Self-assembling fluidic machines

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This letter describes dynamic self-assembly of two-component rotors floating at the interface between liquid and air into simple, reconfigurable mechanical systems (''machines''). The rotors are powered by an external, rotating magnetic field, and their positions within the interface are controlled by: (i) repulsive hydrodynamic interactions between them and (ii) by localized magnetic fields produced by an array of small electromagnets located below the plane of the interface. The mechanical functions of the machines depend on the spatiotemporal sequence of activation of the electromagnets. [DOI: 10.1063/1.1664019]

Dynamic self-assembly[1–4]—that is, self-assembly in nonequilibrium systems[5,6] that organize only when dissipating energy—is a promising route to ordered structures that could convert a portion of the energy delivered to them externally into useful mechanical work. Such systems could serve as mechanical devices that could be reconfigured by, for example, changes in an external flux of energy. In this work, we describe the design and operation of simple mechanical systems (''machines'') whose components self-assemble at the interface between liquid and air under the influence of two external magnetic fields: one the field produced by a large, permanent magnet rotating with constant angular velocity ω ($\sim$500–1000 rpm), and the second the field produced by an array of small electromagnets. Power from the external, rotating magnetic field is harnessed by: (i) a vibrating metal foil (''pump'') that creates an overall flow in the liquid and (ii) two-component rotors (composed of a magnetic core and a nonmagnetic gear-shaped ring around it) floating at the liquid/air interface that direct the motions of nonmagnetic objects in this flow. The positions of the rotors at the interface are controlled by localized magnetic fields produced by an array of electromagnets immersed in the liquid. Because the fluid motion associated with the rotation of the rotors gives rise to hydrodynamic repulsions between them, no two rotors can aggregate above the same electromagnet.[1] Thus, for a given configuration of active electromagnets, the rotors always self-assemble into a unique structure, and the configuration of the machine (and its function) is uniquely determined.

Figure 1(a) outlines the experimental arrangement. A permanent bar magnet (KIKA Labortechnik) of dimensions 5.6 cm$\times$4 cm$\times$1 cm and magnetization $M\sim$1000 G/cm^3 along its longest dimension rotated with angular velocity ω ($\sim$500–1000 rpm) below a dish filled with a 1:1 v/v solution of methanol and water (this mixture provided the optimal combination of relatively low surface tension and viscosity and high heat capacity). The distance between the upper face of the magnet and the interface between the liquid and air was $\sim$20 mm.

An aluminum plate 2 mm thick and having a hexagonal array of holes (0.6 mm in diameter) was placed at the bottom of the dish and immersed in the fluid. The electromagnets were made of ferromagnetic steel rods of circular cross-section (0.9 mm in diameter, 3 mm long) and had 75–200 coils of 50-μm-thick, insulated copper wire wound around their top 1 mm. The electromagnets were positioned in the holes of the supporting plate, and situated 1 mm above the plane of the plate. To minimize the effects of convection due to dissipation of heat from the operating electromagnets on the self-assembly of the pieces floating at the interface, a 100-μm-thick glass slide was placed on top of the electromagnets as a thermal insulator.

The rotors were fabricated in poly(dimethylsiloxane) (PDMS) using soft lithography.[7] The magnetic cores were cones 0.75 mm in diameter (inclination of 45°) and were doped with 15% w/w of magnetite. The conical shape minimized the precession along the long axis of the particles when they rotated above the electromagnets. The nonmagnetic rings (inner diameter 1.6 mm, outer diameter 3.6 mm, t=0.2 mm thick) and the particles to be manipulated by the rotors were all made out of PDMS. Plasma oxidation minimized the capillary interactions[8] between the floating components of the system by making them hydrophilic.

The magnetically actuated pump was made from a thin, U-shaped strip of aluminum foil (10 mm$\times$4 mm$\times$0.2 mm) and had a small electromagnet (25 coils of 100-μm-thick

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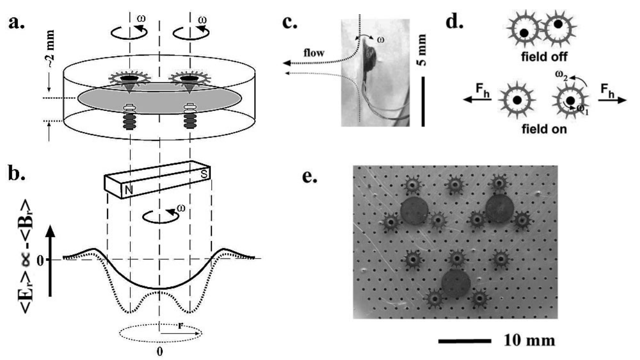

FIG. 1. (a) is a scheme outlining the experiment. The solid line in graph (b) is the profile of the average radial component of magnetic induction (proportional to the energy of the magnetic field) above a rotating magnet. The dotted line shows the profile of the magnetic induction along the line joining two electromagnets shown in (a). Rotors organize in the local energy minima above the electromagnets. (e) Top view—along the direction perpendicular to the plane of the interface—of a thin, vibrating strip of aluminum foil creating the unidirectional flow in the liquid. The flow near the vibrating end of the foil is stronger than that near its fixed end. At $\omega \sim 1000$ rpm, the vibration gave rise to flows with maximal fluid velocities of ~ 5 cm/s. (d) When the external, permanent magnet does not rotate (upper picture), the magnetic cores stick to the inner walls of the nonmagnetic rings, and the rotors stick to each other. When the magnet rotates (lower picture), the cores self-center within the rings, and the rotors repel one another by pairwise hydrodynamic forces F_h. The rotational speeds of the cores, ω_1, are larger than the rotational speeds of the rings, ω_2. The picture in (e) shows a system of 12 rotors self-assembled above an array of 12 electromagnets, and powering three nonmagnetic, circular disks. Each electromagnet has 50 coils of an isolated copper wire, is powered by a current of ~ 0.5 A, and produces a magnetic field of ~ 0.2 T at the level of the interface.

copper wire) attached to one of its sides. The foil had one of its ends fixed and was fully immersed in the liquid. When the electromagnet was turned on, the magnetic field it created interacted with the field of the rotating permanent magnet. This interaction caused the foil to vibrate, and the vibration gave rise to a fluid flow, first along the strip, and then in the direction perpendicular to it [Fig. 1(c)].

In the absence of the rotating field, the particles floating at the interface aggregated by residual capillarity [Fig. 1(d), upper picture]. When the magnet rotated, the cores rotated with angular velocity ω_1 equal to that of the magnet and centered themselves inside the nonmagnetic rings. The torque generated by the spinning cores was transferred to the surrounding rings through the liquid between them (i.e., by hydrodynamic shear). Assuming that the torque on the nonmagnetic ring is equal to the torque generated by the spinning core, and noting that the force on a particle rotating in a liquid is proportional to the product of the shear stress and the area of the portion of this particle immersed in the liquid, we estimate that the angular velocity of the nonmagnetic ring ω_2 is smaller than, and linearly proportional to, the angular velocity of the rotating magnetic core ω_1. The constant of proportionality is evaluated by simple geometric arguments as the ratio of the conical surface immersed in the fluid to the submerged surface area of the nonmagnetic ring (i.e., lower base and he side walls): $rL/[R_{\rm out}^2 - R_{\rm in}^2 + 2t(R_{\rm out}+R_{\rm in})]$; in this relationship, r is the radius of the base of the conical core, L is the length of its side, $R_{\rm out}$ is the outer radius of the nonmagnetic ring (measured at the ends of the "teeth" protruding outwards), $R_{\rm in}$ is its inner radius, and t is the thickness of the ring. For the particles of dimensions used in the experiments, this equation predicts the nonmagnetic rings should rotate approximately 30 times more slowly than the magnetic cores (i.e., $\omega_2 \sim 33$ rpm when $\omega_1 = 1000$ rpm). This prediction agrees with experiment.

Rotors repelled one another hydrodynamically by the vortices they created in the surrounding fluid[1] [Fig. 1(d), lower picture]. These repulsions guided their self-assembly above the array of electromagnets. When turned on ("activated"), the electromagnets modified the profile of the energy of the magnetic field in the plane of the liquid/air interface in such a way that every active electromagnet created a local energetic minimum above it.[9] All rotors were attracted into these minima; the hydrodynamic repulsions between the rotors prevented more than one of them from localizing above one electromagnet. If the number of active electromagnets was equal to the number of rotors, the rotors distributed themselves with one rotor per electromagnet; in other words, the rotors self-organized into a unique structure [Fig. 1(e)]. We note that self-organization was inefficient with rotors lacking the nonmagnetic rings around the magnetic cores. When such "core-only" rotors were small and rotated slowly, several of them could aggregate above one electromagnet; when they rotated rapidly, their motions were often unstable, and even if they were caught above a desired electromagnet, they often sank towards it. When the rotors were made larger and rotated slowly, they precessed around the dish following the poles of the slowly rotating permanent magnet; when they rotated rapidly, they repelled their neighbors so strongly that the system never equilibrated into an ordered array.

Although the disks could, in principle, have been driven by the rotors having no teeth, the teeth minimized capillary attraction between the rotors and disks. When toothless rotors and/or disks were used, they sometimes stuck irreversibly to one another, and this sticking destroyed the array.

The unique feature of this fluidic mechanical system is that the axes of rotation of the rotors are not permanently fixed, and can be changed by modifying the magnetic fields produced by the electromagnets: the rotors can be thus moved across the interface by activating different electromagnets. The rotary motion of the rotors facilitates moving them from one electromagnet to another. In the absence of the rotating external magnetic field, the dipole moment induced in nonrotating magnetic cone is parallel to the magnetic field produced by a ferromagnetic core of the electromagnet below the cone. The energy of this interaction is higher that in the case of a rotating cone in which the induced dipole has a horizontal component due to the rotating permanent magnet. Hence, it is harder to move a stationary rather than a spinning rotor away from an electromagnet.

The ability to reconfigure the rotors above active electromagnets was the basis of two simple mechanical systems in which the rotors directed the motions of nonmagnetic particles moving in an unidirectional flow-field produced by a magnetically powered pump. The designs of these prototypic fluidic machines were stimulated by large-scale devices: a particle sorter, and a rotary carousel.

Figure 2 shows a particle sorter consisting of three rotors organizing above an array of seven electromagnets. In the absence of external magnetic fields, the rotors rested at ran-

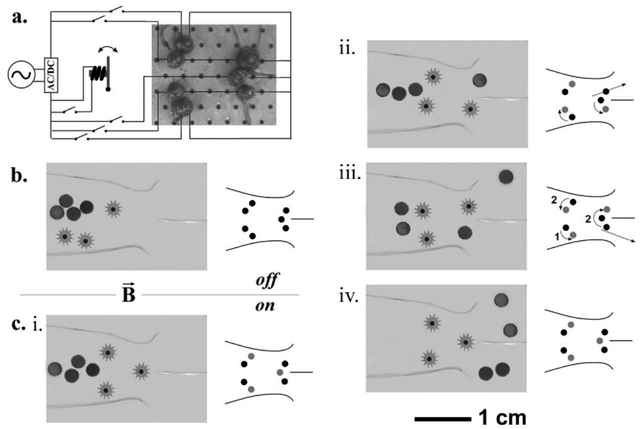

FIG. 2. (a) shows the scheme of the sorting device consisting of three rotors, seven electromagnets (200 coils each, 0.5 A per electromagnet) and a magnetically actuated pump. (b) When the magnetic fields are turned off, the rotors and the nonmagnetic particles to be sorted (light-gray and dark-gray) rest at random positions of the interface. (c) When the magnetic fields are turned on, the rotors organize above the active electromagnets and sort the nonmagnetic particles. The electromagnets active in each step are colored gray in the inserts on the right. The nonmagnetic particles to be sorted are pushed from left to right by the magnetic pump (not shown). The interface is partitioned into three distinct regions by stripes of aluminum foil perpendicular to the plane of the interface.

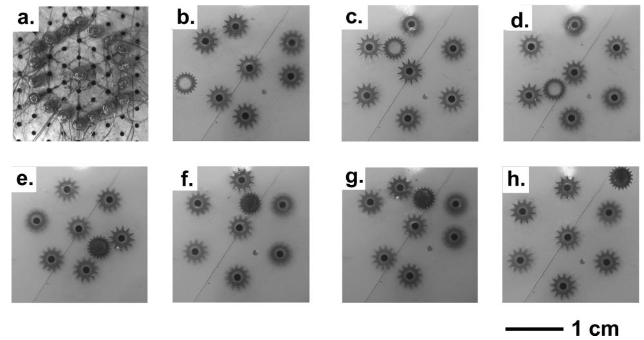

FIG. 3. (a) shows 19 electromagnets (200 coils each, 0.5 A per electromagnet) used in the carrousel system. Seven gears organize above these electromagnets to manipulate nonmagnetic containers floating at the interface in the flow field produced by a magnetic pump (not shown) and in the direction from the lower left to the upper right corner of each picture. The carousel first incorporates an empty container (b), (c), turns it around (d) until the filling point (e), completes the revolution (f), expels the filled container (g), and returns to its initial state (h). The motions of the carrousel are caused by synchronous activation of the electromagnets: When the carousel opens or closes, three electromagnets are simultaneously turned on; when the carousel rotates, six electromagnets are activated at a time.

dom locations of the interface [Fig. 2(b)]. When the external permanent magnet was caused to rotate, and when three electromagnets were turned on, the rotors organized above these active electromagnets: two of the rotors formed a gate, and the third one directed the particles to be sorted (light-gray and dark-gray nonmagnetic disks). Initially, the gate was open [Fig. 2(c)]. When one disk floated past it, the gate was closed, preventing other disks from entering the sorter. Concurrently, the sorting gear blocked one of the outlets and the disk was directed it to one of the two regions of the interface; light-gray disks were collected in the upper region, and the dark-gray disks in the lower region. The gate then opened again, and the cycle repeated until all disks were sorted.

Figure 3 a rotary carousel system that manipulated small containers floating at the surface of the liquid. This device comprised seven rotors organizing above an array of 19 electromagnets. The containers to be manipulated were nonmagnetic PDMS rings; each contained a droplet of mineral oil. Initially, the rotors organized into a symmetric hexagonal structure, and the reactors floated outside of this structure. When two neighboring, outer-layer rotors were moved slightly apart from each other [Fig. 3(b)], a single reactor could be transferred into the carousel [Fig. 3(c)]. The carousel then turned around by synchronous activation of the electromagnets, and the container moved with the rotating carousel [Fig. 3(d)]. After an approximately 180° rotation, the reactor passed above a thin needle that was connected to a syringe pump, and that delivered mineral oil dyed with rhodamine [Fig. 3(e)]. After the application of the desired amount of the colored solution (usually 10 μL), the carousel turned another ~120° [Fig. 3(e)], and then opened to liberate the reactor [Fig. 3(f)]. The device then returned to its original state and was ready to manipulate another container.

This work demonstrates that dynamic self-organization (here, the self-centering of magnetic cores inside nonmagnetic rings, and the redistribution of two-component rotors over active electromagnets) provides a route to types of simple mechanical systems. Although the functions of the devices we built are elementary, the phenomena we described can provide the basis of far more complex designs using, for example, rotors of nonsymmetric shapes, rotors having magnetic cores of different sizes (and thus rotating at different rates), or systems of rotors-within-rotors. Since the hydrodynamic vortex–vortex repulsions are effective between rotating particles tens-of-microns in diameter, it should, in principle, be possible to assemble fluidic machines using microscale components.

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