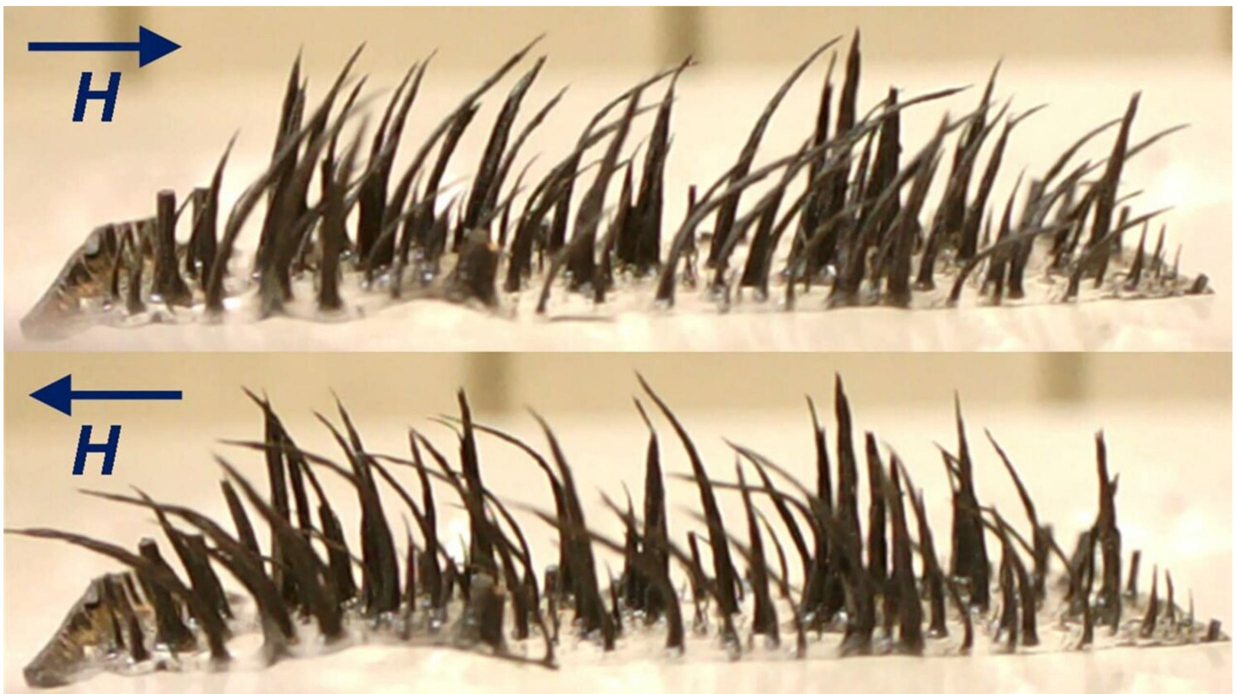
Researchers show it's possible to teach old magnetic cilia new tricks

April 24 2024, by Matt Shipman



Bending of NdFeB-based magnetic cilia magnetized pointing up in horizontal magnetic fields. Credit: Matthew R. Clary.

Magnetic cilia—artificial hairs whose movement is powered by embedded magnetic particles—have been around for a while, and are of interest for applications in soft robotics, transporting objects and mixing liquids. However, existing magnetic cilia move in a fixed way.

Researchers have now demonstrated a technique for creating magnetic cilia that can be "reprogrammed," changing their magnetic properties at room temperature to change the motion of the cilia as needed.

Most magnetic cilia make use of "soft" magnets, which do not generate a magnetic field but become magnetic in the presence of a magnetic field. Only a few previous magnetic cilia have made use of 'hard' magnets, which are capable of producing their own magnetic field.

One of the advantages of using hard magnets is that they can be programmed, meaning that you can give the magnetic field generated by the material a specific polarization. Controlling the magnetic polarization—or magnetization—allows you to essentially dictate precisely how the cilia will flex when an external magnetic field is applied.

"What's novel about this work, is that we have demonstrated a technique that allows us to not only program magnetic cilia, but also controllably reprogram them," says Joe Tracy, corresponding author of a paper on the work and professor of materials science and engineering at North Carolina State University.

"We can change the direction of the material's magnetization at room temperature, which in turn allows us to completely change how the cilia flex. It's like getting a swimmer to change their stroke."

For this work, the researchers created magnetic cilia consisting of a polymer embedded with magnetic microparticles. Specifically, the microparticles are neodymium magnets—powerful magnets made of neodymium, iron and boron. The paper, "Magnetic Reprogramming of Self-Assembled Hard-Magnetic Cilia," is published in the journal *Advanced Materials Technologies*.

To make the cilia, the researchers introduce the magnetic microparticles into a polymer dissolved in a liquid. This slurry is then exposed to an electromagnetic field that is sufficiently powerful to give all of the microparticles the same magnetization.

By then applying a less powerful magnetic field as the liquid polymer dries, the researchers are able to control the behavior of the microparticles, resulting in the formation of cilia that are regularly spaced across the substrate.

"This regularly ordered cilia carpet is initially programmed to behave in a uniform way when exposed to an external magnetic field," Tracy says. "But what's really interesting here, is that we can reprogram that behavior, so that the cilia can be repurposed to have a completely different actuation."

To do that, the researchers first embed the cilia in ice, which fixes all of the cilia in the desired direction. The researchers then expose the cilia to a damped, alternating magnetic field which has the effect of disordering the magnetization of the microparticles. In other words, they substantially erase the preprogrammed magnetization that was shared by all of the microparticles when the cilia were fabricated.

"The reprogramming step is fairly straightforward," Tracy says. "We apply an oscillating field to reset the magnetization, then apply a strong magnetic field to the cilia which allows us to magnetize the microparticles in a new direction."

"By mostly erasing the initial magnetization, we're better able to reprogram the magnetization of the microparticles," says Matt Clary, first author of the paper and a Ph.D. student at NC State. "We show in this work that if you leave out that erasing step you have less control over the orientation of the microparticles' magnetization when reprogramming."

"We also found that when the magnetization of the microparticles is perpendicular to the long axis of the cilia, we can cause the cilia to 'snap' in a rotating field, meaning they abruptly change their orientation," says Tracy.

In addition, the research team developed a computational model that allows users to predict the bending behavior of magnetic cilia based on hard magnets, depending on the orientation of the cilia's polarization.

"This model could be used in the future to guide the design of hard-magnetic cilia and related soft actuators," says Ben Evans, co-author of the paper and professor of physics at Elon University.

"Ultimately, we think this work is valuable to the field because it allows repurposing of magnetic cilia for new functions or applications, especially in remote environments," Tracy says. "Methods developed in this work may also be applied to the broader field of magnetic soft actuators."

The paper was co-authored by Saarah Cantu, a former graduate student at NC State; and Jessica Liu, a former Ph.D. student at NC State.

More information: Matthew R. Clary et al, Magnetic Reprogramming of Self-Assembled Hard-Magnetic Cilia, *Advanced Materials Technologies* (2024). DOI: 10.1002/admt.202302243

Provided by North Carolina State University

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