# Resilient bug-sized robots keep flying even after wing damage

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The insect-scale aerial robot and its actuators. Credit: Photography and art by Julian Kamzol and Sampson Wilcox

Bumblebees are clumsy fliers. It is estimated that a foraging bee bumps into a flower about once per second, which damages its wings over time. Yet despite having many tiny rips or holes in their wings, bumblebees can still fly.

Aerial robots, on the other hand, are not so resilient. Poke holes in the robot's wing motors or chop off part of its propellor, and odds are pretty good it will be grounded.

Inspired by the hardiness of bumblebees, MIT researchers have developed repair techniques that enable a bug-sized aerial robot to sustain severe damage to the actuators, or artificial muscles, that power its wings—but to still fly effectively.

They optimized these artificial muscles so the robot can better isolate defects and overcome minor damage, like tiny holes in the actuator. In addition, they demonstrated a novel laser repair method that can help the robot recover from severe damage, such as a fire that scorches the device.

Using their techniques, a damaged robot could maintain flight-level performance after one of its artificial muscles was jabbed by 10 needles, and the actuator was still able to operate after a large hole was burnt into it. Their repair methods enabled a robot to keep flying even after the researchers cut off 20% of its wing tip.

This could make swarms of tiny robots better able to perform tasks in tough environments, like conducting a search mission through a collapsing building or dense forest.

"We spent a lot of time understanding the dynamics of soft, artificial muscles and, through both a new fabrication method and a new understanding, we can show a level of resilience to damage that is comparable to insects. We're very excited about this. But the insects are still superior to us, in the sense that they can lose up to 40% of their wing and still fly. We still have some catch-up work to do," says Kevin Chen, the D. Reid Weedon, Jr. Assistant Professor in the Department of Electrical Engineering and Computer Science (EECS), the head of the Soft and Micro Robotics Laboratory in the Research Laboratory of Electronics (RLE), and the senior author of the paper published in *Science Robotics* on these latest advances.

## Robot repair techniques

The tiny, rectangular robots being developed in Chen's lab are about the same size and shape as a microcassette tape, though one robot weighs barely more than a paper clip. Wings on each corner are powered by dielectric elastomer actuators (DEAs), which are soft artificial muscles that use mechanical forces to rapidly flap the wings. These artificial muscles are made from layers of elastomer that are sandwiched between two razor-thin electrodes and then rolled into a squishy tube. When voltage is applied to the DEA, the electrodes squeeze the elastomer, which flaps the wing.

The insect-scale aerial robot and its actuators. Credit: Yi-Hsuan Hsiao

But microscopic imperfections can cause sparks that burn the elastomer and cause the device to fail. About 15 years ago, researchers found they could prevent DEA failures from one tiny defect using a physical phenomenon known as self-clearing. In this process, applying [high voltage](https://techxplore.com/tags/high+voltage/) to the DEA disconnects the local electrode around a small defect, isolating that failure from the rest of the electrode so the artificial muscle still works.

Chen and his collaborators employed this self-clearing process in their robot repair techniques.

First, they optimized the concentration of carbon nanotubes that comprise the electrodes in the DEA. Carbon nanotubes are super-strong but extremely tiny rolls of carbon. Having fewer carbon nanotubes in the electrode improves self-clearing, since it reaches higher temperatures and burns away more easily. But this also reduces the actuator's power density.

"At a certain point, you will not be able to get enough energy out of the system, but we need a lot of energy and power to fly the robot. We had to find the optimal point between these two constraints—optimize the self-clearing property under the constraint that we still want the robot to fly," Chen says.

However, even an optimized DEA will fail if it suffers from severe damage, like a large hole that lets too much air into the device.

Credit: Suhan Kim, Yufeng Chen

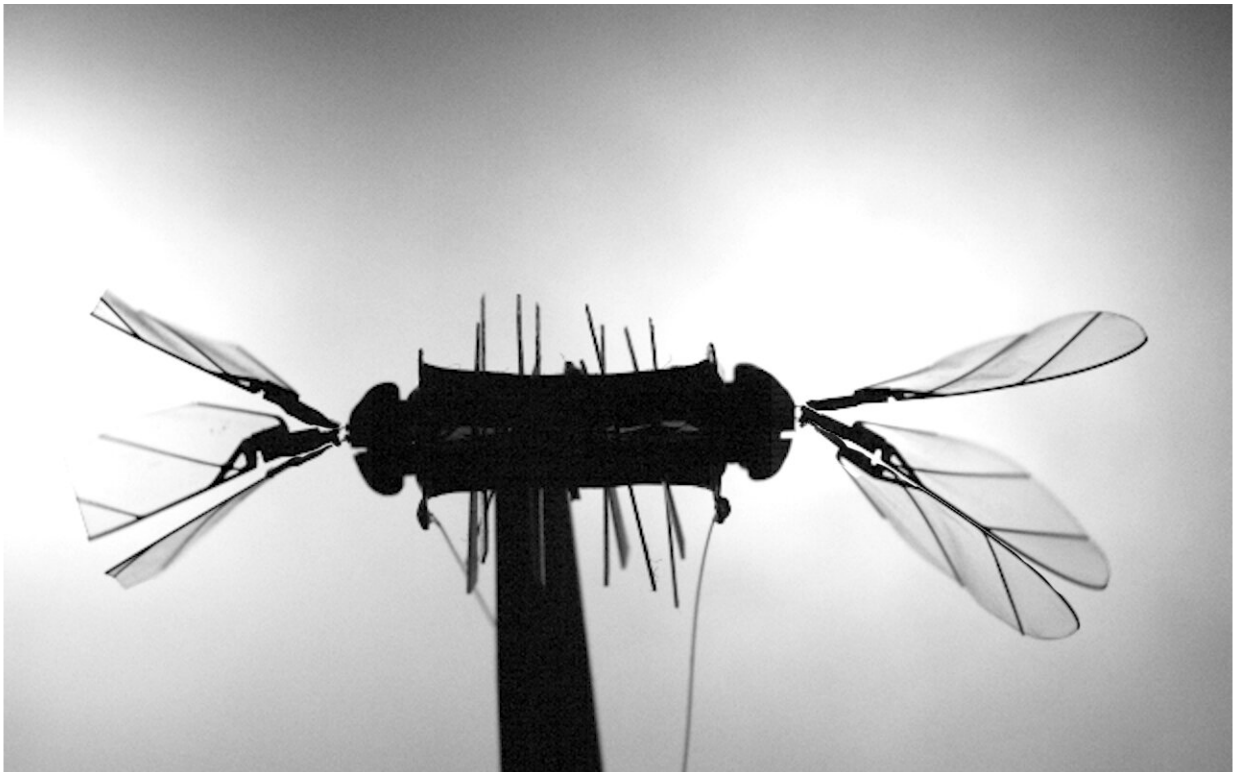
Chen and his team used a laser to overcome major defects. They carefully cut along the outer contours of a large defect with a laser, which causes minor damage around the perimeter. Then, they can use self-clearing to burn off the slightly damaged electrode, isolating the larger defect.

"In a way, we are trying to do surgery on muscles. But if we don't use enough power, then we can't do enough damage to isolate the defect. On the other hand, if we use too much power, the laser will cause severe damage to the actuator that won't be clearable," Chen says.

The team soon realized that, when "operating" on such tiny devices, it is very difficult to observe the electrode to see if they had successfully isolated a defect. Drawing on previous work, they incorporated electroluminescent particles into the actuator. Now, if they see light shining, they know that part of the actuator is operational, but dark patches mean they successfully isolated those areas.

## Flight test success

Once they had perfected their techniques, the researchers conducted tests with damaged actuators—some had been jabbed by many needles while other had holes burned into them. They measured how well the robot performed in flapping wing, take-off, and hovering experiments.



Credit: Suhan Kim, Yufeng Chen

Even with damaged DEAs, the repair techniques enabled the robot to maintain its flight performance, with altitude, position, and attitude errors that deviated only very slightly from those of an undamaged robot. With laser surgery, a DEA that would have been broken beyond repair was able to recover 87 percent of its performance.

"I have to hand it to my two students, who did a lot of hard work when they were flying the robot. Flying the robot by itself is very hard, not to mention now that we are intentionally damaging it," Chen says.

These repair techniques make the tiny robots much more robust, so Chen and his team are now working on teaching them new functions, like landing on flowers or flying in a swarm. They are also developing new control algorithms so the robots can fly better, teaching the robots to control their yaw angle so they can keep a constant heading, and enabling the robots to carry a tiny circuit, with the longer-term goal of carrying its own power source.

**More information:** Suhan Kim et al, Laser-assisted failure recovery for dielectric elastomer actuators in aerial robots, *Science Robotics* (2023). DOI: 10.1126/scirobotics.adf4278. www.science.org/doi/10.1126/scirobotics.adf4278

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