Magnetic Microdisks Don't Always Reciprocate

A model system of floating disks can be tuned to execute a variety of behaviors by controlling the interactions between the disks.

By **David Ehrenstein**

Bird flocks and fish schools are examples of the large-scale order that can result from individual interactions between pairs of entities that are part of a large group. To study the effects of these pairwise forces on the large-scale patterns, researchers have now demonstrated a model system where the interactions can be switched between two types: either reciprocal—the force on A by B is equal and opposite to the force on B by A—or nonreciprocal [**1**]. This control over the interactions led to a variety of surprising effects that the researchers say may be useful for developing future microrobot swarms.

Gaurav Gardi and Metin Sitti of the Max Planck Institute for Intelligent Systems in Germany have previously created 300-µm-wide magnetic disks that float on water [**2**]. Each disk has six corrugations around the edge that cause neighboring disks to attract one another through the capillary effect when their corrugations are aligned. The disks also have permanent magnetic moments, so they act like compass needles and try to align with any external magnetic field.

As the duo has shown previously, the microdisks spin in an oscillating external magnetic field, and they interact through three forces: magnetic (they try to align with each other), capillary (they can be attracted or repelled through liquid surface forces), and hydrodynamic (their spinning stirs the fluid and pushes neighbors away) [**2**]. Now the researchers have demonstrated two ways to make the pairwise forces nonreciprocal.

In one scenario, two identical disks subjected to an oscillating magnetic field either rotate in the same direction or in opposite directions, by random chance. When the disks rotate in the same direction, their interaction is reciprocal, and the pair orbit one another. But when they rotate in opposite directions, the net force on each is in the same direction, so the pair travels across the liquid surface rather than staying in place.

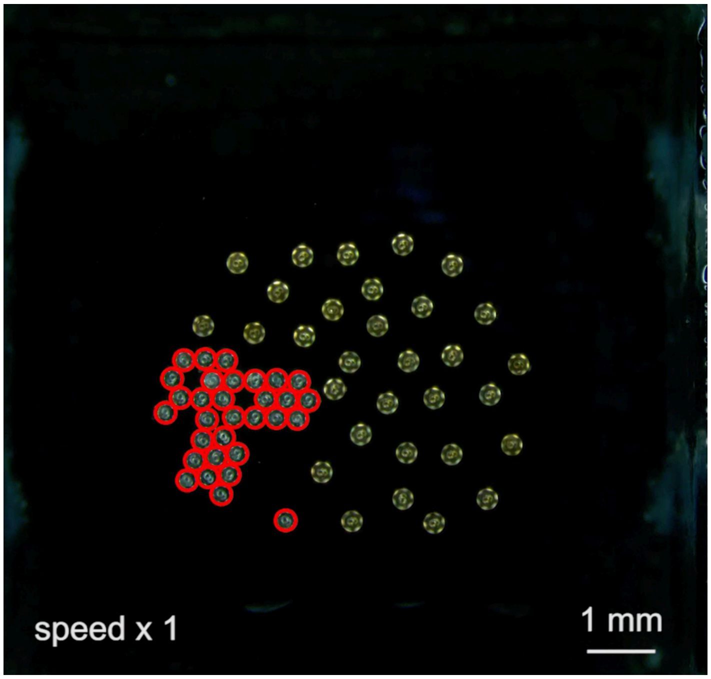
The researchers created another nonreciprocal scenario with a field whose direction oscillated over a range of 90°, which they applied to two disks with different magnetic moments. The pair also moved across the water but by a different mechanism and could be steered by appropriately directing the field.

Gardi and Sitti explored a range of behaviors of a large group of disks having two different magnetic moments by using a range of field oscillation frequencies and protocols. For example, they could cause the two sets of disks to segregate, with only the low-magnetic-moment disks aggregating into a dense cluster. And they could cause small "mixed" groups of disks to move away in all directions. The researchers believe that developing this type of control over a repertoire of microdisk behaviors could benefit research on microrobot swarms. These tiny machines have little room for "onboard" computation, so the new techniques could help researchers design complex operations that could be centrally controlled.

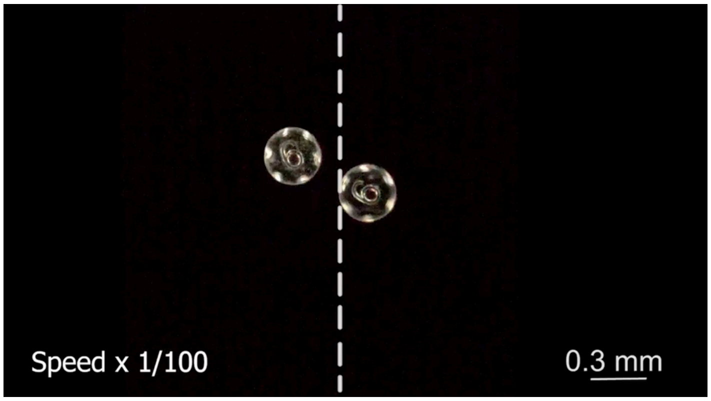
David Ehrenstein is a Senior Editor for ***Physics Magazine***.

REFERENCES

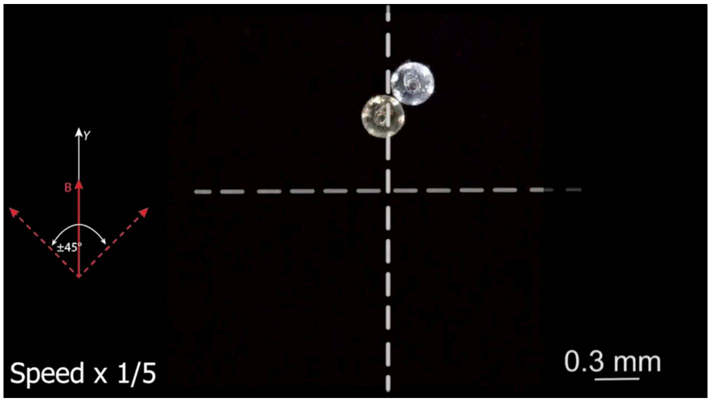
1. G. Gardi and M. Sitti, "On-demand breaking of action-reaction reciprocity between magnetic microdisks using global stimuli," **Phys. Rev. Lett. 131, 058301 (2023).**
2. G. Gardi *et al.*, "Microrobot collectives with reconfigurable morphologies, behaviors, and functions," **Nat. Commun. 13, 2239 (2022).**



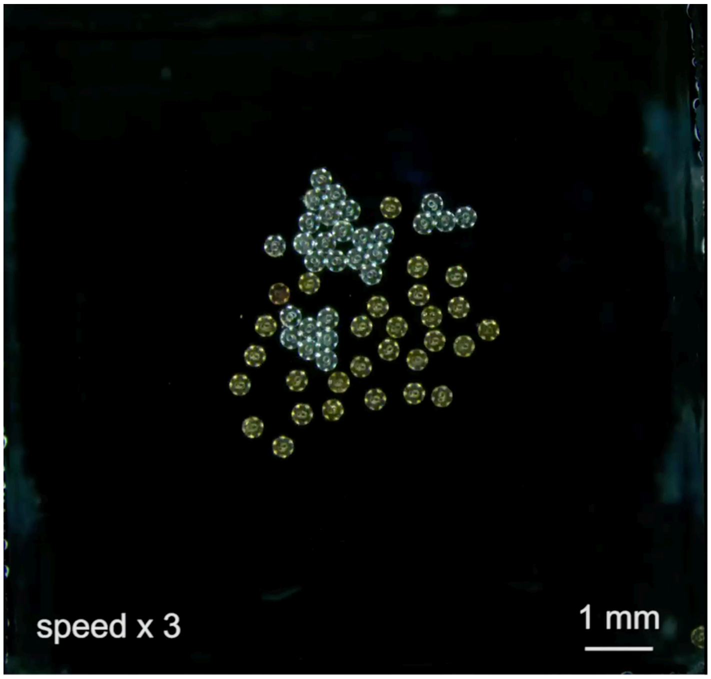
A magnetic field rotating at 30 Hz causes the low-magnetic-moment disks (inside red rings) to aggregate into a cluster, while the high-magnetic-moment disks remain more sparse. The low-moment disks experience a weaker torque from the field and cannot keep up with the rotations at this frequency, given that there is fluid friction. This reduced rotation lowers their hydrodynamic repulsion and allows them to attract one another through capillary forces. (See additional videos below.)
Credit: G. Gardi and M. Sitti [1]



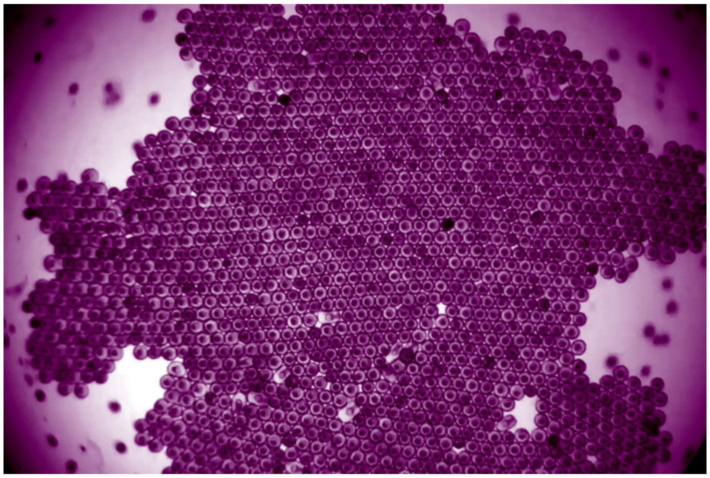
In a magnetic field oscillating between pointing rightward and pointing leftward, two identical disks either move across the surface if they are rotating in opposite directions or orbit one another in place if they are rotating in the same direction. (Here the magnetic field oscillates at 30 Hz.)
Credit: G. Gardi and M. Sitti [1]



When the field direction oscillates over a range of 90° and two disks have sufficiently different magnetic moments, they will move together in the direction of the average field. Partway through this video, the average field direction changes from upward to leftward. The low-magnetic-moment disk experiences a weaker torque from the field, so its rotation lags behind the other disk, which leads to a wavy motion of the pair that propels the disks, much like an undulating fish. (Here the magnetic field oscillates at 10 Hz.)
Credit: G. Gardi and M. Sitti [1]



Here the field proceeds through several configurations that keep the low-magnetic-moment disks (gray) densely clustered, while the high-magnetic-moment disks (gold) demonstrate various behaviors (rotation, remaining still, oscillation, and a gas-like mode). At the start, the field rotates at 15 Hz. Then it switches to a 10-Hz oscillation along the horizontal axis. Finally, it changes to two successive protocols where it oscillates along both vertical and horizontal axes but with different *x* and *y* frequencies.
Credit: G. Gardi and M. Sitti [1]



Living crystal. Starfish embryos are 200-μm-wide spinning spheres that naturally form this crystal-like structure at the water's surface. It exhibits unusual elastic properties based on nonreciprocal interactions among the embryos.
Credit: Nikta Fakhri/MIT (CC BY-NC-ND)