Robotics

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Microrobotic cilia that sense and reshape their surroundings

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Complementary metal–oxide–semiconductor (CMOS)-integrated microrobotic cilia that pump fluid in response to temperature show how microscale actuators can both sense and actively modify their surroundings.

When termites build a mound, no single termite has a blueprint. Each one senses local airflow, temperature and pheromone cues and adjusts its behaviour accordingly. This behaviour in turn reshapes the cues the next termite will respond to. Over time, this loop between environment and organism produces the mound's elaborate ventilation architecture[1]. Writing in *Nature Electronics*, Wei Wang, Jinsong Zhang, Itai Cohen and colleagues now show that such a feedback loop can be engineered into a machine barely larger than a human cell — a monolithic microrobotic cilium that senses its thermal environment and pumps fluid to actively change it[2].

Microscopic robots — devices with footprints comparable to biological cells — have already been shown to walk[3], fold[4] and swim[5] under onboard electronic control, owing to advances in integrating complementary metal–oxide–semiconductor (CMOS) circuitry with microscale actuators[3–5]. What has been missing is the second half of the loop: an ability for the device's own actions to feed back and alter the environmental signal it is sensing, the way a termite's mound-building alters local airflow, or the way a bacterium's swimming pattern reshapes the chemical gradient it is following[6]. The researchers — who are based at Cornell University, the University of Cambridge, Tel Aviv University, the University of Illinois Chicago and Westlake University — close the loop with the microrobotic cilium: a single CMOS circuit wired directly

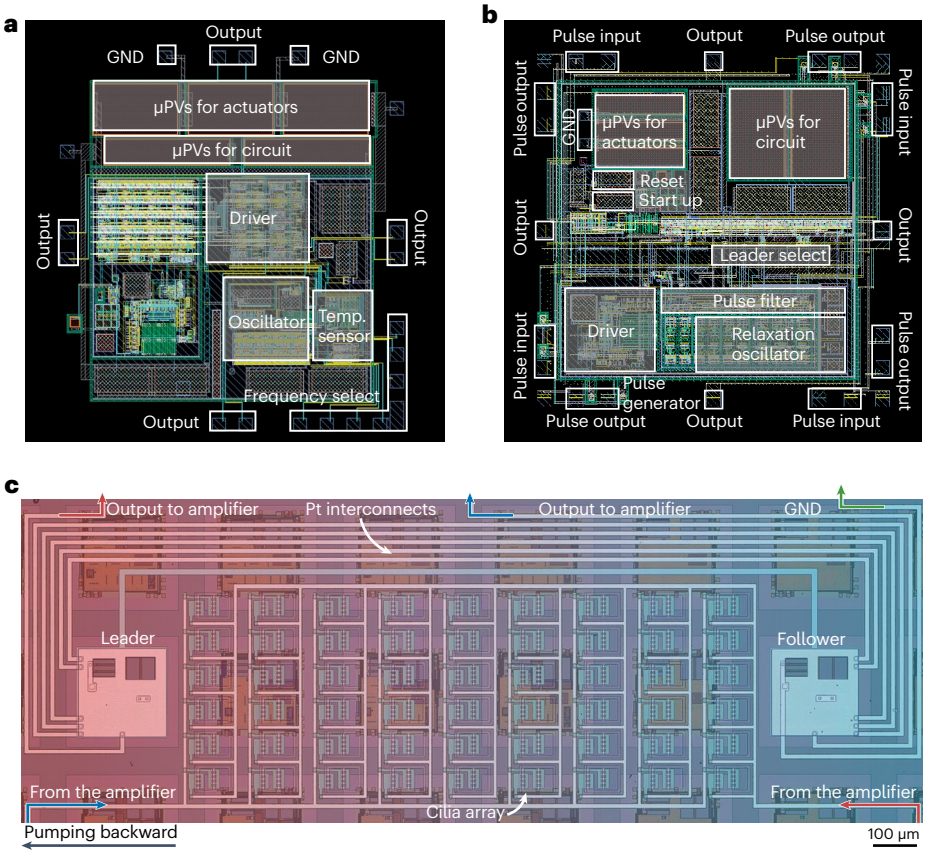


Fig. 1 | Coupling the behaviour of microscopic robots to the temperature of their surrounding environment. a–**c**, CMOS circuit layouts for binary temperature sensing (**a**) and continuous and gradient sensing (**b**), and an optical micrograph of collective cilia arrays for closed-loop thermal regulation (**c**). GND, ground; μPVs, microphotovoltaics. Figure adapted from ref. 2, Springer Nature Limited.

to an electrochemically actuated artificial cilium, so that sensing, computation and actuation are integrated onto one monolithic chip.

Each microrobotic cilium's actuator is a two-hinged structure made from a titanium–palladium bilayer. Applying a small voltage causes the palladium layer to absorb or release hydrogen, bending or flattening each hinge; cycling the two hinges out of phase drives a non-reciprocal stroke that pumps fluid, much like a biological cilium does. The direction and speed of that stroke are set entirely by the phase and frequency of two electronic clock signals generated on-chip, providing a simple way to translate a thermal sensing scheme directly into a mechanical output.

The team demonstrate three thermal modalities. In the first and simplest, a relaxation oscillator compares a temperature-dependent voltage against two fixed thresholds; crossing 30 °C on heating or 26 °C on cooling flips the phase relationship between the two clock signals and reverses the pumping direction, giving the cilium a thermally triggered on–off switch with built-in hysteresis (Fig. 1a). In the second scheme, two oscillators are coupled through pulse exchange, an approach adapted from the classic theory of pulse-coupled biological oscillators[7], so that the faster (warmer) circuit becomes the leader and drives a common frequency; because oscillator frequency rises with temperature, this converts continuous temperature changes into continuously tunable pumping speed (Fig. 1b). Placing an identical pair of oscillators across a spatial temperature gradient turns the same leader–follower logic into a gradient sensor: the circuit on the warmer side always leads, so the direction of pumping automatically tracks the sign of the gradient.

In the third scheme, many microrobotic cilia are wired into a 6 × 9 array and then the whole chip is immersed in fluid under an imposed thermal gradient (Fig. 1c). Once switched on, the array pumps fluid from the cooler to the warmer side, inducing thermal advection and locally cooling the leader circuit by around 0.4 °C, enough to slow its own oscillation and settle the whole system into a new, self-consistent steady state. Performance is captured with a thermal advection metric, quantifying how far cilia pumping can displace an imposed isotherm. Although modest in magnitude, the result is conceptually elegant: each unit's sensing, computation and actuation are now coupled in both directions, so that the environment shapes the cilium's behaviour, and the cilium's behaviour reshapes the environment in turn.

The development of a microrobotic cilium that measurably alters the physical field it is reading — and on a chip small enough to be manipulated with a micromanipulator — is an exciting feat. It opens a route towards microscopic systems that behave less like remote-controlled tools and more like simple responsive organisms. This is also achieved without any central controller: each circuit only ever compares itself to a fixed threshold or to its immediate neighbour, and the environment-wide response emerges from many such local, hardwired decisions. This is precisely the kind of decentralized logic that governs collective construction in colonies of social insects.

The demonstrated microrobotic cilia are currently hardwired for one sensing mode at a time and powered externally; the natural next step, as the researchers note, is wireless or optical communication between circuits alongside onboard photovoltaic power, which would allow larger, more autonomous collectives to be built from the same basic unit. The team also suggest a broader sensing repertoire could be possible, including coupling chemical, optical or mechanical sensing. Making the interaction between neighbouring circuits non-reciprocal could also allow more complex, decentralized pattern formation to emerge, closer to the collective morphogenesis seen in termite colonies or bacterial biofilms. With such extensions, the same basic architecture could become a platform for localized chemical delivery, environmental remediation, or steering conditions inside engineered tissue, turning a single microrobotic cilium into a working unit of a genuinely adaptive microscopic machine.

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Competing interests

The author declares no competing interests.