microscale requires an integrated system that senses environmental cues, processes them through onboard computation and generates physical responses that alter the local environment.

In this Article, we report a monolithic microscopic robot platform that heterogeneously integrates CMOS circuitry for onboard thermal sensing, signal processing and actuator driving with electrochemically actuated artificial cilia for fluid manipulation (Fig. 1a). The miniaturized CMOS–cilia integration provides on-chip operation in small fluid volumes, allowing microfluidic transport to be manipulated at scales that would otherwise be difficult to access. In response to local thermal perturbations, the system uses cilia pumping to drive advection, thereby reshaping local thermal transport and establishing a new thermal profile.

Coupling microscopic robots and thermal environments

To enable programmable thermal sensing and responses, we designed two CMOS circuit architectures that implement three distinct temperature-sensing modes: binary, continuous and gradient sensing (Fig. 1a,b). Within each mode, changes to the temperature in the surrounding fluid generate changes in the frequency or phase of clock circuits, which are applied to adjust the cilia pumping speed or direction. These adjustments, in turn, modify the flows and thermal environment, establishing three forms of temperature-responsive interaction with the environment, including threshold-based flow reversal in the binary sensing mode, smooth flow-speed modulation in the continuous sensing mode and flow alignment along spatial temperature gradients in the gradient sensing mode. For binary sensing, we used a compact temperature-sensing clock circuit that generates two oscillating voltage signals with a fixed phase difference of 90° (binary sensing, Fig. 1a (bottom right)). When the temperature crosses a predefined threshold, the output signals are swapped, reversing the relative phases of the two signals, changing the pumping direction when these are applied to actuators. To achieve continuous and gradient sensing, we integrated subthreshold logic^{23,24} into low-power pulse-coupled oscillators (PCOs). The frequency of these oscillators is particularly sensitive to temperature changes²⁵. PCOs will arrange themselves in a leader–follower configuration in which the fastest oscillators will lead in phase, creating a wave-like behaviour^{26–28}. The frequency of each coupled oscillator will be determined by the fastest oscillator, and will track the temperature of the environment as shown in previous work²⁵ (continuous sensing, Fig. 1a (bottom right)). For gradient sensing, two identical circuits were placed across a thermal gradient. The oscillator in the high-temperature region oscillates faster and will fire first in the network, becoming the ‘leader’. Slower, colder oscillators act as ‘followers’. Reversing the thermal gradient causes the leader and follower roles to switch. This mechanism enables the microscopic robots to detect spatial temperature differences and reconfigure their actuation patterns accordingly (gradient sensing, Fig. 1a (bottom right)).

The circuits are commercially fabricated via a 180-nm CMOS process (X-FAB Silicon Foundries). Each circuit occupies a footprint of approximately 200 µm × 200 µm, enabling tens of thousands of devices

to be produced on a single 8-inch wafer (Fig. 1b). This miniaturized, wafer-scale architecture provides a scalable route to large populations of low-cost microscopic robots, which can be heterogeneously integrated with artificial cilia through post-photolithographic processing (Fig. 1d shows the fully integrated device and Extended Data Fig. 1 shows the fabrication process).

The signals from the circuits in each sensing mode are then routed to electronically actuated hinged artificial cilia²⁹ (Fig. 1a (bottom left)). Each cilium contains two independently addressable hinges, with each hinge subdivided into strips fabricated from a 10-nm titanium (Ti) base layer topped with 15-nm palladium (Pd) (Methods and Extended Data Fig. 1 provide the detailed fabrication process). The top Pd layer serves as the electrochemically active material, absorbing and desorbing hydrogen under the applied voltages (Fig. 1c)³⁰. Residual stress from fabrication causes the hinges to bend upwards (Fig. 1d). When a negative bias of approximately –1.2 V is applied, the Pd layer absorbs hydrogen atoms, which flattens the hinge. Conversely, a positive voltage of approximately +0.6 V induces hydrogen desorption, returning the device to its original bent configuration (Fig. 1c; Extended Data Fig. 2 shows the cyclic voltammetry curve). When two distinct oscillating voltages with a fixed phase delay are applied separately to each hinge, the cilium cycles through four distinct configurations: (i) both hinges bent, (ii) hinge 1 bent and hinge 2 flat, (iii) both hinges flat and (iv) hinge 1 flat and hinge 2 bent (Fig. 1a (bottom left)). The configuration sequence (i)→(ii)→(iii)→(iv)→(i) results in forward pumping, whereas reversing the sequence ((i)→(iv)→(iii)→(ii)→(i)) results in backward pumping (Fig. 1a,c (bottom left)). The cyclic actuation in either direction breaks time-reversal symmetry, producing non-reciprocal strokes that enable switchable, bidirectional fluid pumping with programmable frequency and phase. This cilia-driven pumping converts temperature-responsive circuit outputs into interactions with the surrounding fluidic environment. Below, we describe the working principles behind the circuits driving these three modes and the environmental manipulations that result from their implementations.

Binary sensing for threshold-based flow reversal

For binary sensing, a relaxation oscillator generates clock signals that pass through a frequency divider and phase shifter to produce slower phase-delayed clocks at 1.6 Hz (Fig. 2a and Extended Data Fig. 3). The circuit provides two sets of output clocks, each with a phase difference of 90°. When the temperature crosses a threshold, a temperature sensor triggers the circuit to swap the phases. Temperature sensing is realized by comparing a temperature-dependent voltage V_{temp} with two predefined reference voltages, V_{ref1} and V_{ref2} (Fig. 2b, blue). V_{temp} is a diode-derived complementary-to-absolute-temperature (CTAT) voltage that follows the approximately linear decrease in the forward voltage of a biased p–n junction with increasing ambient temperature. The reference voltages are generated using proportional-to-absolute-temperature (PTAT) bias currents and resistors with negative temperature coefficients. These opposing temperature dependencies keep the resulting reference voltages approximately constant over the operating temperature range. To suppress threshold chatter caused by electrical noise, comparator offset, reference fluctuations and supply-coupled perturbations (–5 mV), we introduced a comparator hysteresis window. From the calibrated dependence of V_{temp} on temperature, the measured slope of approximately –2 mV °C^{–1} (Fig. 2c, left) maps the –5-mV perturbation level to an equivalent temperature uncertainty of –2.5 °C. The measured switching temperatures of approximately 30 °C and 26 °C, corresponding to V_{ref1} and V_{ref2} , respectively, define a 4 °C hysteresis window (Fig. 2c, black line). This window exceeds the estimated perturbation level and provides sufficient switching margin. When Out = 0, the phase generator and driver produce two oscillating voltages where signal 1 lags signal 2 by 90°. When Out = 1, signal 2 lags signal 1 by 90°. We find that the measured output voltage signals align closely with the design specifications, demonstrating clear transitions at approximately 26 °C and 30 °C (Fig. 2d).

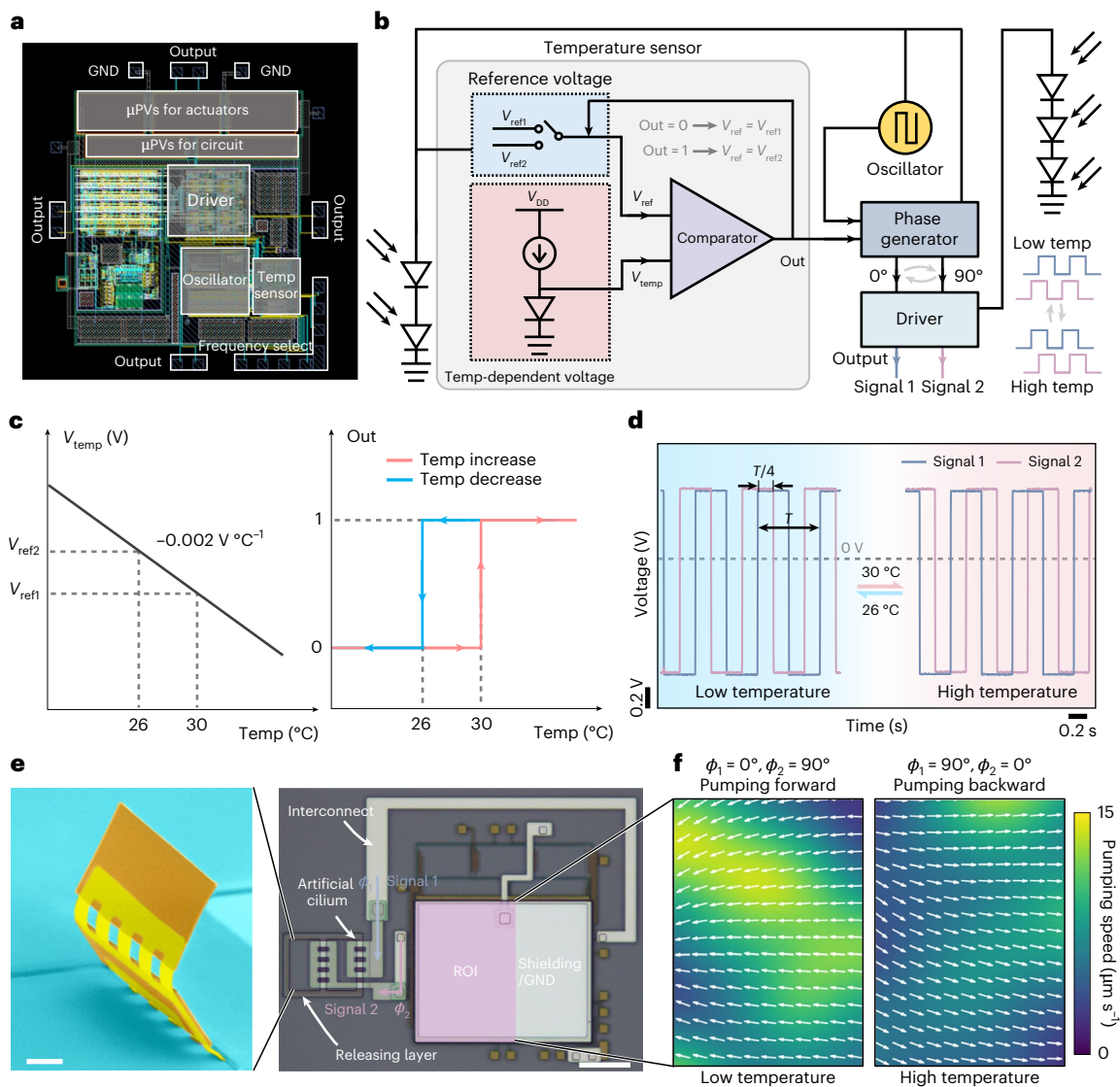


Fig. 2 | Binary sensing for switchable bidirectional pumping. **a**, Layout of the circuit for binary sensing. GND denotes the actuator-signal ground, and the frequency selector provides selectable output frequencies from 0.4 to 12.8 Hz. **b**, Circuit block diagram. A diode-based temperature-sensing circuit generates the temperature-dependent voltage V_{temp} , which is compared with the selected reference voltage V_{ref} . V_{ref1} and V_{ref2} are the two reference voltages, V_{DD} is the circuit supply voltage and Out is the comparator output. Out selects V_{ref1} or V_{ref2} , producing hysteretic switching between the two thermal states. The blue- and pink-shaded blocks denote the reference-voltage selector and temperature-dependent voltage generator, respectively, and black arrows indicate the signal flow. The oscillator, phase generator and driver produce signal 1 and signal 2 with phases ϕ_1 and ϕ_2 , respectively. A phase of 0° denotes the reference phase, whereas 90° denotes a phase lead of one-quarter period, $T/4$, where T is the output period. **c**, Schematics based on the measured calibration and switching

thresholds. Left: V_{temp} decreases with temperature with a measured slope of approximately $-2 \text{ mV } ^\circ\text{C}^{-1}$; the intersections with V_{ref1} and V_{ref2} correspond to approximately 30°C and 26°C . Right: hysteretic comparator output during heating and cooling; arrows indicate the direction of thermal sweep. **d**, Measured two output signals at different temperature thresholds, showing the switchable phase delay at 26°C and 30°C . The blue and pink backgrounds denote the low- and high-temperature states, respectively. **e**, Left: false-colour SEM image of the released two-hinged cilium. Right: optical image showing the CMOS-circuit-integrated two-hinged cilium, with labelled interconnects, signal pathways (signal 1 and signal 2), releasing layer and region of interest (ROI) for PIV analysis. Scale bars, $10 \mu\text{m}$ (left), $50 \mu\text{m}$ (right). **f**, Time-averaged full-field fluid velocity generated by the cilium. The cilium pumps fluid forward at low temperature and backward at high temperature due to circuit-driven signal phase switching.

These signals were applied to a two-hinged cilium (Fig. 2e, left). The optical micrograph (Fig. 2e, right) displays the CMOS-circuit-integrated cilium with labelled interconnects and signal pathways before release. Once released, the system was transferred into phosphate-buffered saline (PBS; $1\times$, pH 7.45) to test its actuation (Extended Data Fig. 4 shows the experimental setup). Particle image velocimetry (PIV) was used to quantify the resulting time-averaged flow fields (Methods provides details of the PIV analysis), with the region of interest highlighted in semitransparent purple (Fig. 2e, right). At low temperatures (below 26°C), the cilium pumped fluid forward (Fig. 2f (left)

and Supplementary Video 1), whereas at high temperatures (above 30°C), the pumping direction reversed (Fig. 2f (right) and Supplementary Video 1). PIV measurements revealed consistent and uniform flow profiles in both directions, with peak velocities of approximately $15 \mu\text{m s}^{-1}$. This bidirectional pumping, enabled solely by the temperature-dependent switching of CMOS-generated phase signals, constitutes a fundamental building block for more complex and programmable flow operations. It directly demonstrates the binary sensing modality in which discrete thermal states map onto opposite flow directions. The flow direction, therefore, reflects the thermal

loading history relative to the preset hysteretic thresholds. During heating, the flow switches direction above 30 °C, whereas during cooling, it switches back below 26 °C. This history-dependent response converts thermal threshold crossings into stable cilia-driven flow reversal. This basic functionality, when coupled with multiple cilia, can be used to generate thermally responsive complex flow patterns (experiment and simulation details are described in Methods and Extended Data Fig. 5; see unidirectional, one-vortex, two-vortex flow patterns in Extended Data Fig. 6 and Supplementary Videos 2–4).

Continuous and gradient sensing for adaptive flow regulation

To achieve continuous and gradient sensing for adaptive flow regulation, we implemented a CMOS-integrated PCO architecture similar to that described in ref. 28 (Fig. 3a,b and Extended Data Fig. 7). Briefly, PCOs achieve synchronization by exchanging pulses. Each circuit incorporates a relaxation oscillator, a pulse filter, a pulse generator and an actuator driver (Fig. 3a). The oscillator charges up towards a threshold that defines its phase. On reaching the threshold, the pulse generator fires a coupling pulse to its neighbouring oscillator (Fig. 3b (top right) and Extended Data Fig. 7b,c) and resets. Incoming pulses are used to speed up the instantaneous frequency of the oscillator, speeding up the next firing event and maintaining phase stability. In a connected network of coupled oscillators, the oscillator with the higher free-running frequency naturally assumes the leader role by firing first, whereas the slower unit synchronizes as a follower. This pulse exchange forms a coupled pair that locks to the leader's frequency with a fixed phase offset (Fig. 3b, bottom right). This pulse-coupling strategy is scalable to larger oscillator networks, with larger networks requiring more cycles to reach the phase-locked state^{25,28}.

To enable the temperature-modulated control of the oscillator frequency, the circuit incorporates a dynamic-leakage-suppression (DLS) relaxation oscillator that maps the local temperature T to a free-running frequency $f(T)$ (ref. 25). Thermal sensing is realized by exploiting the temperature dependence of the leakage current $I_{\text{LKG}}(T)$ in each block of the oscillator (Fig. 3c). When the input (V_{in}) changes, the leakage current determines how quickly the output (V_{out}) will respond (charge or discharge). The speed of this update in each block dictates the frequency of the oscillator. Thus, the temperature dependence of the leakage current forces a temperature dependence on the oscillator frequency³¹. The oscillator circuit is connected to a flying capacitor C_{AB} and the voltage across this capacitor V_{AB} reflects the oscillator signal (Extended Data Fig. 7b). As the temperature rises, the leakage current I_{LKG} increases, accelerating the V_{AB} ramp so that the DLS threshold is reached earlier and the period shortens. Consequently, the frequency follows $f \propto I_{\text{LKG}}/(C_{\text{AB}}V_{\text{AB}})$ and increases monotonically with temperature, as confirmed in simulations and experiments (Fig. 3c,d). We implement a 20% offset in the flying capacitor C_{AB} of the follower

circuit through hardwiring, which forces the initial frequency of the follower to be slower. As designed, we observed that the circuits exhibit temperature-dependent frequencies that increase approximately in an Arrhenius manner over this range of temperatures (Fig. 3d). From this calibration, the circuit exhibits a local frequency–temperature sensitivity on the order of $10^{-1} \text{ Hz } ^\circ\text{C}^{-1}$, enabling the detection of sub-degree temperature differences between spatially separated oscillators to produce a measurable frequency bias before synchronization. The minimum resolvable temperature difference is set by oscillator jitter and read-out noise, corresponding to a temperature resolution of approximately 0.12 °C for two coupled circuits (Methods shows the frequency–temperature calibration and validation, and Extended Data Table 1 lists the key sensing metrics).

For continuous sensing, we predefined the leader and follower configurations by hardwiring the circuits (Fig. 3e). Once synchronized, the coupled circuits phase lock to the leader frequency, so that the collective output retains the temperature-dependent frequency set by the leader oscillator. As designed, we observed that the oscillation frequency of the circuit increased with the temperature (Methods provides the measurement details). Recorded voltage traces for 20 °C, 25 °C and 30 °C show phase-locked oscillating signals whose frequency increases with temperature (Fig. 3f). During fabrication, the output of each oscillator was wired to a designated cilium hinge. After releasing the cilium from the substrate, the system was placed in a fluidic environment with a uniform temperature profile. We observed that both cilium pumping speed and frequency increased with temperature (Fig. 3g and Supplementary Video 5), in a manner consistent with the circuit characterization shown in Fig. 3d,f. Thus, the temperature-dependent circuit outputs were converted into continuously tuneable fluidic pumping that can modify the local temperature field.

For gradient sensing, we positioned an identical oscillator pair across imposed thermal gradients (Fig. 3h, Cases I and II). In each case, the oscillator on the hotter side was automatically designated as the leader, whereas the oscillator on the cooler side synchronized as the follower (Fig. 3i). Therefore, the gradient-responsive mode encoded the sign of the thermal gradient through leader–follower selection and the subsequent pumping direction. The outputs of the oscillators were connected to the hinged cilium so that the cilium would always transport the fluid from the low-temperature to high-temperature regions. After releasing the cilium into a fluid, we imposed a thermal gradient via patterned heating. As designed, we observed that regardless of the thermal gradient direction, the cilium pumped the fluid from cooler to hotter regions (Fig. 3h–j and Supplementary Video 6).

Closed-loop thermal regulation

In principle, each of the three operating modes can be used to achieve a closed-loop coupling between the thermally responsive circuits, ciliary actuation and thermal environment. For practical reasons including

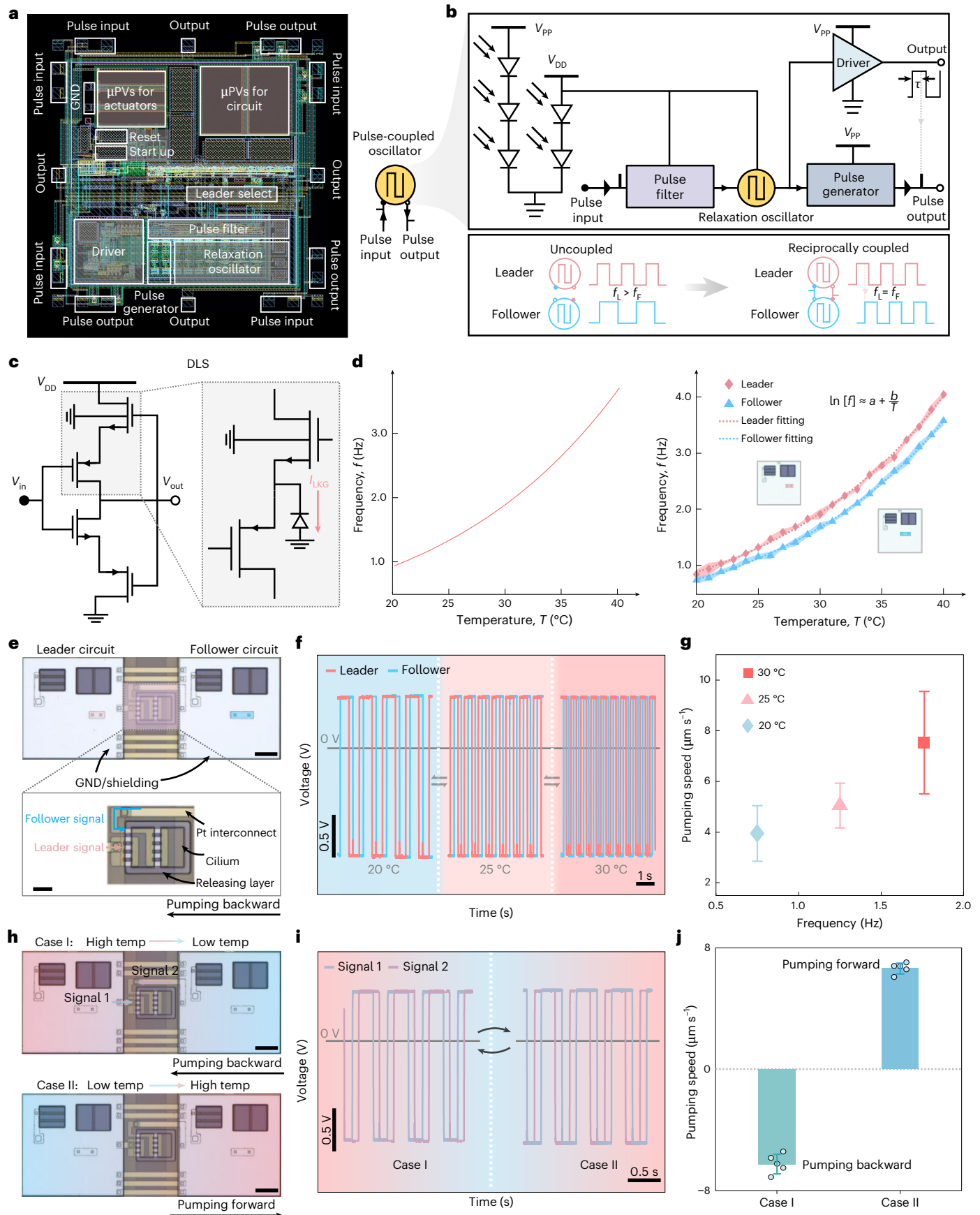
Fig. 3 | Continuous and gradient sensing for programmable fluid pumping.

a, Layout of the PCO circuit. Labels identify the pulse inputs and outputs, actuator output, GND, reset and start-up blocks, leader-selection block, pulse filter, driver, relaxation oscillator, pulse generator, and μPV regions supplying the circuit and actuators. **b**, Circuit operation. Top: block diagram of the relaxation oscillator, pulse filter, pulse generator and driver. V_{DD} and V_{PP} denote the circuit and actuator supply rails, respectively, and τ denotes the pulse-width-setting delay in the output stage. Bottom: uncoupled oscillators have free-running frequencies $f_i > f_f$; reciprocal pulse coupling synchronizes the follower to the leader so that $f_i = f_f$ with a fixed phase offset. **c**, Schematic of the DLS logic. V_{in} and V_{out} are the gate input and output voltages, V_{DD} is the circuit supply and I_{LKG} is the temperature-dependent leakage current represented in the expanded branch. **d**, Left: Cadence simulation of free-running oscillator frequency f versus temperature. Right: measured leader and follower frequencies. Markers show mean values and shaded bands show standard deviation from ten repeat measurements of each circuit at each temperature set-point. The dashed curves are the Arrhenius-type fits and the insets are optical images of the two circuits. **e**, Optical image of cilia integrated

with coupled oscillators configured for continuous sensing. Inset shows magnified details indicating the cilium and interconnects. Scale bars, 50 μm (top), 25 μm (bottom). **f**, Measured voltage signals of coupled oscillators demonstrating temperature-dependent frequency synchronization at temperatures of 20 °C, 25 °C and 30 °C. **g**, Average pumping speeds corresponding to frequencies at different temperatures, showing monotonic increase with rising temperature. The data points are mean values over five different measurements at 20 °C, 25 °C and 30 °C. The error bars indicate the standard deviation. **h**, Optical images of cilia integrated with coupled oscillators demonstrating gradient sensing under two opposing thermal gradients (Case I: high to low temperature, pumping backward; Case II: low to high temperature, pumping forward). Scale bars, 50 μm . **i**, Measured voltage signals demonstrating reversible switching of leader and follower roles under opposing temperature gradients. **j**, Average pumping speeds under opposing temperature gradients, clearly indicating bidirectional flow pumping driven by the gradient direction. The bars show the mean pumping speed over five separate measurements (overlaid circles), and the error bars indicate the standard deviation.

thermal sensitivity and strength of circuit synchronization (Methods shows the analysis), we demonstrate this coupling using the continuous sensing modality (Mode II). To achieve closed-loop control, we used the coupled circuits to drive a 6×9 cilia array (Fig. 4a). We note

that it was necessary to add external power to drive the additional cilia (Extended Data Fig. 2 shows the actuator characterization, and Methods and Extended Data Figs. 3 and 7 show the circuit characterizations), though larger PV cells could enable full autonomy in future devices. The



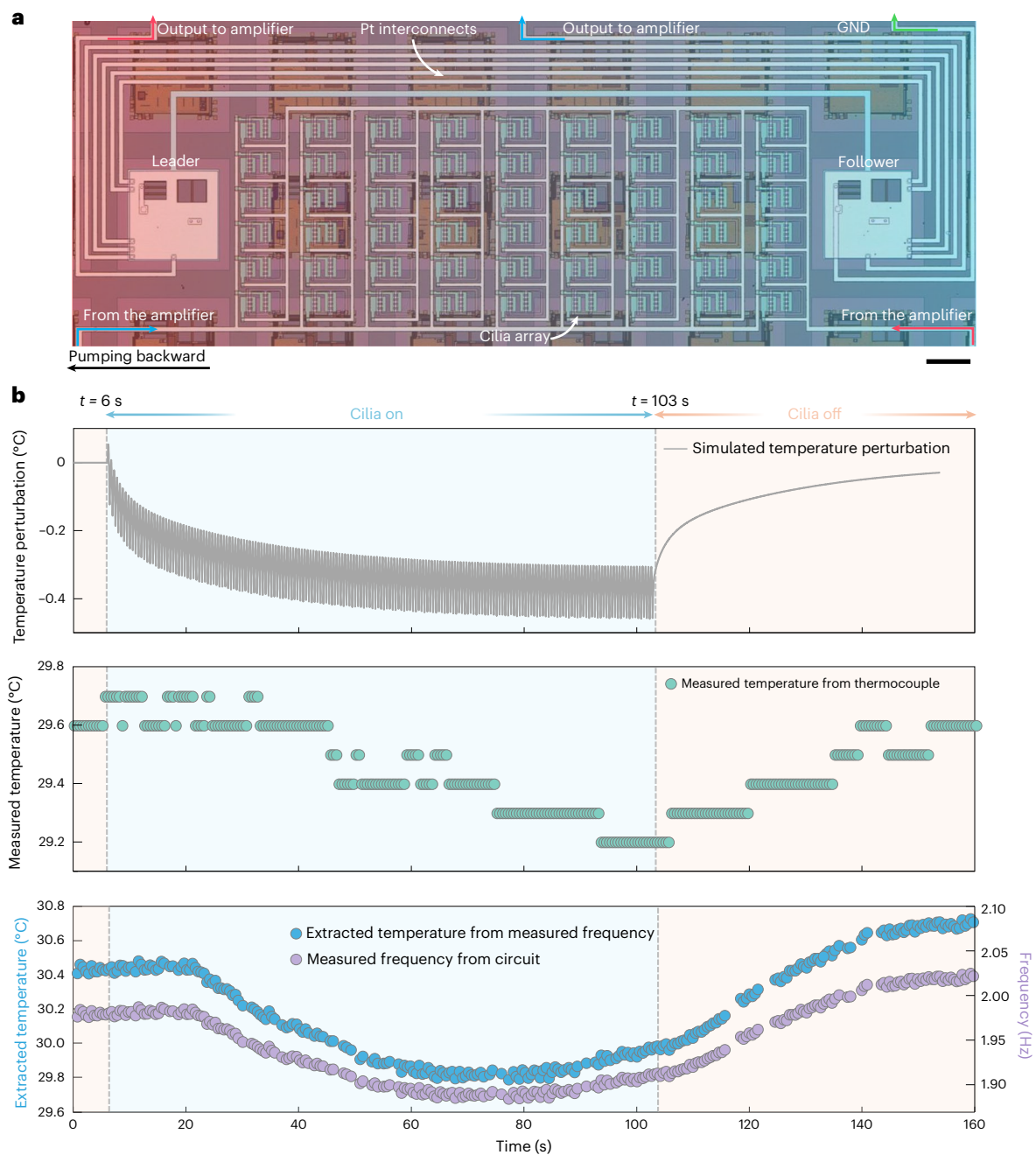


Fig. 4 | Closed-loop thermal regulation with collective cilia arrays. a, Optical micrograph showing a fabricated 6×9 artificial cilia array used for flow pumping and thermal advection. A semitransparent red–blue overlay indicates the applied thermal gradient (hot→cold) across the device, whereas the coloured arrows indicate the output signals from the circuits and the input signals for driving the cilia. Scale bar, 100 μm . **b**, Top: thermal advection model predicted local temperature perturbation due to cilia actuation (from $t \approx 6$ s to $t \approx 103$ s) with the

applied temperature gradient of $1.89^\circ\text{C mm}^{-1}$ and actuation frequency of 1.95 Hz. Middle, temperature measured by a micro-thermocouple. Bottom: extracted temperature (left axis), calculated from the measured circuit frequency (right axis) using the frequency–temperature calibration. On initiating cilia pumping, the local temperature drops by -0.4°C and the circuit frequency decreases accordingly, and both recover after the cilia are turned off.

full microsystem was immersed in a fluid in which a thermal gradient was established using a patterned hotplate (Methods and Extended Data Figs. 4 and 8 provide the experimental details). Once the system was activated, the thermal gradient was detected by the circuits and manipulated by driving the cilia to produce an advective flow from cooler to hotter regions (Supplementary Video 7). This advection made the temperature at the leader circuit cooler and caused the pumping frequency dictated by both circuits to decrease. This closed-loop cycle allowed the system to come to a new steady state with an altered thermal gradient.

We used a thermal advection–conduction model to predict the expected shift in temperature for the leader circuit (Methods and Extended Data Fig. 9a,b show the model and simulation details). Under an imposed thermal gradient $|k|$ of $-1.89^\circ\text{C mm}^{-1}$, the model predicts a shift ΔT_{reg} of -0.4°C , and the predicted trace T_{pert} is shown in Fig. 4b (top). We experimentally tested the temperature shift at the leader circuit in two independent ways: first, we measured the temperature using a micro-thermocouple; second, we measured the circuit frequency using an oscilloscope (PicoScope 3404D) and used the calibration shown in Fig. 3d to extract the temperature. We find that the

micro-thermocouple read-outs (Fig. 4b, middle) and oscilloscope measurements (Fig. 4b, bottom) show temperature differences of $\sim 0.4^\circ\text{C}$, in rough agreement with the model predictions. To quantify this cilia-induced thermal advection, we define a thermal stretching length (TSL) $L = \Delta T_{\text{reg}}/|k|$, which converts the measured temperature perturbation into the effective displacement of a local isotherm in the imposed linear background field. Using the values above, the closed-loop response corresponds to $L_{\text{max}} \approx 0.2\text{ mm}$ (Methods and Extended Data Fig. 9c,d show the time-resolved $L(t)$ and the corresponding cycle-resolved increment ΔL_n during actuation). We further introduce an actuation-window-averaged TSL-derived thermal-profile advection coefficient, $\bar{h} = \rho c_p L_{\text{max}}/\Delta t$, to quantify the average areal heat-capacity transport rate associated with the build-up of cilia-induced isotherm displacement over the whole actuation window, where L_{max} is the maximum TSL during cilia actuation, Δt is the actuation window and ρc_p is the volumetric heat capacity of the surrounding fluid. Using $L_{\text{max}} \approx 0.2\text{ mm}$, $\Delta t \approx 97\text{ s}$ and $\rho c_p \approx 4.2 \times 10^6\text{ J m}^{-3}\text{ K}^{-1}$ for a PBS solution gives $\bar{h} \approx 8.7\text{ W m}^{-2}\text{ K}^{-1}$ (Methods and Extended Data Fig. 9e show the cycle-resolved coefficient $h_n = \rho c_p \Delta L_n/T_b$ and its decay during thermal-profile stabilization). The time-resolved TSL analysis shows that $L(t)$ approaches a plateau, whereas ΔL_n and h_n decrease with successive pumping cycles (Extended Data Fig. 9d,e), indicating that cilia pumping drives the system towards a new period-averaged quasi-steady thermal profile, where further isotherm displacement is balanced by thermal diffusion and boundary constraints (Methods shows a detailed analysis). These results demonstrate that this platform, which combines microscale onboard thermal sensing, computation and coordinated cilia actuation, enables adaptive closed-loop thermal regulation.

Conclusions

We have reported a closed-loop coupling between microscopic robots and their local surroundings, which allows the robots to actively reshape their environment. We demonstrated three modalities: binary sensing, continuous sensing and gradient sensing. The approach could be extended by making the coupling between circuits non-reciprocal, expanding the platform from simple leader–follower behaviours to patterns that evolve according to the robots' surroundings^{32–35}. Although communication between the two circuits and programming of the cilia beating patterns were hardwired in this work, larger circuit networks could interact through wireless near-field communication or optical pathways to produce collective effects and real-time reprogramming. Future devices could integrate additional chemical, optical, electrical and mechanical inputs to sense and manipulate other aspects of their environment. These capabilities, combined with programmable coupling within and between circuit networks, could produce nested feedback loops and spatiotemporal coordination for the directed pumping of localized chemical reactions, terraformation and other emergent dynamics found in biology^{1,2,36–38}.

Methods

Experiments

Fabrication of artificial cilia. The fabrication process of the artificial cilia consisted of sequentially depositing a release layer, patterning the Pd- and Ti-based actuator, adding a top Ti adhesion layer, and forming the top rigid panels (Extended Data Fig. 1a,b). (1) A 180-nm AlN releasing layer was first deposited on a fused silica wafer using Oxford OEM Endeavor. (2) To form the cilia actuators, a 10-nm Ti layer was sputtered at 3 mtorr and 400 W using the AJA sputter tool, followed by electron-beam evaporation of a 15-nm Pd layer using a CVC SC4500 Odd-Hour Evaporator. The cilia structures were patterned via a standard lift-off process using a negative photoresist (NLOF 2020). (3) Then, a 10-nm Ti layer was deposited on top of the Pd layer to serve as an adhesion layer for the top panel. (4) Finally, a 1.6- μm -thick rigid polymer panel was patterned on top using a negative photoresist (NLOF

2020) and hard baked at 170°C for 30 min. As an alternative, a rigid panel can be fabricated from $\text{SiN}_x/\text{SiO}_2$ by depositing a 550-nm layer followed by patterning through inductively coupled plasma etching (Oxford PlasmaLab 80+).

Fabrication of CMOS-circuit-integrated artificial cilia. The fabrication of the CMOS-integrated artificial cilia was built on a silicon-on-insulator substrate with a CMOS circuit from X-FAB Silicon Foundries. The main process contains exposing the metal contact, growing the interconnect wires, patterning the releasing layer and fabricating the cilia structures (Extended Data Fig. 1c). The detailed fabrication process is as follows:

(1) The SiO_2 layer on top of the CMOS circuit was first thinned from $2\text{ }\mu\text{m}$ to 500 nm with the inductively coupled plasma etching (Oxford PlasmaLab 80+).

(2) To select the electrical output contact pads of the circuit for growing the interconnect wires to the artificial cilia, a positive photoresist (Microposit S1813) was spin coated and patterned. The SiO_2 layer was then etched with inductively coupled plasma etching (Oxford PlasmaLab 80+) and the selected metal pads were exposed.

(3) To grow and pattern the interconnect wires to actuate the artificial cilia, a negative photoresist (NLOF 2020) was spin coated and patterned, and 10-nm Ti and 60-nm Pt at 3 mtorr and 400 W were then sputtered using the AJA sputter tool.

(4) To fabricate the ground (GND) layer (also serving as the shielding layer), a negative photoresist (NLOF 2020) was spin coated and patterned. Subsequently, 10-nm Ti and 800-nm Pt were deposited at 3 mtorr and 400 W using the AJA sputter tool.

(5) To fabricate the releasing layer, a negative photoresist (NLOF 2020) was spin coated and patterned. Subsequently, a 180-nm AlN layer was deposited through reactive sputtering at 3 mtorr and 400 W using the AJA sputter tool, with nitrogen and argon flow rates of 25 s.c.c.m. and 5 s.c.c.m., respectively.

(6) To fabricate the actuator, a negative photoresist (NLOF 2020) was spin coated and patterned. First, 10-nm Ti was deposited at 3 mtorr and 400 W using the AJA sputter tool and then 15-nm Pd was evaporated with CVC SC4500 Odd-Hour Evaporator.

(7) To fabricate the adhesion layer, a negative photoresist (NLOF 2020) was spin coated and patterned. Then, 10-nm Ti was deposited and sputtered at 3 mtorr and 400 W using the AJA sputter tool.

(8) To fabricate the rigid panel, a negative photoresist (NLOF 2020) was spin coated, patterned and hard baked at 170°C for 30 min.

To release the artificial cilia from the substrate, a 5% tetramethylammonium hydroxide solution was used to etch the releasing layer, and the solution was then transferred to PBS ($1\times$, pH 7.45) to mimic the bioenvironment.

We note that the polymer panels were suitable for operation below 30°C . To prevent distortion at higher temperatures or higher temperature gradient, a 550-nm-thick SiO_2 layer was deposited by plasma-enhanced chemical vapour deposition (Oxford 100), patterned with a positive photoresist (Microposit S1813), and etched using CHF_3/O_2 plasma at 240 W in an inductively coupled plasma etcher (Oxford PlasmaLab 80+).

Characterization of actuation of artificial cilium. To characterize the actuation performance of the artificial cilia composed of 10-nm Ti and 15-nm Pd layers, an inverted microscope (Olympus IX71) integrated with a three-axis micromanipulator (Sensapex) and a CMOS camera (Basler ace 2) was used. Voltage signals were generated using a function generator (SDGI032X, Siglent Technologies) and delivered through a blunted tungsten microprobe (blunted tip, Microprobes for Life Science) in direct contact with the cilium, with an Ag/AgCl electrode (World Precision Instruments) serving as the reference (Extended Data Fig. 2a). The corresponding cyclic voltammetry response of the cilium during a voltage sweep from -1.2 V to 0.6 V at a sweep rate of 50 mV s^{-1} is shown in Extended Data Fig. 2b.

Visualization of flow pattern generated by artificial cilia. To visualize the flow pattern generated by the artificial cilia, we used a customized optical setup integrating a microscope and the same CMOS camera (Basler ace 2) (Extended Data Fig. 4a). A 635-nm laser (LSR-PS-II, Laserver) was used to power the microphotovoltaics (μ PVs). A white light source (FO-150, Chiu Technical), coupled through a fibre and collimating lens, was used for bright-field illumination. The sample was placed in a Petri dish on a temperature-controlled hotplate mounted on an XYZ stage. To eliminate the influence of the laser on imaging, a 600-nm short-pass optical filter (FESH0600, Thorlabs) was mounted in front of the camera. Here 2- μ m polymer tracer particles (FluoSpheres sulfate-modified microspheres) were added to the PBS solution to enable flow tracking and PIV analysis.

The fluid motion, including particle trajectories, streamlines and velocity fields, was processed in MATLAB. PIV analysis was conducted with the PIVlab toolbox³⁹, using a multipass fast Fourier transform algorithm with window deformation. Interrogation window sizes were reduced from 128 pixels to 32 pixels with 50% overlap. To improve the spatial resolution of the velocity field, sub-pixel displacement estimation was performed using a 2×3 -point Gaussian peak-fitting algorithm. The experimental PIV analysis reports time-averaged in-plane velocity fields obtained from tracer-particle motion within the optical imaging volume. Owing to the finite depth of field of the microscope, the measured PIV field presents an effective finite-depth average over a limited axial region around the focal plane. In our experiments, this focal plane was positioned near the cilium-height region, with an estimated effective imaging window of $z \in [60, 80] \mu\text{m}$.

Complex thermally switchable flow patterns with a three-cilia array.

To achieve more complex flow patterns with the binary sensing functionality, we adjusted the wiring layouts and phase delays to accommodate three cilia. We present six representative flow patterns realized under three wiring configurations, each tested at both low and high temperatures (Extended Data Fig. 6). In each panel, the top row shows an optical micrograph of the wiring. Insets at the top left of the middle and bottom rows indicate the thermal state, with semitransparent blue for low temperature and semitransparent red for high temperature. Coloured arrows indicate the prescribed pumping direction for each cilium (blue for forward and red for backward). In each configuration, we present a composite image combining the PIV experimental results (bottom), simulated three-dimensional flow geometry projected onto the surfaces of a 3/4 cuboid (middle) and depth-averaged simulation flow patterns (top) (see the 'Model of two-hinged cilium' and 'Flow simulations of cilia array' sections). In the first configuration (Extended Data Fig. 6a and Supplementary Video 2), synchronized wiring yields a unidirectional flow, thermally switching between the forward and backward directions. The second configuration (Extended Data Fig. 6b and Supplementary Video 3) uses differential wiring to generate a single vortex that reverses the rotation direction with the temperature threshold. The third configuration (Extended Data Fig. 6c and Supplementary Video 4) realizes a pair of symmetric counter-rotating vortices whose rotation directions simultaneously flip in response to thermal changes. The excellent correspondence between simulations and experimental flow fields across these configurations highlights the capacity of CMOS-integrated cilia arrays to interact with their ambient environment and achieve programmable manipulation of microfluidic flow fields.

Circuit design. All CMOS circuits used in this study were designed in Cadence Virtuoso Studio IC23.1 (Cadence Design Systems, Inc.) and fabricated using the XT018 180-nm CMOS process provided by X-FAB Silicon Foundries. We designed and implemented two core circuit architectures: a compact temperature-sensing clock circuit (Extended Data Fig. 3a) and a PCO circuit (Extended Data Fig. 7a).

The compact temperature-sensing clock circuit for binary sensing (Extended Data Fig. 3a) uses the forward voltage of a biased p-n junction to generate the CTAT signal V_{temp} . This signal is compared with two

approximately temperature-independent reference voltages generated using PTAT bias currents and resistors with CTAT characteristics to determine the output phase configuration. A multiplexer toggles the phase between two square wave outputs ($[0^\circ, 90^\circ]$ or $[90^\circ, 0^\circ]$), and the signals are downsampled to actuator-compatible frequencies (0.4–12.8 Hz) via a flip-flop chain. This mechanism enables discrete flow reversal in response to thermal thresholds.

The PCO circuit (Extended Data Fig. 7a) was designed to enable analogue temperature response and autonomous synchronization among distributed oscillator units, which would generate coordinated signals to drive the hinged cilia. Each oscillator consists of a compact relaxation loop built from a DLS oscillator and provides one of the two drive inputs required for the two-hinged cilium. The core voltage node (V_{AB}) toggles between high and low states as capacitors charge and discharge, with the oscillation frequency increasing monotonically with temperature due to accelerated charging dynamics. This internal structure allows for the scalable integration of temperature-sensitive clock generators (Extended Data Fig. 7b). When multiple oscillators are interconnected, the one with the highest frequency naturally assumes the leader role by emitting more digital pulses per given time frame relative to that of other oscillators (followers). This difference in average pulse output forces the followers to speed up, allowing the overall network to achieve a stable synchronized state with phase-delayed outputs to appropriately actuate cilia with the express purpose of fluid manipulation. This leader–follower behaviour emerges dynamically without centralized control, supporting both continuous modulation and gradient-driven directional flow (Extended Data Fig. 7c).

Circuit characterization. CMOS circuits were characterized under controlled illumination and thermal conditions using both benchtop and on-chip setups. All circuits are powered wirelessly, by integrated μ PV cells, through a collimated 635-nm laser. To suppress spurious photocurrent from ambient light, exposed circuit regions were shielded using a patterned top metal layer (also serving as the ground layer). Signal and ground pads were accessed via Pt/Ir microelectrodes mounted on micro-manipulators. The experimental platform, including the microscope, laser illumination and temperature-controlled stage, was identical to that used for flow visualization (Extended Data Fig. 4). Output signals were recorded using a digital oscilloscope (PicoScope 3404D), either directly or via a preamplifier (Stanford Research SR570). For high-impedance voltage measurement, a 100-M Ω resistor was inserted before amplification, and voltages were calculated from the measured current using Ohm's law.

We characterized the output current of the μ PVs under illumination intensities ranging from 1 kW m^{-2} to 10 kW m^{-2} (equivalent to 1 sun to 10 suns). The measured current responses are shown in Extended Data Figs. 3b and 7d, respectively. Under an illumination of 1 kW m^{-2} , the μ PVs generated $-0.78 \mu\text{A}$ for the binary sensing circuit and $-0.19 \mu\text{A}$ for the PCO circuit. Cyclic voltammetry measurements (Extended Data Fig. 2b) indicated a peak actuation current density of approximately 0.62 mA mm^{-2} during hydrogen absorption at -1.2 V . For the two-hinged artificial cilium with an effective electrochemical reaction area of $300 \mu\text{m}^2$, a binary sensing circuit can support up to four cilia, whereas a coupled oscillator circuit (consisting of two oscillator units with independent μ PVs) can jointly deliver up to $0.38 \mu\text{A}$, sufficient to drive two cilia.

Scanning electron microscopy. For scanning electron microscopy (SEM) imaging, the fabricated devices were first released in an AZ 726 MIF developer, followed by sequential rinsing in deionized water and isopropanol. Samples were then dried using a critical point dryer (Leica CPD300), coated with a thin gold layer by sputtering (Polaron gold sputtering system), and imaged using a ZEISS Ultra 55 SEM device.

Thermal manipulation with collective cilia array. On the basis of circuit characterization and cyclic voltammetry test of the cilia, additional drive was required to power larger cilia arrays. To enable thermal manipulation

with the cilia array, we boosted the oscillator output using two preamplifiers (Stanford Research SR570). Outputs from the circuits were routed to bond pads and wire bonded to the amplifier. Exposed bonds and metal wires were immobilized and protected with an optical adhesive (NOA 60, Norland Products). The amplified outputs were then returned to dedicated pads to drive the cilia, which were simultaneously monitored via a digital oscilloscope (PicoScope 3404D). To reduce heat conduction from chip–dish contact, we formed a peripheral wall with adhesive (NOA 60, Norland Products) to seal the die edges and create a shallow, air-filled cavity beneath the chip, minimizing direct solid–solid contact under the active region and improving thermal isolation. An Ag/AgCl electrode was used as the reference electrode. Two micro-thermocouples (Type-K, 76- μm bare wire, Evolution Sensors and Controls) were placed near the circuit surface to measure the thermal gradient. After stabilization, the cool-side probe was removed to minimize flow disturbance, and the hot-side probe was retained for monitoring the temperature perturbation caused by the cilia pumping. The measurement response time was approximately 0.25 s with a resolution of 0.1 $^{\circ}\text{C}$.

Theories and simulations

Model of two-hinged cilium. We model the artificial cilium as two rigid panels connected in series and mounted on a no-slip wall (Extended Data Fig. 5). The motion is confined to the x – z plane, and the induced flow is evaluated in the three-dimensional half-space above the wall using the Blake image system. This hybrid approach provides a reduced-order three-dimensional near-wall Stokes-flow approximation based on two-dimensional cilium kinematics. The bottom and top panels have lengths L_1 and L_2 and their instantaneous postures are described by angles θ_1 and θ_2 measured from the wall, respectively. The beat cycle is decomposed into four phases that alternate the motion between the two joints to capture an effective stroke and a recovery stroke with minimal kinematic complexity. Within each phase, a single angle varies linearly, whereas the other remains fixed. In particular, when θ_1 varies, θ_2 remains fixed, corresponding to a vanishing fluid torque on the top panel. Accordingly, we assume that the hinges, when inactive, are incapable of generating torques, in line with previous cilium modelling²⁹. We parameterize time in each phase by $s \in [0, 1]$ and write

$$\begin{aligned} \text{Phase 1 : } & \theta_1 = \theta_{1,\min} + (\theta_{1,\max} - \theta_{1,\min})s, \quad \theta_2 = \theta_{2,\min}, \\ \text{Phase 2 : } & \theta_1 = \theta_{1,\max}, \quad \theta_2 = \theta_{2,\min} + (\theta_{2,\max} - \theta_{2,\min})s, \\ \text{Phase 3 : } & \theta_1 = \theta_{1,\max} - (\theta_{1,\max} - \theta_{1,\min})s, \quad \theta_2 = \theta_{2,\max}, \\ \text{Phase 4 : } & \theta_1 = \theta_{1,\min}, \quad \theta_2 = \theta_{2,\max} - (\theta_{2,\max} - \theta_{2,\min})s. \end{aligned} \quad (1)$$

This piecewise-linear schedule preserves asymmetry between the effective and recovery portions of the cycle and keeps the kinematics analytically tractable. At a low Reynolds number, the hydrodynamic effect of each panel can be represented to a leading order by regularized point forces that are centred at characteristic locations along the panels. We resolve the motion into three contributions. The rotation of the bottom panel produces a point force $\mathbf{F}_a$ located two-thirds along its length. The rotation of the top panel produces a point force $\mathbf{F}_b$ located two-thirds along the top panel measured from its base. The translation of the top panel due to the rotation of the bottom panel produces a point force $\mathbf{F}_c$ located at the centre of the top panel. To express these contributions compactly and in a form that is convenient for subsequent analysis, we introduce the unit vectors $\mathbf{e}_x = (1, 0)^T$ and $\mathbf{e}_z = (0, 1)^T$, and the planar rotation matrix

$$\mathbf{R}(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}. \quad (2)$$

We introduce the drag coefficients $D_{\perp,1}$, $D_{\perp,2}$ and $D_{\parallel,2}$ to denote the perpendicular and parallel hydrodynamic drag per unit length and velocity

of the panels. Since the bottom panel undergoes pure rotation (with no tangential translation along its own axis), no parallel drag coefficient is required. These coefficients can be initialized from slender-body theory of low-Reynolds-number hydrodynamics and subsequently refined to match experiments^{40,41}. The top-panel drag is direction dependent, with distinct tangential and normal components. Therefore, we write the corresponding drag tensor in the global (x, z) coordinates as

$$\mathbf{D}_2(\theta_2) = \mathbf{R}(\theta_2) \begin{pmatrix} D_{\parallel,2} & 0 \\ 0 & D_{\perp,2} \end{pmatrix} \mathbf{R}(\theta_2)^T. \quad (3)$$

With these definitions, the point-force locations and magnitudes can be written as

$$\begin{aligned} \mathbf{r}_a &= \begin{pmatrix} x_a \\ z_a \end{pmatrix} = \frac{2}{3}L_1 \mathbf{R}(\theta_1)\mathbf{e}_x, & \mathbf{F}_a &= \frac{1}{2}D_{\perp,1}L_1^2\dot{\theta}_1 \mathbf{R}(\theta_1)\mathbf{e}_z, \\ \mathbf{r}_b &= \begin{pmatrix} x_b \\ z_b \end{pmatrix} = L_1 \mathbf{R}(\theta_1)\mathbf{e}_x + \frac{2}{3}L_2 \mathbf{R}(\theta_2)\mathbf{e}_x, & \mathbf{F}_b &= \frac{1}{2}D_{\perp,2}L_2^2\dot{\theta}_2 \mathbf{R}(\theta_2)\mathbf{e}_z, \\ \mathbf{r}_c &= \begin{pmatrix} x_c \\ z_c \end{pmatrix} = L_1 \mathbf{R}(\theta_1)\mathbf{e}_x + \frac{1}{2}L_2 \mathbf{R}(\theta_2)\mathbf{e}_x, & \mathbf{F}_c &= \mathbf{D}_2(\theta_2) \mathbf{R}(\theta_1)\mathbf{e}_z L_1 L_2 \dot{\theta}_1. \end{aligned} \quad (4)$$

The translational contribution depends on $\dot{\theta}_1$ because the top panel translates when the bottom panel rotates, whereas $\dot{\theta}_2$ does not enter this term since the motion of the top panel about its hinge is purely rotational and is already represented by $\mathbf{F}_b$.

To compute the flow, we place the cilium in a half-space bounded by a no-slip wall and evaluate the velocity field induced by each point force using the Blake image system for a stokeslet (that is, point force) near a plane rigid boundary⁴². The point forces are then regularized over a length scale on the same order as the cilium panel sizes to avoid singularities⁴³. For a force parallel to the wall, the induced velocity components follow the standard near-wall expressions, whereas for a force normal to the wall, the complementary set applies. These kernels ensure the no-slip condition at the wall and allow straightforward superposition of multiple forces.

At a given configuration, the instantaneous velocity field is the linear superposition of the contributions from the three forces:

$$\mathbf{u}(\mathbf{x}; \theta_1, \theta_2, \dot{\theta}_1, \dot{\theta}_2) = \sum_{m \in \{a,b,c\}} \mathbf{G}(\mathbf{x}; \mathbf{x}_m, z_m) \mathbf{F}_m. \quad (5)$$

Since each force is linear in either $\dot{\theta}_1$ or $\dot{\theta}_2$, the flow is linear in the angular rates (a consequence of the linearity of Stokes flows). We, therefore, precompute unit-rate responses on a grid of (θ_1, θ_2) and later scale by the actual rates to construct time-resolved fields. This linear structure also enables interpolation in configuration space and in physical space; therefore, the full family of flows can be evaluated without fixing a particular time history of the cilium, enabling much faster simulations.

For numerical evaluation, we discretize each phase by N_s samples of s from 0 to 1. For each sample, we compute the kinematics (θ_1, θ_2) and then the force locations and magnitudes. We evaluate the Blake kernels at the target field points and sum the contributions. If streamlines or transport are required, we advance massless tracers in the instantaneous field using an explicit time step and repeat over a full period to extract cycle-averaged quantities. The net pumping velocity can be reported as the period average of u_x across a line at height z_0 or as a flux across a vertical section.

Flow simulations of cilia array. To simulate the flow field generated by the three-cilia array, each cilium was modelled using the method described above, and the resulting velocity field was then averaged over one beating period to obtain the cycle-averaged flow. All velocities were normalized such that the peak velocity component in the pumping direction had unit magnitude. The flow was computed over

a domain matching the experimental field of view in the lateral directions and extending vertically from $z = 0$ to $z = 140 \mu\text{m}$. To enable direct comparison with the experimental two-dimensional visualizations, we projected the three-dimensional flow onto the imaging plane by depth averaging the velocity field over $z \in [60, 80] \mu\text{m}$, which corresponds to the region around the experimental imaging plane. This procedure yielded an effective two-dimensional (but generally two-dimensional compressible) flow-field representation (Extended Data Fig. 6).

Circuit simulation of PCO. The temperature-dependent behaviour of the PCO was simulated through Cadence. The d.c. operating frequency of a stand-alone test cell with real-world conditions was derived through a simulated temperature sweep from 20°C to 40°C with a step size of 0.1°C . Convergence tolerances were tightened to ensure numerical accuracy at low-current levels.

Frequency–temperature calibration and validation. The DLS-based oscillators operate in the subthreshold regime and, therefore, exhibit an Arrhenius-type temperature dependence. Although the subthreshold leakage current contains a weak polynomial prefactor in temperature, often expressed as T^n , the exponential dependence through the thermal voltage dominates across our operating range. As a result, the oscillation frequency f can be described by a compact Arrhenius form³¹:

$$f(T) \approx \exp\left(a + \frac{b}{T}\right), \quad (6)$$

where a is a fitting parameter for the frequency magnitude, $b \approx -E_a/k_B$ relates to the activation energy E_a of the dominant leakage mechanism, k_B is the Boltzmann constant and T is the absolute temperature in kelvin.

We calibrated the oscillation frequency over 20 – 40°C using ten repeated measurements at each temperature set-point. The parameters were obtained by linear regression of the log-transformed data against inverse absolute temperature, that is, $\ln[f]$ versus $1/T$. The fitted relationships for the leader and follower circuits are

$$f_L(T) = \exp\left(23.8 - \frac{7,027}{T}\right), \quad (7)$$

and

$$f_F(T) = \exp\left(24.5 - \frac{7,261}{T}\right), \quad (8)$$

respectively. Both datasets closely follow the Arrhenius model: the leader fit yields $R^2 > 0.99$ with RMSE = 0.065 Hz , whereas the follower fit yields $R^2 > 0.99$ with RMSE = 0.057 Hz . These results indicate that the simplified Arrhenius model accurately captures the thermal response of the oscillators.

The local frequency–temperature sensitivity can be obtained by differentiating equation (6):

$$\frac{df}{dT} = -\frac{b}{T^2} f(T). \quad (9)$$

Using equations (7) and (8), the sensitivities of the calibrated leader and follower circuits are

$$\frac{df_L}{dT} = \frac{7,027}{T^2} f_L(T), \quad \frac{df_F}{dT} = \frac{7,261}{T^2} f_F(T). \quad (10)$$

Over the calibrated range of 20 – 40°C , the fitted leader and follower frequencies increase from approximately 0.84 to 3.90 Hz and from 0.76 to 3.72 Hz , respectively. The corresponding local frequency–temperature sensitivities increase from 0.069 to $0.279 \text{ Hz } ^\circ\text{C}^{-1}$ for the

leader circuit and from 0.065 to $0.275 \text{ Hz } ^\circ\text{C}^{-1}$ for the follower circuit. Thus, sub-degree temperature differences between spatially separated oscillator nodes can generate pre-synchronization frequency biases throughout the calibrated range.

For two spatially separated oscillators, a local temperature difference ΔT produces a pre-synchronization frequency bias:

$$\Delta f \approx \frac{df}{dT} \Delta T. \quad (11)$$

For an imposed spatial gradient $|\nabla T|$ and oscillator spacing d , this bias can be written as

$$\Delta f \approx \frac{df}{dT} |\nabla T| d. \quad (12)$$

The gradient magnitude, therefore, sets the size of the pre-synchronization frequency bias, whereas the sign of the gradient determines which oscillator has the higher free-running frequency and becomes the leader.

The jitter-limited temperature resolution was estimated using the standard frequency-based sensor relation between normalized frequency jitter and normalized thermal drift:

$$D_{\text{avg}} = \frac{\ln[f(T_2)] - \ln[f(T_1)]}{T_2 - T_1}, \quad \Delta T_{4\sigma} = \frac{J_{4\sigma}}{D_{\text{avg}}}, \quad (13)$$

where D_{avg} is the average normalized thermal drift over the calibrated temperature range and $J_{4\sigma}$ is the normalized 4σ frequency jitter.

From the calibration over 20 – 40°C , D_{avg} is $7.65\% ^\circ\text{C}^{-1}$ for the leader and $7.91\% ^\circ\text{C}^{-1}$ for the follower. To quantify the frequency jitter, we extracted the oscillator frequency from fixed-temperature cycle-to-cycle measurements of the same DLS PCO circuit (the method is described in ref. 25). Specifically, the frequency distribution obtained from 72 consecutive oscillation periods gives a normalized 1σ jitter of $\sim 0.17\%$, corresponding to a 4σ frequency jitter of $J_{4\sigma} = 0.68\%$.

This gives

$$\Delta T_{L,4\sigma} \approx \frac{0.68\%}{7.65\% ^\circ\text{C}^{-1}} = 0.089^\circ\text{C}, \quad \Delta T_{F,4\sigma} \approx \frac{0.68\%}{7.91\% ^\circ\text{C}^{-1}} = 0.086^\circ\text{C}. \quad (14)$$

Given the independent frequency jitter in different oscillator read-outs, the uncertainty of a differential temperature comparison follows standard uncertainty propagation^{44–49}. For continuous sensing, the combined temperature resolution for the hardwired leader–follower PCOs is $\sqrt{(\Delta T_{L,4\sigma})^2 + (\Delta T_{F,4\sigma})^2} \approx 0.124^\circ\text{C}$. For gradient sensing, two identical follower PCOs are connected, giving a combined temperature resolution of $\sqrt{2} \Delta T_{F,4\sigma} \approx 0.122^\circ\text{C}$.

Extended Data Table 1 compares these values with representative low-power temperature sensors and microscopic robotic platforms with onboard sensing. The PCO circuit used in this work provides a compact and ultralow-power route for temperature sensing in microscopic robotic systems. Specifically, the circuit achieves a temperature resolution of $\sim 0.09^\circ\text{C}$ for a single PCO and $\sim 0.12^\circ\text{C}$ for two coupled PCOs, whereas occupying only 0.04 mm^2 and consuming $\sim 5 \text{ pW}$ per PCO circuit. Beyond stand-alone thermal read-out, the pulse-coupled architecture directly converts local temperature-dependent frequency changes into synchronized actuation signals. This sensing-to-actuation transduction enables a microscopic robotic platform in which onboard thermal sensing is coupled to cilia-driven pumping to actively reshape the surrounding fluidic and thermal environment.

Thermal advection induced by collective cilia pumping. To capture the essential features of the temperature profiles caused by cilia pumping, we prescribe a reduced flow field generated by a doubly infinite array of cilia on the base plate, all beating along $\mathbf{e}_x$ (Extended Data Fig. 9a,b).

On the basis of the experiments shown in Fig. 4a, we define the same cilia spacing and use a constant actuation frequency of 1.95 Hz. The resulting velocity field is doubly periodic in the lateral directions, and we, therefore, spatially average it over x and y , yielding a reduced description that depends only on height and time. Because the net transport is predominantly along x , we neglect the vertical component of the velocity (the y component vanishes under averaging) and use a unidirectional flow $\mathbf{u} = u(z, t)\mathbf{e}_x$.

We impose a constant temperature-gradient boundary condition at the base plate, $T(x, 0, t) = kx$, and a zero normal heat-flux condition at the upper boundary, $\partial T/\partial z|_{z=H} = 0$, consistent with a fluid–air interface (Extended Data Fig. 9b). The temperature field $T(x, z, t)$ satisfies the advection–diffusion equation

$$\frac{\partial T}{\partial t} + u(z, t)\frac{\partial T}{\partial x} = D\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right), \quad (15)$$

where D is the thermal diffusivity of the fluid.

To remove the imposed linear background, we define the temperature perturbation as

$$T_{\text{pert}} = T - kx, \quad (16)$$

which obeys $T_{\text{pert}} = 0$ at $z = 0$ and $\partial T_{\text{pert}}/\partial z = 0$ at $z = H$. Since $u(z, t)$ and the boundary conditions are independent of x , the perturbation is also independent of x , that is, $T_{\text{pert}} = T_{\text{pert}}(z, t)$. The governing equation reduces to the one-dimensional form as

$$\frac{\partial T_{\text{pert}}}{\partial t} + k u(z, t) = D \frac{\partial^2 T_{\text{pert}}}{\partial z^2}. \quad (17)$$

We solve this equation numerically using a second-order central finite-difference discretization in z and a forward Euler time-stepping scheme. Unless otherwise noted, simulations use $H = 3 \times 10^{-3}$ m, $D = 1.4 \times 10^{-7}$ m² s⁻¹ and $k = -1.89$ °C mm⁻¹. We report T_{pert} at $z_m = 5 \times 10^{-4}$ m above the base plate to match the experimental conditions.

To quantify the cilia-induced regulation of the thermal profile, we define a signed thermal displacement as

$$\ell(z, t) = \frac{T_{\text{pert}}(z, t)}{k}, \quad (18)$$

where k is the imposed temperature gradient along the pumping direction. With this definition, the full temperature field can be written as

$$T(x, z, t) = kx + T_{\text{pert}}(z, t) = k[x + \ell(z, t)]. \quad (19)$$

Thus, $\ell(z, t)$ provides a signed measure of thermal-profile displacement along the imposed thermal coordinate. Its magnitude quantifies the effective displacement of a local isotherm induced by cilia-driven advection.

Substituting equation (18) into the reduced perturbation equation gives

$$\frac{\partial \ell}{\partial t} + u(z, t) = D \frac{\partial^2 \ell}{\partial z^2}. \quad (20)$$

This equation shows that cilia-driven advection shifts the thermal profile, whereas thermal diffusion smooths and relaxes the displacement.

At the measurement height z_m , we define the actuation-induced TSL relative to the onset of cilia actuation as

$$L(t) = |\ell(z_m, t) - \ell(z_m, t_{\text{on}})| = \frac{|T_{\text{pert}}(z_m, t) - T_{\text{pert}}(z_m, t_{\text{on}})|}{|k|}, \quad (21)$$

where t_{on} is the onset of cilia actuation. In the analysis below, $L(t)$ is calculated from the period-averaged temperature perturbation trace shown in Extended Data Fig. 9c.

To resolve the cycle-by-cycle dynamics, we compute the TSL increment generated during each complete pumping cycle. Let $T_b = 1/f$ be the cilia actuation period and $t_n = t_{\text{on}} + (n-1)T_b$; the TSL increment generated during the n th pumping cycle can then be written as

$$\Delta L_n = L(t_n + T_b) - L(t_n). \quad (22)$$

This quantity measures the additional isotherm displacement generated during one complete pumping cycle.

On the basis of this cycle-resolved increment, we define a TSL-derived thermal-profile advection coefficient, h_n , to estimate the areal heat-capacity transport rate associated with newly generated isotherm displacement as

$$h_n = \rho c_p \frac{\Delta L_n}{T_b}, \quad (23)$$

where ρ is the fluid density, c_p is the specific heat capacity at constant pressure and ρc_p is the volumetric heat capacity of the surrounding fluid. The coefficient h_n describes the rate at which each pumping cycle builds new thermal-profile displacement.

As shown in Extended Data Fig. 9d, the cumulative TSL trace rises rapidly and then approaches a late-time plateau. We describe this approach using an exponential form

$$L(t) = L_{\infty} - A \exp\left[-\frac{t - t_{\text{on}}}{\tau}\right], \quad (24)$$

where L_{∞} is the late-time TSL, A is a fitting constant and τ is the build-up timescale. Equivalently, the cycle-resolved increments decay approximately as

$$\Delta L_n \propto \exp\left[-\frac{(n-1)T_b}{\tau}\right]. \quad (25)$$

The semilogarithmic plot of ΔL_n versus actuation time gives $\tau \approx 25.5$ s, characterizing the approach to a new period-averaged quasi-steady thermal profile.

The corresponding h_n is plotted against the actuation time in Extended Data Fig. 9e. As shown in Extended Data Fig. 9d,e, both ΔL_n and h_n decrease with successive pumping cycles. This indicates that each successive pumping cycle generates diminishing additional thermal stretching as the system approaches a quasi-steady thermal profile. The cilia-driven displacement of the thermal profile becomes progressively balanced by thermal diffusion and boundary constraints, and the rate of generating additional TSL decreases towards zero.

To report the overall thermal regulation capability over the full actuation window, we use actuation-window-averaged metrics. The maximum TSL during cilia actuation is

$$L_{\text{max}} = \max_t L(t) = \frac{\Delta T_{\text{reg}}}{|k|}. \quad (26)$$

For the period-averaged simulation trace shown in Extended Data Fig. 9d, $L_{\text{max}} \approx 0.20$ mm. We then define the actuation-window-averaged TSL-derived thermal-profile advection coefficient as

$$\bar{h} = \rho c_p \frac{L_{\text{max}}}{\Delta t}, \quad (27)$$

where $\Delta t = t_{\text{off}} - t_{\text{on}}$ is the actuation window. Using $L_{\text{max}} \approx 0.20$ mm, $\Delta t \approx 97$ s and $\rho c_p \approx 4.2 \times 10^6$ J m⁻³ K⁻¹ for the PBS solution gives $\bar{h} \approx 8.7$ W m⁻² K⁻¹.

Data availability

Source data are provided with this paper.

Code availability

Source codes that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

W.W., J.Z., A.A., V.V., I.G. and I.C. conceived the project. W.W. and J.Z. designed and fabricated the devices, and performed the experiments. P.C. and K.S. designed the circuits and performed the circuit simulations. W.W. and J.Z. characterized the circuits. J.Z., C.Z. and J.P. conducted the cyclic voltammetry measurements of the actuators. J.Z. and Z.L. designed the setup for fluid temperature control and J.Z. conducted the experiments. J.Z. and Y.J. performed the SEM imaging. J.Z., I.G., D.S., J.S. and E.L. established the theoretical model. J.S. and E.L. conducted the simulations for thermal advection analysis. W.W., J.Z. and I.C. wrote the paper with input from all authors.

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Competing interests

I.C. and J.P. are inventors on a patent application submitted by Cornell University that covers electrically programmable microscale bulk electrochemical actuators and related robotic devices. I.C. and W.W. are inventors on a provisional patent application (63/267,190) submitted by Cornell University that covers actuators and control electronics for cilia metasurfaces and a provisional patent application (63/368,751) submitted by Cornell University that covers ICs for controlling microscopic robots. The other authors declare no competing interests.

Additional information

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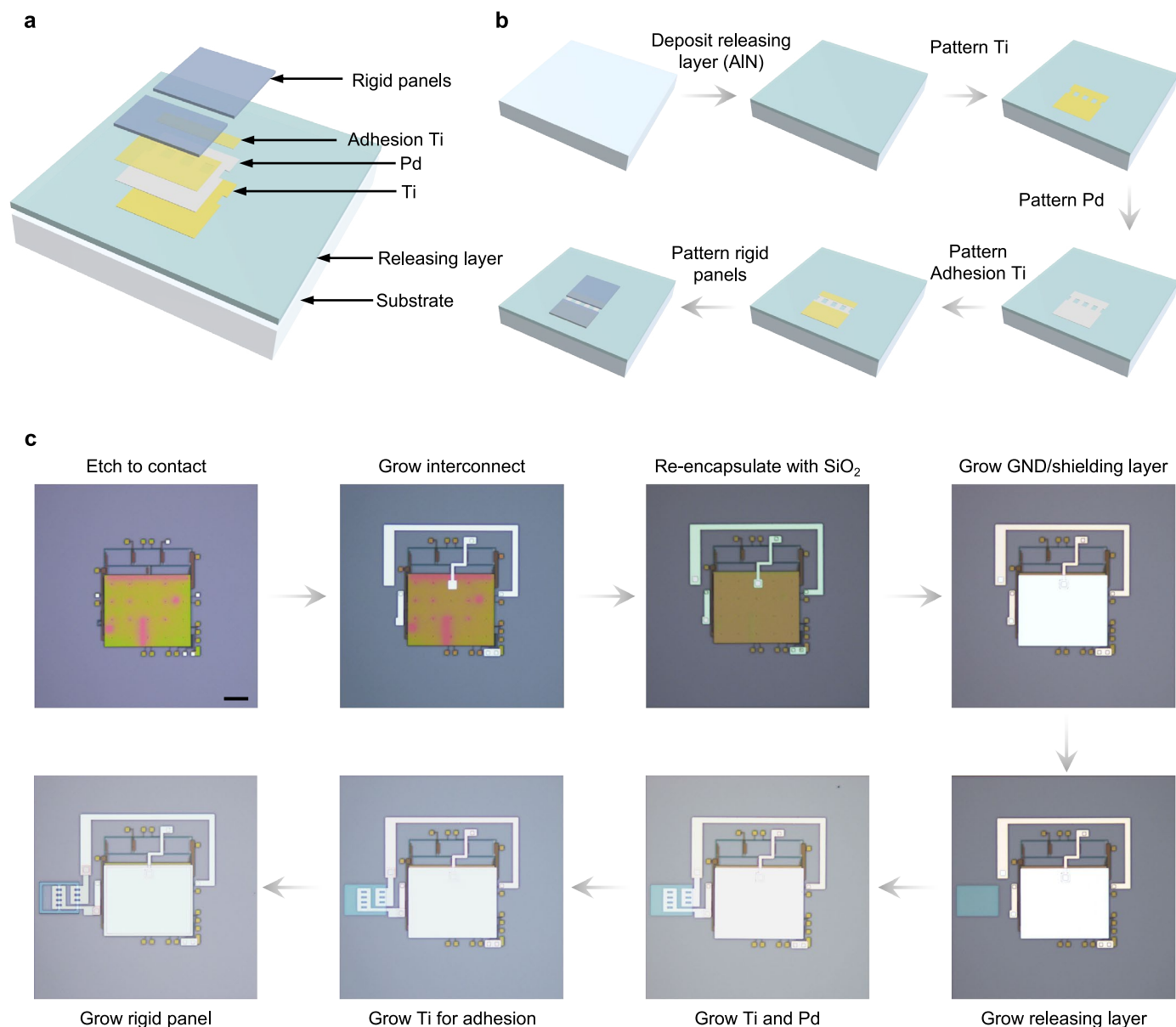
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Extended Data Table 1 | Performance comparison of representative low-power temperature sensors and microscopic robotic platforms with onboard sensing

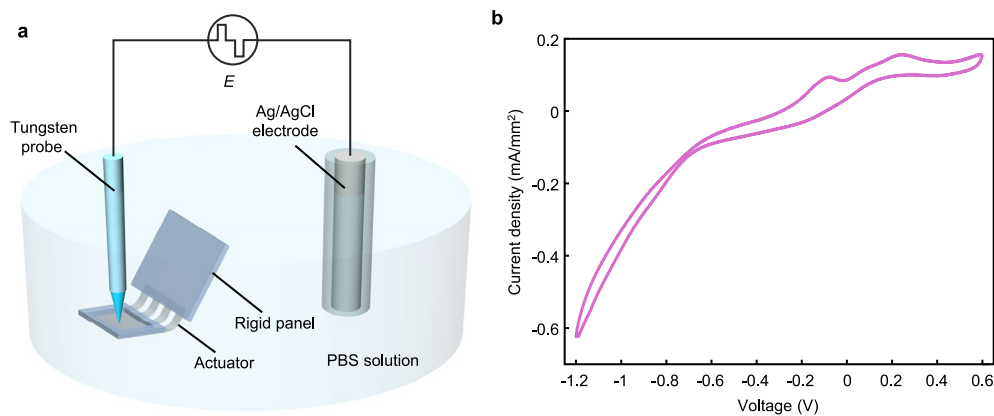
Ref.	Platform	Temperature range	Resolution	Size	Power
45	Temperature sensor only	0–100 °C	0.3 °C	0.05 mm ²	220 nW
46	Temperature sensor only	0–100 °C	0.25 °C	0.18 mm ²	36 μW
47	Temperature sensor only	–40–125 °C	0.063 °C	0.085 mm ²	600 nW
48	Temperature sensor only	–55–125 °C	0.02 °C	0.08 mm ²	5.1 μW
49	Temperature sensor only	–20–80 °C	0.3 °C	0.26 mm ²	< 15.5 μW
21	Microscopic robot with onboard sensing: thermal sensing and robot locomotion	20–40 °C	~ 0.3 °C	0.06 mm ²	0.19 nW for temperature sensing circuit 100 nW for robot integration
This work	Microscopic robot with onboard sensing: thermal sensing, cilia actuation and environmental coupling	20–40 °C in fluid ^a	~ 0.09 °C for single PCO ~ 0.12 °C for two coupled PCOs ^b	0.04 mm ² for single PCO circuit	5 pW for single PCO circuit

The platform reported in this work uses a complementary metal–oxide–semiconductor (CMOS) pulse-coupled oscillator (PCO) for temperature sensing and coordinated actuation. ^a The fluidic experiments in this work were performed over 20–40 °C, while the same circuit architecture can work over 20–100 °C in air ²⁵. ^b Resolution = frequency jitter / temperature drift.



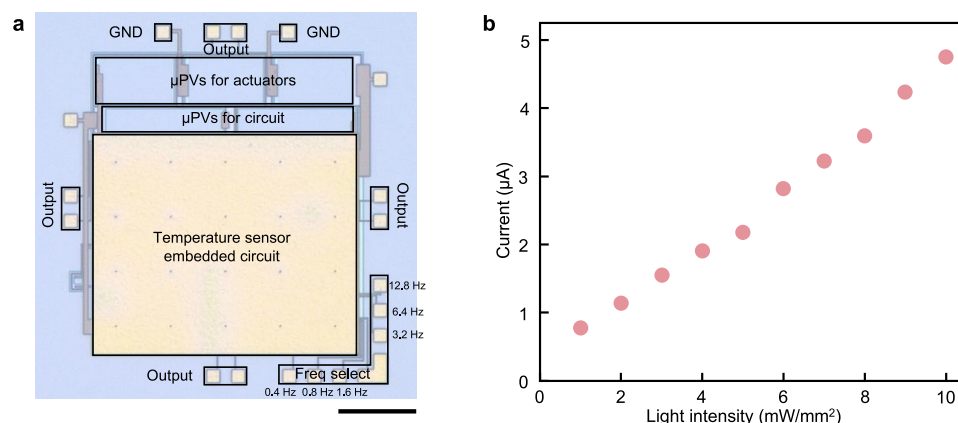
Extended Data Fig. 1 | Artificial cilium structure and fabrication. **a**, Exploded schematic of the artificial cilium. From bottom to top, the structure comprises the substrate, aluminium nitride (AlN) release layer, titanium (Ti) base layer, palladium (Pd) electrochemically active layer, Ti adhesion layer and rigid panels. **b**, Fabrication sequence for a standalone cilium. The process comprises deposition and patterning of the AlN release layer, Ti/Pd actuator stack and Ti adhesion layer, followed by formation of the rigid panels. Arrows indicate the

process order. **c**, Optical micrographs showing fabrication of a complementary metal-oxide-semiconductor (CMOS)-integrated cilium. The sequence proceeds from etching the top dielectric to expose the electrical contacts, through formation of the Ti/Pt interconnects, SiO₂ re-encapsulation, grounded shielding layer, AlN release layer, Ti/Pd actuator, Ti adhesion layer and rigid panel. GND denotes ground. Arrows indicate the process order. Scale bar, 50 μm .



Extended Data Fig. 2 | Electrochemical characterisation of the actuator.
a, Cyclic-voltammetry (CV) measurement in phosphate-buffered saline (PBS). A blunted tungsten probe contacts the Ti/Pd actuator, an Ag/AgCl electrode

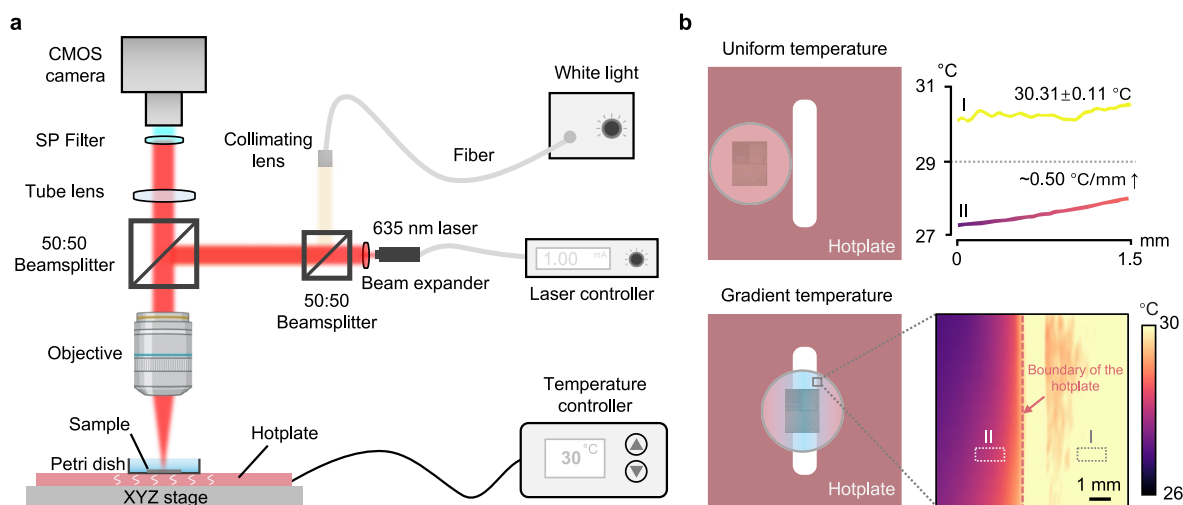
provides the reference potential and E denotes the applied potential relative to Ag/AgCl. **b**, Actuator current density during a potential sweep from -1.2 V to +0.6 V at 50 mV s^{-1} .



Extended Data Fig. 3 | CMOS circuit for binary sensing. a, Optical image of the binary sensing circuit. GND denotes ground, Freq select denotes the frequency-selection pads and μPV denotes the microscale photovoltaic regions supplying the circuit and actuators. The binary temperature sensor switches the output

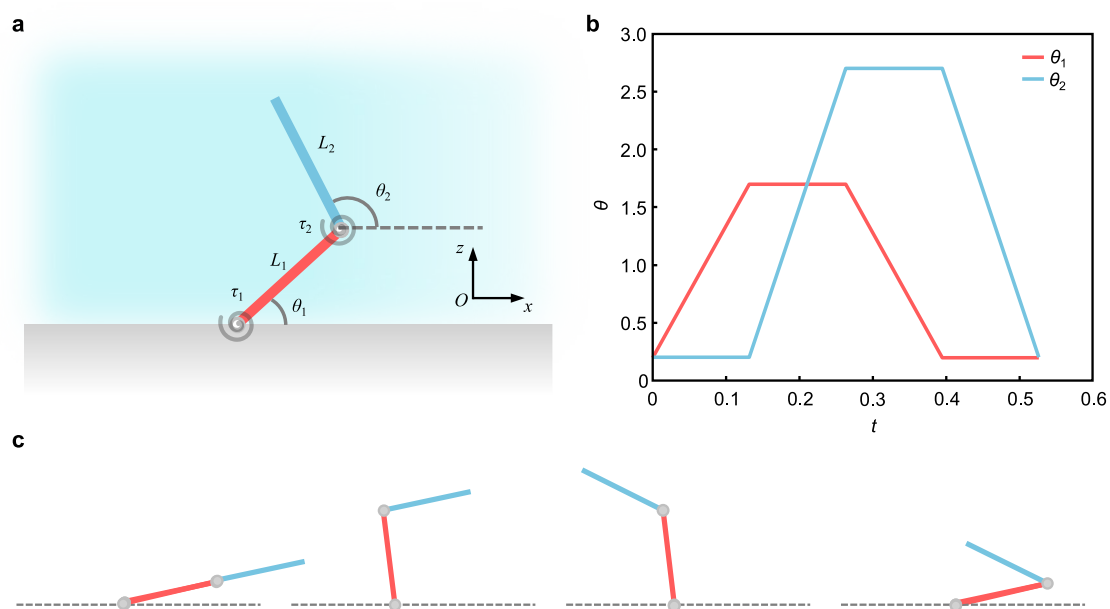
phase configuration at 26°C and 30°C. Available output frequencies range from 0.4 to 12.8 Hz, while 1.6 Hz was used for cilium actuation. Scale bar, 50 μm .

b, Measured μPV current versus incident light intensity. The current ranges from approximately 0.78 μA at one sun (1 kW m^{-2}) to approximately 4.8 μA at ten suns.



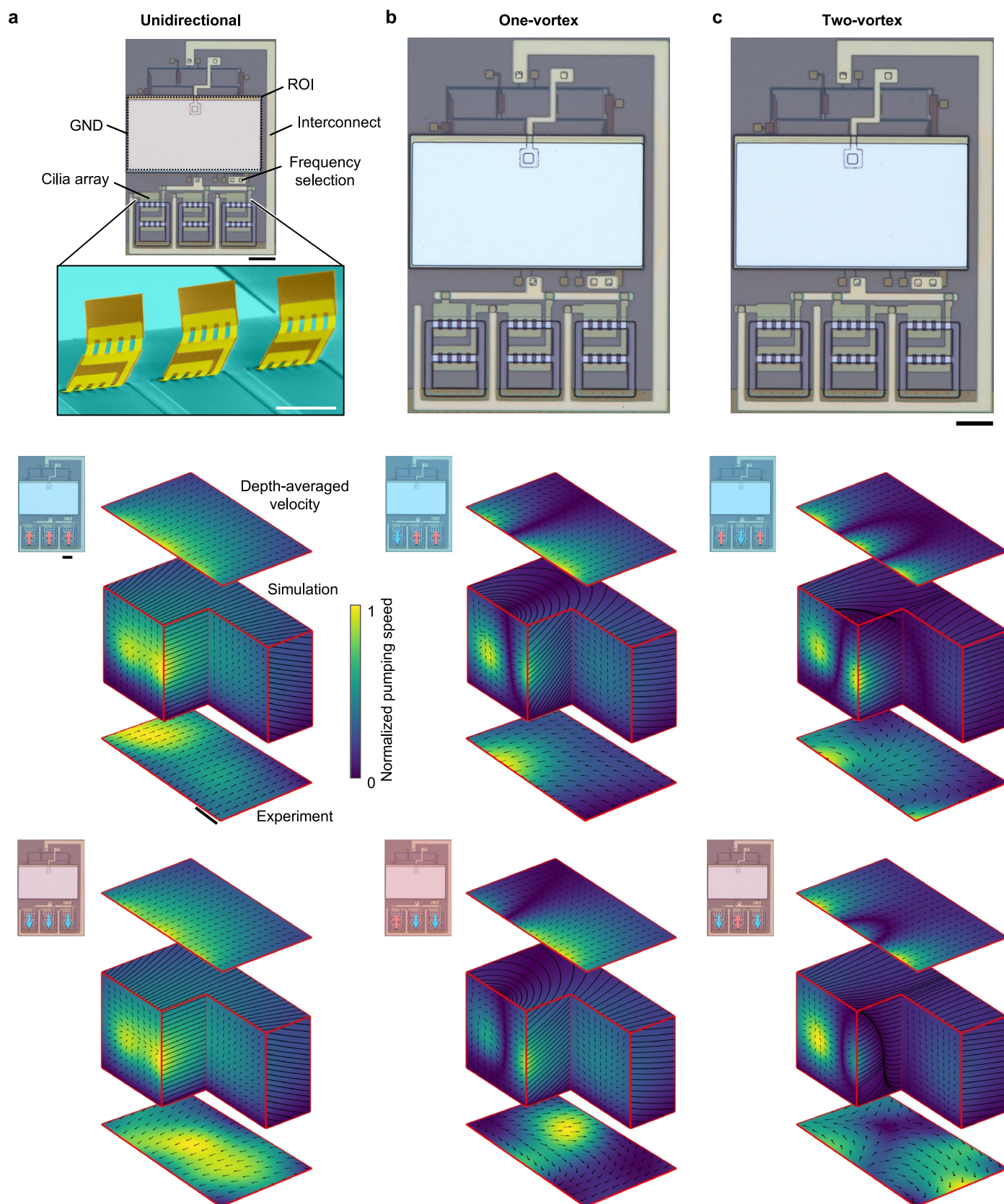
Extended Data Fig. 4 | Optical and thermal experimental platform. a, Optical setup for powering, imaging and thermally controlling the artificial cilia. A 635 nm laser powers the μ PVs through a beam expander and beam splitter. White light is delivered through a fibre and collimating lens for bright-field illumination. The imaging path contains the objective, beam splitter, tube lens and short-pass (SP) filter before the CMOS camera. The sample is held in a Petri dish on a temperature-controlled hotplate mounted on an XYZ stage. **b,** Generation of uniform and gradient thermal conditions by centring or offsetting the Petri dish relative to the

hotplate opening. Region I is the nominally uniform line profile and Region II is the gradient line profile. Infrared thermography of the dry sample gives a mean temperature of 30.31 °C with a spatial standard deviation of 0.11 °C along Region I and a gradient of approximately 0.5 °C mm⁻¹ along Region II. The infrared image was acquired with an Infra Tec ImageIR 5300 camera. Scale bar, 1 mm. We note that thermal imaging was performed on dry samples only and is not applicable in fluid because PBS strongly absorbs mid-IR radiation. Accordingly, with fluid present we used a micro-thermocouple for single-point in-liquid temperature measurements.



Extended Data Fig. 5 | Kinematic model of an artificial cilium with two hinges. **a**, Two rigid panels of lengths L_1 and L_2 connected by rotational hinges at the substrate and internal joint. The panel angles θ_1 and θ_2 are measured from the x direction in the x - z plane. **b**, Prescribed angular trajectories over one beat.

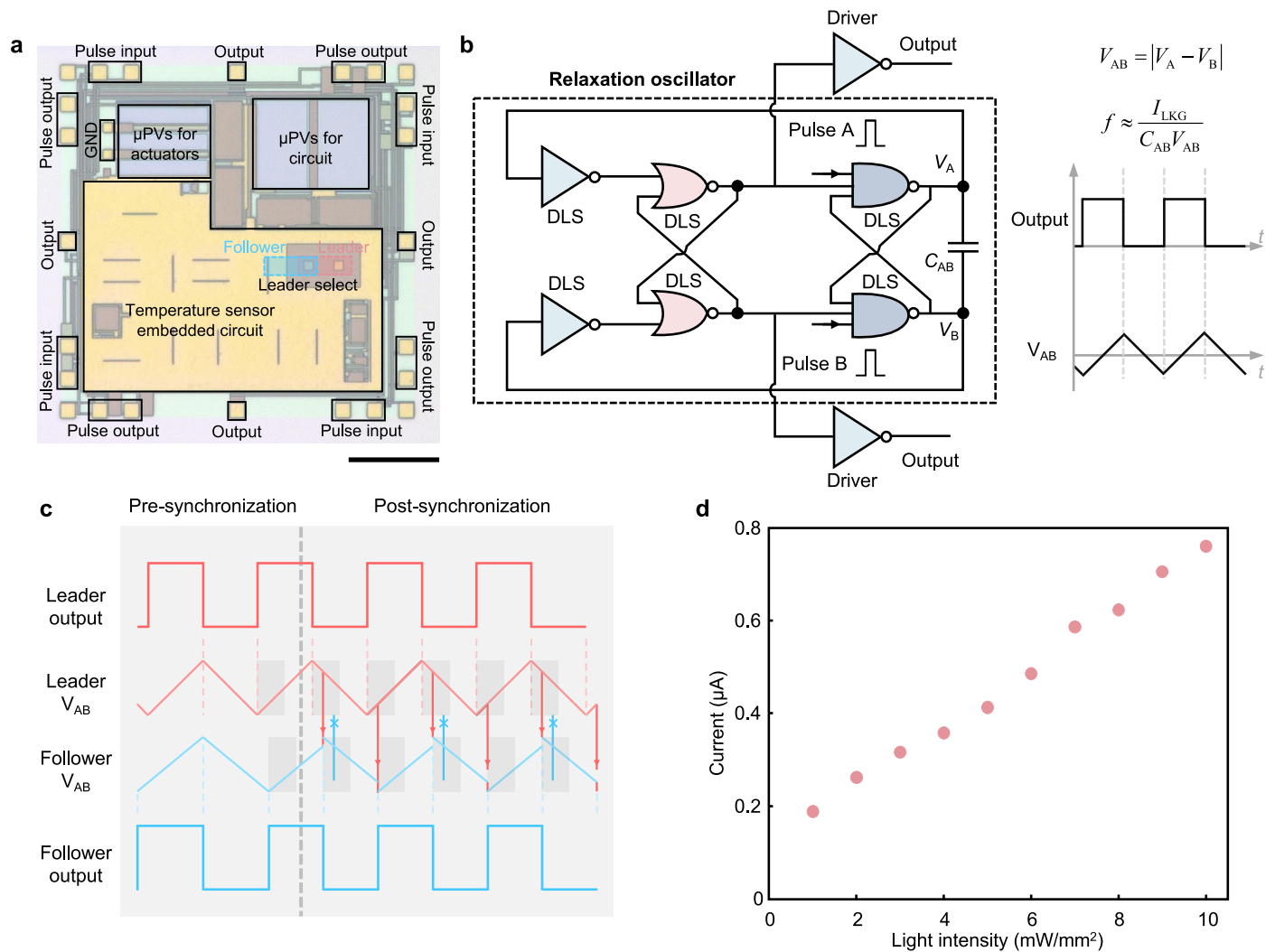
t is time in seconds, and θ_1 and θ_2 are in radians; the complete trajectory spans one actuation period T_b . **c**, Representative configurations during the four sequential hinge motions that form the non-reciprocal beat cycle.



Extended Data Fig. 6 | See next page for caption.

Extended Data Fig. 6 | Thermally switchable flow patterns generated by the binary sensing circuit integrated cilia array. Each case shows a closed-loop sensing-response configuration in which an integrated temperature sensor modulates cilia actuation through distinct output wiring. The top row shows optical images of the circuit-to-cilia wiring; the middle and bottom rows show the resulting low- and high-temperature flow patterns. A false-colour scanning electron microscopy image and the region of interest (ROI) used for flow calculations are shown in **a**. Insets indicate the thermal condition (blue,

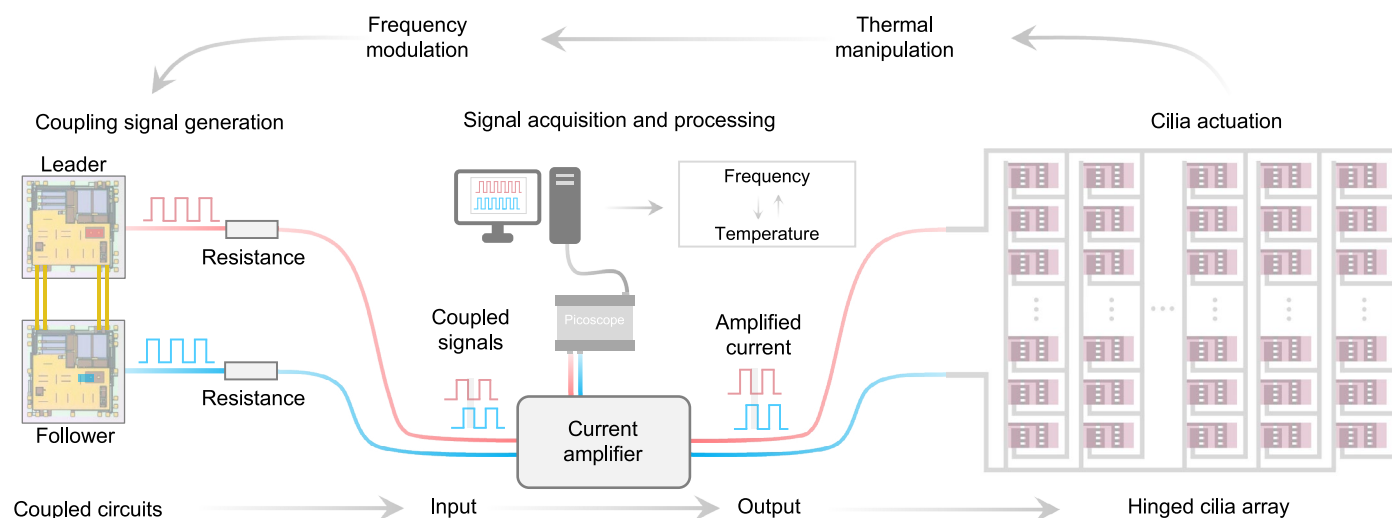
low temperature; red, high temperature), and arrows on the cilia indicate the prescribed pumping directions. Each composite panel contains the experimental particle-image-velocimetry flow field (bottom), the simulated three-dimensional flow projected onto the indicated planes (middle) and the depth-averaged simulation (top). **a**, Unidirectional pumping reverses between low and high temperature. **b**, A single vortex reverses its rotation direction with temperature. **c**, A symmetric pair of counter-rotating vortices reverses both rotation directions at high temperature. Scale bars, 50 μm .



Extended Data Fig. 7 | CMOS circuit for continuous and gradient sensing.

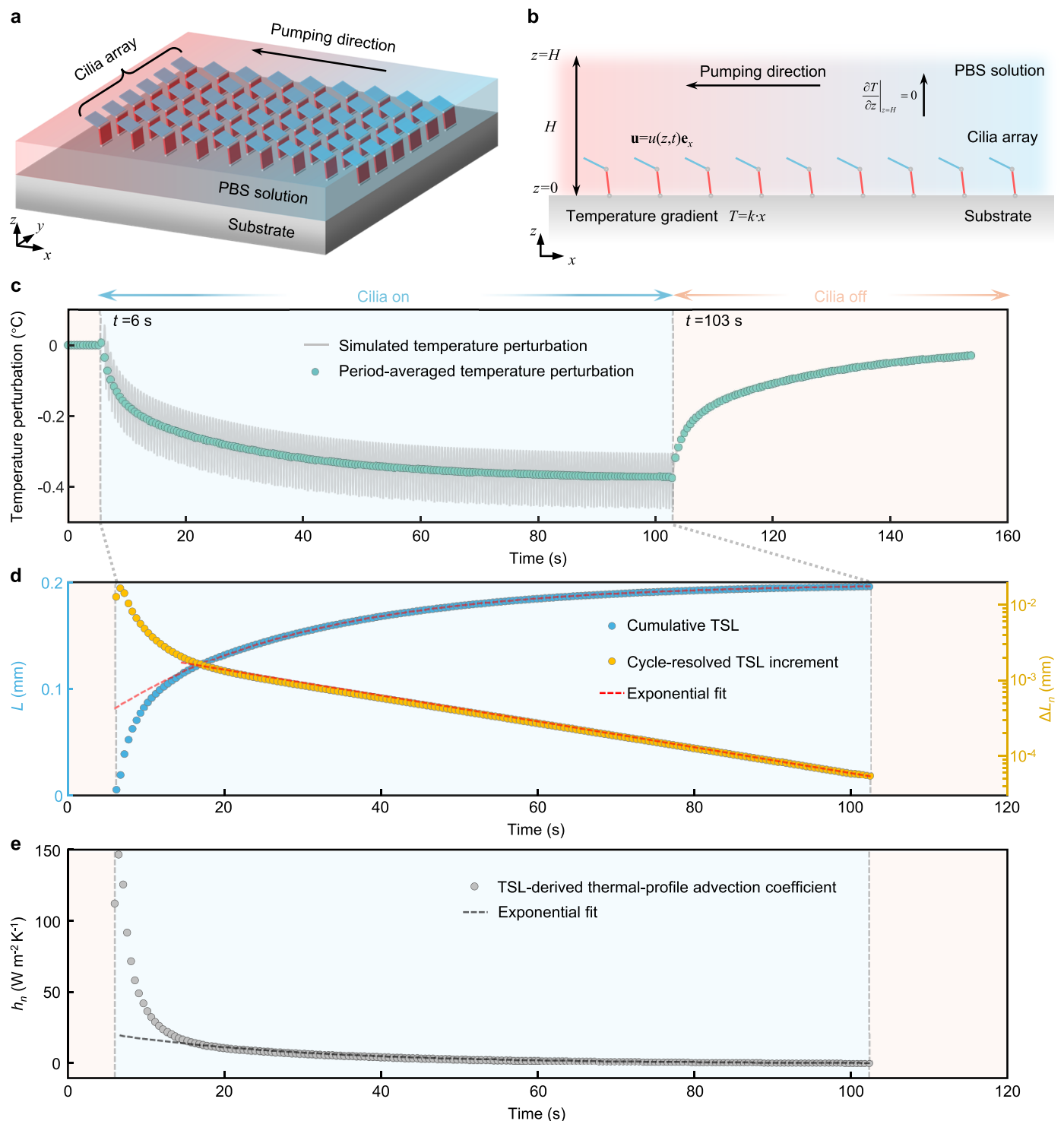
a, Optical image of the pulse-coupled oscillator (PCO) circuit. Labels identify the pulse inputs and outputs, actuator outputs, leader-selection block, embedded temperature-sensing circuit and μ PV regions supplying the circuit and actuators. Scale bar, 50 μ m. **b**, Relaxation-oscillator architecture implemented with dynamic-leakage-suppression (DLS) gates. V_A and V_B are the internal oscillator-node voltages, C_{AB} is the flying capacitance, $V_{AB} = |V_A - V_B|$ is the voltage across that

capacitance, I_{LKG} is the leakage current and f is the oscillation frequency. The output clock changes as V_{AB} ramps between its upper and lower thresholds. **c**, Pre-synchronisation and post-synchronisation waveforms. Red and blue traces denote the leader and follower, respectively. Coupling pulses advance the follower until the two output frequencies lock with a fixed phase offset. **d**, Measured μ PV current versus light intensity, increasing from approximately 0.19 μ A at one sun (1 kW m^{-2}) to approximately 0.76 μ A at ten suns.



Extended Data Fig. 8 | Experimental platform for closed loop thermal coupling. Two coupled oscillators generate phase-locked, temperature-dependent signals. Red and blue identify the leader and follower signal paths, respectively. The signals are acquired with an oscilloscope (PicoScope 3404D), converted to frequency and temperature using the calibration, and routed

through a current amplifier to a 6×9 hinged-cilia array. Cilia pumping advects fluid and reshapes the local temperature field, and the resulting temperature change feeds back to shift the oscillator frequency, forming a closed-loop interaction among the circuit response, cilia actuation and temperature distribution.



Extended Data Fig. 9 | Thermal advection model and thermal stretching analysis. **a**, Three-dimensional representation of the cilia array in phosphate-buffered saline (PBS). The red-to-blue background denotes the imposed temperature gradient and the arrow indicates pumping direction. x , y and z define the coordinate system. **b**, Reduced two-dimensional model. The laterally averaged flow is $\mathbf{u} = u(z, t)\mathbf{e}_x$, where $\mathbf{e}_x$ is the unit vector in the x direction, t is time and z is height above the substrate. H is the fluid height, $T = kx$ is the imposed linear temperature field with gradient k , and $\partial T / \partial z$ at $z = H$ equals zero at the upper surface.

c, Simulated temperature perturbation T_{pert} at the measurement height. Grey curves show the cycle-resolved perturbation and green markers show period-averaged values. Blue and pale-orange backgrounds denote cilia on and off, and dashed lines mark $t_{\text{on}} \approx 6$ s and $t_{\text{off}} \approx 103$ s. **d**, Thermal stretching length $L(t)$ and cycle-resolved TSL increment ΔL_n . Blue markers show cumulative $L(t)$, orange markers show ΔL_n on the logarithmic right axis and the red dashed line is an exponential fit. **e**, Cycle-resolved thermal-profile advection coefficient h_n . Grey markers show h_n , the dashed line is an exponential fit and the shading denotes cilia-on and cilia-off intervals.