Programmable matter

Ara N. Knaian

A new kind of electric motor is the cornerstone of a chain that can bend itself into multiple shapes.

Ara Knaian is a visiting scientist at the Massachusetts Institute of Technology's Center for Bits and Atoms and a principal engineer at NK Labs, both in Cambridge.

Imagine you had a bag of tiny, programmable robotic modules that could sense their neighbors and move as directed. After running the appropriate program, you could reach into the bag and pull out a wrench, a coffee cup, or whatever else you wanted. Then, when you were done, you could put the modules back in the bag and command them to re-form into the next thing you needed.

Thanks to the semiconductor industry, it's easy enough to make the tiny computing elements needed to realize that vision; but scientists and engineers need to work out a host of other technological problems. How would the modules get power? How would they communicate? How would they exert forces on each other and the outside world? How could we make them strong, durable, and cheap enough to be useful? And how could we ensure that the system keeps operating in the inevitable case that a few of the modules become damaged?

Research groups worldwide are exploring many design possibilities for programmable matter. They include cubes and cylinders that roll over one another, sheets that fold themselves into origami-like shapes, and blocks that manage their self-assembly by controlling liquid flows.

Two years ago my colleagues at MIT and I constructed a different kind of prototype of programmable matter: a four-link chain that can bend itself into a variety of shapes. The idea of chains folding into shapes is not new; such folding happens in our own bodies when chains of amino acids assemble into proteins. But our chain can bend into several different shapes on command. If it were long enough, it could in principle fold itself into a digitized approximation of any shape. (The first of the additional resources gives the mathematics behind that assertion.)

We call our device the milli-motein, short for millimeter-scale motorized mechanical protein. It consists of a chain of interlocked motors, wrapped with a flexible electronic circuit for power and control. The center-to-center spacing of the modules, or nodes, is just 1 cm. To keep our nodes mechanically simple, we decided not to use any gearing. In addition to its mechanical elements, each node has a magnetic sensor to measure its joint angle, a motor drive circuit, and an eight-bit microcontroller.

A new kind of electric motor

Early in the design process, we looked for an off-the-shelf motor that could rotate a node and generate enough torque (2 N·mm) to lift at least one other cantilevered module. But we couldn't find any that would produce the needed torque and satisfy our space requirements that the motor thickness be no more than 2 mm and the diameter no more than 10 mm.

Miniaturization is a wonderful thing, but it's not always possible to make an object small and keep its other desirable properties. Electric motors, in particular, get much weaker as they are scaled down in size. The problem is that as the motor's windings are scaled down, the electrical resistance of those windings increases and the length of the moment arm from the magnets to the shaft decreases; as a result, small motors dissipate a lot of power when loaded with a large torque.

To better appreciate the problem, imagine you were to replace a large motor with 1000 smaller motors, each scaled down by a factor of 10 in length and therefore by a factor of 1000 in volume. To make a fair comparison between the original large motor and the smaller replicas, you might connect all 1001 motors to the same long shaft and then drive the 1 large motor forward and all 1000 small motors backward for a game of rotary tug of war. With all the small motors stalled against the large one, the small motors together would dissipate 100 times more heat. Indeed, to prove that result, at least for DC motors consisting of a square coil that rotates in a uniform magnetic field, all you need is the Lorentz force law and Ohm's law.

Permanent-magnet electric motors may not scale in a way our group would have liked, but permanent magnets themselves do. If you take a permanent magnet, shrink its dimensions by a factor of 10 and also shrink the air gap it has to work over by a factor of 10, you only need 100 magnets to equal the lifting capacity of the larger one.

Wrestling with the dichotomy between the useful scaling of permanent magnets and the problematic scaling of the conventional motors made from them, I wondered if a permanent magnet could be turned on and off. If so, you could build a motor entirely from them. Such a motor wouldn't

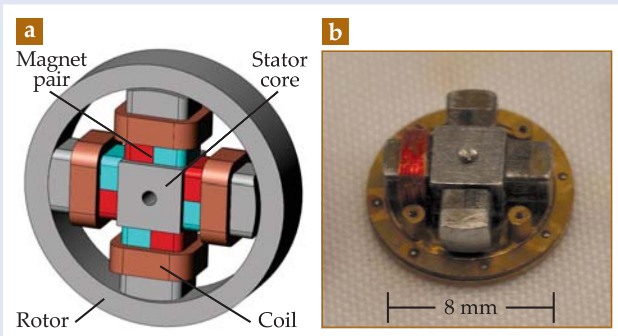

Figure 1. Tiny torquers. Electropermanent magnets power the milli-motein, a prototype form of programmable matter. The miniature motor produces ample torque without dissipating much heat, and it holds its position with the power off. **(a)** This schematic shows the key elements of the motor. **(b)** In this photograph, one coil is visible to the left.

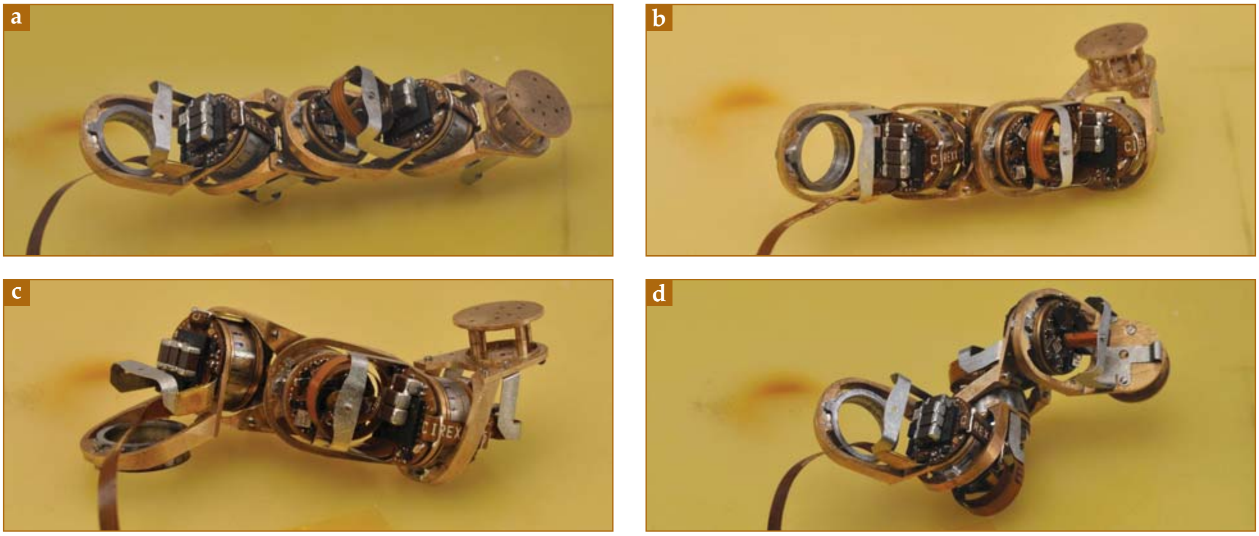

Figure 2. Shape shifting. The milli-motein is a four-segment chain of electropermanent motors, enveloped by a flexible circuit that conveys power and programming instructions; chain segments are separated by 1 cm. The milli-motein can fold itself into several shapes, including **(a)** a straight line, **(b)** an L, **(c)** a periscope, and **(d)** a helix.

need any power when stalled, and it therefore might be scalable to small dimensions.

It turns out that such switchable permanent magnets were already being used in industry, where they are called electropermanent magnets. In steel mills, for example, they move loads weighing many tons. Electropermanent magnets are turned on and off with a momentary pulse of current. You can make one by wrapping a conducting coil around two rods of magnetic material that differ in their magnetic hardness—that is, they differ in their resistance to having their magnetization flipped by a circulating current. A strong current pulse in one direction aligns the fields of the two materials in the same direction; the device is switched on. A reversed pulse with an appropriate magnitude flips the field of the softer material but leaves the field of the harder material unchanged. The two magnets cancel each other and the device is off.

Figure 1 shows our electropermanent motor. At any one time, two adjacent paired magnets, each a red–blue combination in the figure, are on and the other two are off. As we execute a cyclic sequence of turning the magnets on and off, the outer ring (rotor) rolls around the surface of the inner cross (stator). After each cycle, the ring has displaced a small amount; after many cycles, it rotates all the way around.

The torque of an electropermanent motor such as ours scales with the cube of length, as does the torque of an ordinary permanent-magnet DC motor. Thus, since the power required to switch magnet states from on to off and back is proportional to the magnet's volume, there's no penalty in additional power consumption for scaling the motor to small dimensions. Moreover, when our motor is stalled, it doesn't draw any current, so the motor can hold a load without producing excess heat and the charred insulation with which we had become all too familiar.

The shape of things to come

The heart of our prototype programmable matter chain is a series of electropermanent motors connected with metal brackets. For it to form a shape, each of the modules needs to do one of three specific things: bend to the left, bend to the right, or face straight ahead. When the milli-motein is in operation, a host computer conveys folding instructions to the microprocessor on the first link, which forwards the instructions down the chain. Each node can actively lift the weight of one neighboring node and can hold the weight of three modules with the power turned off. As figure 2 shows, even a four-link chain can fold itself into a variety of configurations.

The electronic components were available off the shelf, and the mechanical parts could be fabricated relatively easily with conventional and electric-discharge machining. But the fragility and small size of the milli-motein's parts made assembly a time-consuming process. We had to use tweezers and view everything through a microscope. In the end, it took months of bench work—which included dealing with the cascading effects of blown chips, heat-damaged magnets, shorting coils, and stripped screws—for us to put together a fully functional chain of four units.

Our milli-motein is programmable matter, but it is not yet inexpensive enough, durable enough, or strong enough to be useful for a broad range of applications. Programmable matter may eventually become as commonplace and useful as the programmable computer; but before that happens, many more technological breakthroughs will be required.

The electropermanent motor itself will see action much sooner. We are working with industrial partners to explore applications that are well served by the motor's ability to deliver lots of torque in a small package and to hold its position without power. Such applications include steering solar-array mirrors, angling the tip of endoscopes that view inside the body, and moving horizontal stabilizer fins on aircraft.

Additional resources

▶ K. C. Cheung et al., "Programmable assembly with universally foldable strings (moteins)," *IEEE Trans. Rob.* **27**, 718 (2011).

▶ A. N. Knaian et al., "The milli-motein: A self-folding chain of programmable matter with a one centimeter module pitch," paper presented at the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, 7–12 October 2012; available at http://cba.mit.edu/docs/papers/12.10.IROS.pdf. ■