Self-folding origami machines powered by chemical reactions

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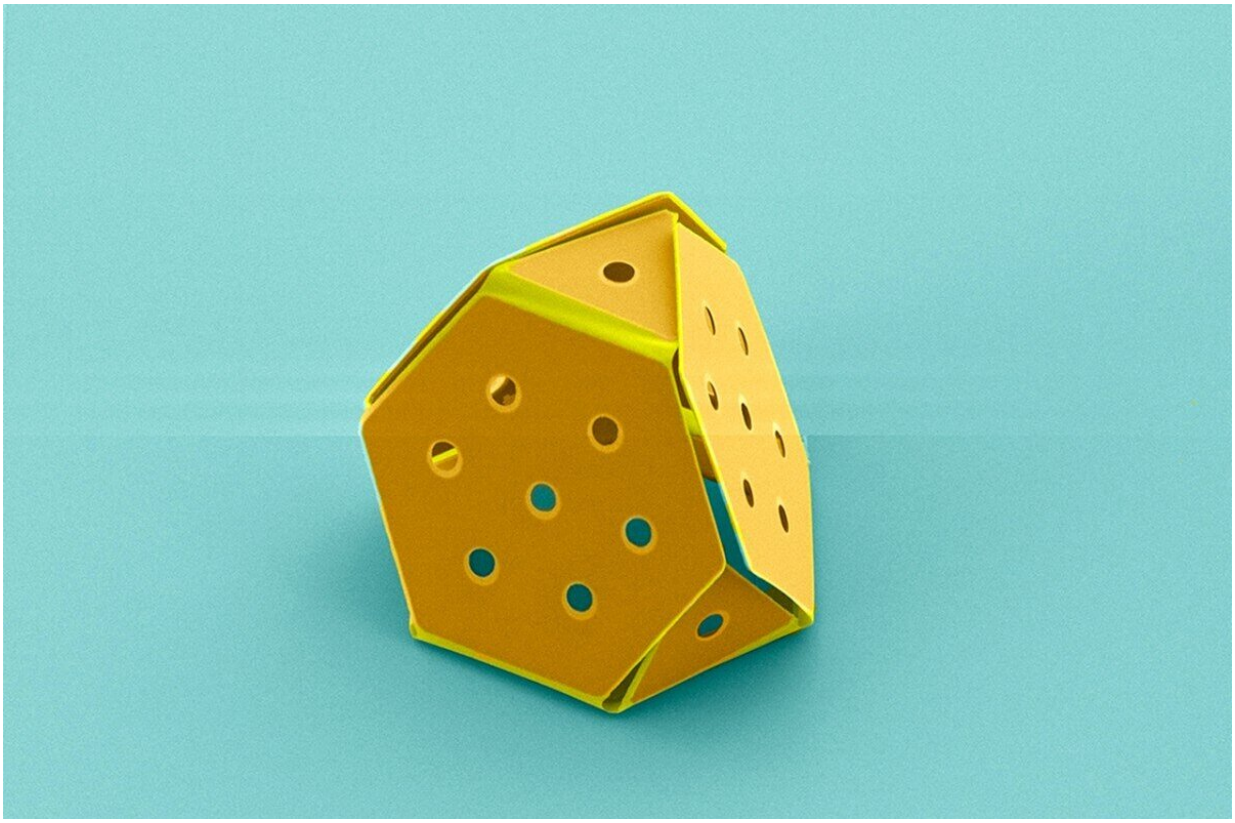

An SEM image shows an origami tetrahedra microstructure that self-folded after it was exposed to hydrogen. Credit: *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2221740120

A Cornell-led collaboration harnessed chemical reactions to make microscale origami machines self-fold—freeing them from the liquids in

which they usually function, so they can operate in dry environments and at room temperature.

The approach could one day lead to the creation of a new fleet of tiny autonomous devices that can rapidly respond to their chemical environment.

The group's paper, "Gas-Phase Microactuation Using Kinetically Controlled Surface States of Ultrathin Catalytic Sheets," published May 1 in *Proceedings of the National Academy of Sciences*. The paper's co-lead authors are Nanqi Bao, Ph.D. '22, and former postdoctoral researcher Qingkun Liu, Ph.D. '22.

The project was led by senior author Nicholas Abbott, a Tisch University Professor in the Robert F. Smith School of Chemical and Biomolecular Engineering in Cornell Engineering, along with Itai Cohen, professor of physics, and Paul McEuen, the John A. Newman Professor of Physical Science, both in the College of Arts and Sciences; and David Muller, the Samuel B. Eckert Professor of Engineering in Cornell Engineering.

"There are quite good technologies for electrical to mechanical energy transduction, such as the electric motor, and the McEuen and Cohen groups have shown a strategy for doing that on the microscale, with their robots," Abbott said. "But if you look for direct chemical to mechanical transductions, actually there are very few options."

Prior efforts depended on chemical reactions that could only occur in extreme conditions, such as at high temperatures of several 100 degrees Celsius, and the reactions were often tediously slow—sometimes as long as 10 minutes—making the approach impractical for everyday technological applications.

However, Abbott's group found a loophole of sorts while reviewing data from a catalysis experiment: a small section of the chemical reaction pathway contained both slow and fast steps.

"If you look at the response of the chemical actuator, it's not that it goes from one state directly to the other state. It actually goes through an excursion into a bent state, a curvature, which is more extreme than either of the two end states," Abbott said. "If you understand the elementary reaction steps in a catalytic pathway, you can go in and sort of surgically extract out the rapid steps. You can operate your chemical actuator around those rapid steps, and just ignore the rest of it."

The researchers needed the right material platform to leverage that rapid kinetic moment, so they turned to McEuen and Cohen, who had worked with Muller to develop ultrathin platinum sheets capped with titanium.

The group also collaborated with theorists, led by professor Manos Mavrikakis at the University of Wisconsin, Madison, who used electronic structure calculations to dissect the chemical reaction that occurs when hydrogen—adsorbed to the material—is exposed to oxygen.

The researchers were then able to exploit the crucial moment that the oxygen quickly strips the hydrogen, causing the atomically thin material to deform and bend, like a hinge.

The system actuates at 600 milliseconds per cycle and can operate at 20 degrees Celsius—i.e., room temperature—in dry environments.

"The result is quite generalizable," Abbott said. "There are a lot of catalytic reactions which have been developed based on all sorts of species. So carbon monoxide, nitrogen oxides, ammonia: they're all candidates to use as fuels for chemically driven actuators."

The team anticipates applying the technique to other catalytic metals, such as palladium and palladium gold alloys. Eventually this work could lead to autonomous material systems in which the controlling circuitry and onboard computation are handled by the material's response—for example, an autonomous chemical system that regulates flows based on chemical composition.

"We are really excited because this work paves the way to microscale origami machines that work in gaseous environments," Cohen said.

More information: Nanqi Bao et al, Gas-phase microactuation using kinetically controlled surface states of ultrathin catalytic sheets, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2221740120

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