Sequence-encoded colloidal origami and microbot assemblies from patchy magnetic cubes

Koohee Han,1,2 C. Wyatt Shields IV,2,3 Nidhi M. Diwakar,2 Bhuvnesh Bharti,1,2* Gabriel P. López,2,3,4† Orlin D. Velev1,2*

Colloidal-scale assemblies that reconfigure on demand may serve as the next generation of soft “microbots,” artificial muscles, and other biomimetic devices. This requires the precise arrangement of particles into structures that are preprogrammed to reversibly change shape when actuated by external fields. The design and making of colloidal-scale assemblies with encoded directional particle-particle interactions remain a major challenge. We show how assemblies of metalloelectric patchy microcubes can be engineered to store energy through magnetic polarization and release it on demand by microscale reconfiguration. The dynamic pattern of folding and reconfiguration of the chain-like assemblies can be encoded in the sequence of the cube orientation. The residual polarization of the metallic facets on the microcubes leads to local interactions between the neighboring particles, which is directed by the conformational restrictions of their shape after harvesting energy from external magnetic fields. These structures can also be directionally moved, steered, and maneuvered by global forces from external magnetic fields. We illustrate these capabilities by examples of assemblies of specific sequences that can be actuated, reoriented, and spatially maneuvered to perform microscale operations such as capturing and transporting live cells, acting as prototypes of microbots, micromixers, and other active microstructures.

INTRODUCTION

Miniaturized and soft robotic devices for biological micromanipulation, cell-level diagnosis, drug delivery, and microsurgery are typically made by reductive (“top-down”) microfabrication (1–6) but could be made much more efficiently by microscale self-assembly (7, 8). Assemblies of colloidal particles with well-defined shape, orientation, and response to external stimulation can form the basis of simple responsive materials (9–19), yet enduring them with more complex functionality has been challenging (7, 8). The primary challenges in realizing these active structures include the remote supply of energy, control over their response, and directional translocation (20, 21). One way to overcome these challenges is to make assemblies from colloidal particles with tailored form factors and surface polarizabilities (22–26). We have previously shown that anisotropically shaped metallic patchy particles can acquire complex polarization patterns in electric and magnetic fields, leading to multidirectional interactions and to the formation of assemblies of unusual structure and symmetry (27). Here, we describe and analyze the emergent, sequence-specific, self-reconfiguration dynamics in supracolloidal assemblies of cube-shaped particles with one metal-coated facet.

RESULTS AND DISCUSSION

Magnetic field assembly and actuation of multicube clusters

We applied intermittent external magnetic fields to drive the assembly of patchy microcubes of edge length ~10 μm, where one face of the microcube is selectively coated with 100 nm of cobalt (Co) metal (see Materials and Methods). When a uniform magnetic field of 0.1 to 10 kA/m is generated (for example, by a collinear pair of electromagnets, as shown in Fig. 1A) and applied across a chamber containing an aqueous suspension of randomly dispersed microcubes, the magnetic patch on each cube acquires a dipole leading to long-range attraction between the cubes, and chain assembly (see the Supplementary Materials for more details on the assembly process with statistical analysis). The magnetized microcubes assemble into stretched chain configurations oriented along the direction of the applied magnetic field (27), as shown in Fig. 1 (B and C). The organization in chains is the result of the dipole-dipole attraction between the magnetic patches on the microcubes (27, 28). The role of the magnetic coating as a structural director of the chains is confirmed through imaging with energy-dispersive spectroscopy (EDS; fig. S1). The ferromagnetic nature of the Co patches (fig. S3) allows for the storage of magnetic energy to locally guide the particle-particle interactions in the absence of an applied magnetic field for reconfiguration (Fig. 1D) while conserving the overall sequence of cubes within the assembly.

The focus of this report is the unusual dynamic rearrangement of the assembled chains of microcubes into partially wrapped and bundled states every time the field is toggled on or off. One example of such dynamics is shown in Fig. 1 (C and D) and movie S1. This phenomenon originates from the change in configurational energy of the assembled chain, which can be divided into two major components: (i) dipole-field and (ii) dipole-dipole interaction energies. The dipole-field interaction predominates in the presence of the external field, which extends the dipolar chain into a stretched linear configuration (Fig. 1C). Upon eliminating this field, the quasi-equilibrium configuration is governed by the residual dipole-dipole interaction energies, resulting in a collapsed, self-folded structure (Fig. 1D). As we explain in detail below, the pattern of this rearrangement is determined by the sequence of the patchy cubes with coated sides facing in the same or opposite direction along the chain (analogically to “cis/trans” orientations).

To understand the driving forces and control the self-reconfiguration of patchy microcube chains, we first analyze the interactions between microcube doublets. The two basic sequence units attained by a doublet are shown in Fig. 1E. We refer to the sequence as AB when the cube body
Field-triggered dynamic reconfiguration of multicube clusters

Two key examples of dynamic reconfiguration are revealed by “isomeric” clusters of four microcubes, whose sequence encodes distinct field-triggered reconfiguration patterns (Fig. 3A). The ABBA assembly forms a cyclic configuration that opens and closes on demand, whereas the BBAA cluster symmetrically wraps and unwraps (movies S3). The dynamic paths of self-folding and field-driven unfolding are repeated with remarkable dexterity (that is, over 20 or more field-on and field-off duty cycles; fig. S5). The rate of self-folding can be tuned by the magnitude of the applied external magnetic field. For an ABBA sequence, for example, the folding rate is proportional to |H|^2, where |H| is the strength of initially applied magnetic field (Fig. 3B). These
dependencies are typical for second-order field-induced interactions and dynamics (31).

**Examples of microbots and colloidal origami with sequence-encoded function**

The reversible, sequence-dependent, reconfiguration described above is actuated by a uniform magnetic field. A further level of control over the dynamics of these assemblies can be achieved by superimposing a magnetic field gradient ($\nabla H\rightarrow$) that can remotely translocate the assemblies. By combining the uniform field-triggered reversible actuation with field gradient–driven spatial navigation, we illustrate how a micro-cube assembly with a BABBAB sequence can form a prototype of a microbot that can manipulate single live cells. Snapshots of this microbot grabbing, transporting, and releasing a target yeast cell are shown in Fig. 4 (A to E) and movie S4. The microbot cluster is transported to the target location in its open configuration (Fig. 4A) by the application of a traversal uniform magnetic field with an imposed additional longitudinal gradient (by turning on all three coils 1, 2, and 3 in Fig. 1A). In the subsequent step, the transverse magnetic field is removed, resulting into chain self-folding into the closed state. Thus, the cluster acts as a “micro-tweezer” and captures the target yeast cell. The cell is then transported in two-dimensional space by tuning the magnitude and direction of the applied magnetic field gradient (Fig. 4, C and D). Upon reaching a target location, the yeast cell is released by activating the uniform magnetic field (Fig. 4E).

To verify and illustrate the origin of the dynamics of these assemblies, we simulated the different scenarios of field interaction with a BABBAB microbot using the COMSOL Multiphysics software package (Fig. 4, F to J). For simplicity, the calculations were carried out in two dimensions, where the three-dimensional microcube was represented as a square and the magnetic plane as a rectangular patch on one of its sides (see Materials and Methods). The calculated field distribution, plotted by color coding, elucidates the migration of the chain structure in the direction of positive magnetic field gradient (Fig. 4, F and H). This analysis confirms the role of the applied uniform magnetic field in unfolding the chain (Fig. 4, G and J) and shows that the reconfiguration of the microbot in the absence of external field is driven by strong
cluster-localized magnetic interactions (as shown by the location of the high field intensity areas in Fig. 4, I and H).

The BABBAB "microbot" is one of many possible examples of small, reversibly actuatable clusters. One route to programmed assembly of these structures is magnetic rotation of the assemblies and sequential addition of single cubes to their chains. This directed addition can be achieved via magnetic torque by modulating the external field characteristics (for example, the direction and strength of the field; see figs. S5 and S6 and movies S5 and S6 for more details). In a more scalable and parallelized fabrication of these structures, an underlying template may allow the assembly of preprogramed sequences by directing the cubes onto patterned micromagnets (32). A larger-scale application of longer "origami" chains could involve embedding reversibly collapsible chains within flexible matrices for making responsive materials that can be expanded, contracted, or folded by magnetic fields. We present one example of these reconfigurable multicube chains as an example of programmable colloidal origami. Scale bars, 20 μm (A and K).

CONCLUSIONS

We demonstrate how microcubes with one metal-coated side can be assembled into structures that store and release magnetic energy when the steric constraints of their cubic building blocks guide their residual magnetic interactions. These assemblies attain various equilibrium and nonequilibrium states, depending on the sequence of the microcubes, which make it possible to program their self-folding and wrapping patterns. Field-manipulated microbot clusters with sequence-determined folding pattern and function (Fig. 4) may find utility in soft robotics, microsurgery, biological separation, and bioinspired colloidal origami (33). In addition to biological manipulations on the microscale, these assemblies can be used to locally probe and interact with their microenvironment. Preliminary studies not reported here show that reversible self-reconfiguration of specific microcube chains could lead to new classes of "active" microswimmers and novel microrheometers for non-Newtonian or biological media. Because the engineered metallic patches provide a foundation for effective magnetic energy storage, the principles of this simple platform actuator can be extended to more advanced, hierarchical structures by using more complex particle shapes, compositions, and field parameters to address a broad range of applications, from robotics and micromanipulation to responsive materials and on-demand reconfigurable structures.

MATERIALS AND METHODS

Sample preparation

One-side coated patchy microcubes, composed of polymer and thin cobalt (Co) films deposited along one of the six facets, were fabricated using standard photolithography and metal deposition techniques (27). SU-8 10 photoresist (MicroChem) was spin-coated on a 3-inch single-side polished silicon (Si) wafer (Addison Engineering Inc.) and exposed to ultraviolet (UV) light (365 nm, MA/BA6 mask aligner, SÜSS MicroTec AG) through a chrome-patterned photomask (consisting of an array of 10-μm transparent squares with a 20-μm pitch; Photo Sciences Inc.) to form the microcubes, which were revealed after development of the photoresist (following the procedures by MicroChem). Note that the fabricated microcubes can sometimes display slightly
rounded edges due to the resolution of chrome-printed photomask or due to the inadequate exposure of UV light through the photomask. The wafer was then mounted inside of an electron beam metal evaporator (Solution E-Beam, CHA Industries) to allow for the deposition of 10 nm of Cr followed by 100 nm of Co on the topside of the wafer. The patchy microcubes were then harvested from the wafer by the application of shear forces from a rubber scraper and dispersed in Milli-Q water, containing 0.1 volume % Tween 20 (Sigma-Aldrich).

Experimental setup
A 30-μl solution of the patchy microcubes was placed into the assembly chamber (Fig. 1A), where a hydrophobic ring secured a 20- to 30-μm gap between a glass slide and a coverslip. A collinear pair of electromagnets (1 and 2) placed on either side of the assembly chamber generated a uniform magnetic field in the range of 0.1 to 10 kA/m, and a single electromagnet (3) placed on the bottom side of the assembly chamber generated a magnetic field gradient in the range of 1 to 100 kA/m², as measured by a gauss meter (GM2, AlphaLab Inc.). The assembly chamber was housed on the table of an optical microscope (BX61, Olympus) to enable the observation of the field-directed assembly and manipulation of patchy microcubes. Videos were taken using a charge-coupled device camera (DP70, Olympus) at 15 frames per second. The videos were analyzed in ImageJ (National Institutes of Health) to measure the interdipolar angle between metallic facets on adjacent particles within an assembly.

**COMSOL Multiphysics simulation**
Magnetostatic calculations were performed using the AC/DC module of COMSOL Multiphysics modeling software (COMSOL Inc.) to investigate the local magnetic field distribution around an assembled chain of patchy microcubes under various configurations. The magnetic permeability of the Co coating (1.1676 × 10⁻¹¹ H/m), the SU-8 polymer (1.257 × 10⁻⁶ H/m), and the surrounding water medium (1.257 × 10⁻⁶ H/m) were incorporated into the model, where the SU-8 unit for electrical inductance. The geometry of the system was confined to a two-dimensional area (200 μm × 200 μm) with an extremely fine triangular mesh at the center of the assembly chamber. The simulations were performed by solving Maxwell’s equations with a fully coupled linear solver.

**SUPPLEMENTARY MATERIALS**
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/e1701108/DC1

**REFERENCES AND NOTES**
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