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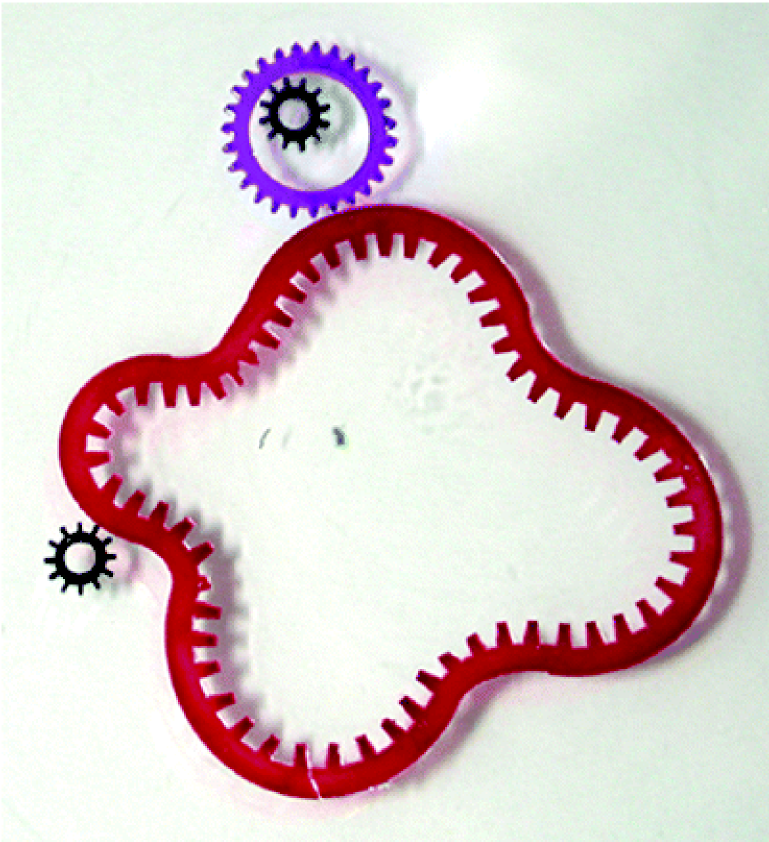

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Self-Assembly of Gears at a Fluid/Air Interface

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Abstract: This paper describes a dynamic system—a system that develops order only when dissipating energy—comprising millimeter to centimeter scale gears that self-assemble into a simple machine at a fluid/air interface. The gears are driven externally and indirectly by magnetic interactions; they are made of poly(dimethylsiloxane) (PDMS) or magnetically doped PDMS, and fabricated by soft lithography. Transfer of torque between gears can take place through three different mechanisms: mechanical interaction, hydrodynamic shear, and capillarity/overlap of menisci. Interplay between these forces allows interactions and motions that are not possible with conventional systems of gears.

Introduction

The field of self-assembly has expanded from molecules to functional devices.[1−3] Most research in self-assembly—especially molecular self-assembly—has focused on systems at equilibrium or steady state.[4,5] The most interesting self-assembling systems may, however, be dynamic—systems that operate away from thermodynamic equilibrium and interact, form patterns, or perform functions only when dissipating energy.[6−9] Dynamic systems are particularly interesting for their relevance to complexity and emergence,[10,11] and for their potential to clarify the properties of complex biological systems (cells and organisms).[12,13]

We have previously described a system in which multiple, millimeter-sized magnetized disks self-assemble dynamically into ordered aggregates when spinning at a fluid/air interface.[14−19] Here, we extend this work by designing and fabricating components that self-assemble into a machine—an assemblage of parts that transmits forces and torques among its components and is capable of doing mechanical work—at a fluid/air interface. One or more of these gears is ferromagnetic (fabricated by doping a polymer with magnetite, Fe_3O_4). The gears position themselves by balancing capillary, hydrodynamic, and magnetic forces. The system is driven by an external rotating bar magnet (Figure 1).[14,18] The gears are held in proximity by capillary forces; they do not require support and orientation by bearings and shafts. This system is self-aligning, self-leveling, externally driven (by magnetic interactions), and tolerant of very eccentric shapes; we expect it to exhibit low wear.

Design of the System

Magnetic Drive. We used magnetic drive to actuate the gears for two reasons: (i) Magnetic actuation involves a simple construction—a rotating permanent bar magnet outside the dish (Figure 1). This arrangement isolates the magnet from the diamagnetic fluid in the dish. (ii) Magnetic actuation does not require direct mechanical coupling or alignment of the driving motor and the driven gears, and multiple magnetic gears can be driven simultaneously using a single bar magnet. The rotation of the permanent magnet creates a magnetic field that rotates a ferromagnetic gear in the same direction, and with the same angular velocity, as the permanent magnet.[20] The radial deriva-

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(20) The ferromagnetic gear rotates with the same angular velocity as the permanent magnet in low viscosity fluids, such as the ones used in these experiments (perfluorodecalin and perfluoromethyldecalin). In highly viscous fluids, the angular velocity of the ferromagnetic gear may be lower than that of the permanent magnet.

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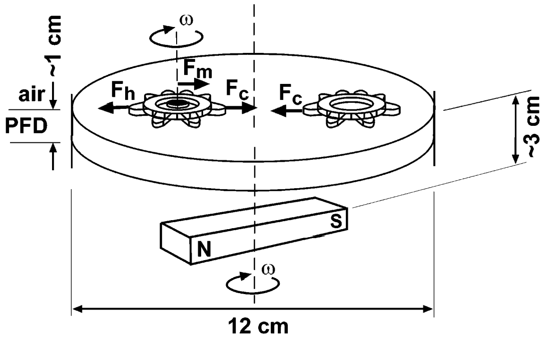

Figure 1. Schematic diagram of a representative experiment, showing two ring gears positioned at the fluid/air interface. The fluid used in these experiments was perfluorodecalin (PFD). The ring gears depicted are diamagnetic; the gear on the left is driven by a ferromagnetic pinion inside the ring gear. The gears interact with each other through a balance of capillary (F_c), hydrodynamic (F_h), and magnetic forces (F_m). The gears are driven externally by a permanent bar magnet (length = 5.6 cm), whose upper face is separated by approximately 3 cm from the fluid/air interface; the magnet rotates at an angular velocity ω below the dish (diameter = 12 cm). The magnetic pinion also rotates at an angular velocity, ω (in units of revolutions per minute, rpm). The angular velocity of the ring gear is less than ω, but depends on various contributions to the drag on it. (Note: Dimensions are not drawn to scale.)

tive of the average radial component of the magnetic field ($\partial B_r/\partial r$) produced by the rotating magnet is approximately zero from the axis of rotation of the magnet to a radial distance of ~1 cm from the axis (for a system with a separation height of ~3 cm between the upper face of the magnet and the fluid/air interface).[14] Thus, a ferromagnetic gear is not necessarily attracted to the direct center of the magnet, but is equally attracted to an area of radius ~1 cm from this center. If the ferromagnetic gear is not positioned within this area, the rotation of the magnetic field also induces a precession of the gear around the axis of rotation of the magnet. (In cases where it is desirable to keep the gear in a fixed position, magnetic flux concentrators can be used.[16]) The simplicity of fabricating ferromagnetic gears by doping poly(dimethylsiloxane) (PDMS) with magnetite (see “Materials” section) also adds to the convenience of this system.

Materials. We fabricated the gears in PDMS because fabrication of shapes of this complexity and size is easy by soft lithography.[21] The surface of unmodified PDMS is hydrophobic, but exposing it to an air plasma makes it hydrophilic.[22,23] The surface of PDMS can therefore be patterned selectively into hydrophilic and hydrophobic regions. The bulk properties of PDMS can also be altered easily by doping the polymer with other materials. Here, we dope PDMS with approximately 15% magnetite (by weight) to make the gears ferromagnetic, and with colored dyes (crystal violet and Sudan red 7B) to facilitate their visualization.[24]

Fluid Interfaces. We chose to make the gears interact at a perfluorodecalin[25] (PFD)/air interface because this interface has a low interfacial free energy (γ = 17.6 mN/m = 0.0176 J/m^2),[26] and therefore weak capillary forces. Capillary forces were necessary to bring the gears together,[27] but under conditions where capillary forces were too strong (for example, at a PFD/H_2O interface: γ = 50 mN/m),[28] the gears stuck irreversibly. PFD is also an inert solvent, it does not swell PDMS, and it has a high density (ρ = 1.91 g/cm^3) so that PDMS (ρ = 1.05 g/cm^3) and magnetite-doped PDMS (ρ = 1.22 g/cm^3) both float at the PFD/air interface.

Experimental Methods

General. PDMS (Sylgard 184) was purchased from Essex Brownell (Edison, NJ). PDMS was made by mixing the two components (10:1 by weight), degassing under vacuum, and curing in a 70 °C oven for 2−5 h. Perfluorodecalin, perfluoromethyldecalin, crystal violet, and Sudan red 7B were purchased from Aldrich and used as received. Magnetite (Fe_2O_3) was purchased from Alfa Aesar (Ward Hill, MA) and Peelers nail polish from CVS (Cambridge, MA). The plasma cleaner was a SPI Plasma Prep II purchased from SPI Supplies (West Chester, PA) and was used under vacuum (~2 mTorr).

Fabrication of the Gears. The gears were fabricated by soft lithography.[21] Briefly, the gears were designed using a computer aided design (CAD) program. The CAD file was printed onto a transparency film that served as a photomask in contact photolithography. A layer of photocurable epoxy (SU-8) was spun onto a silicon wafer, and exposed to UV light through the mask to cross-link the areas that were exposed. Dissolving the un-cross-linked photoresist gave a positive relief of the gears on the wafer.[29] The surface of the wafer was treated with (tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane, a silane containing fluorinated functional groups; this monolayer of silane prevented irreversible bonding between the silicon and PDMS.[22] PDMS prepolymer was poured over the master, and the polymer was cured at 70 °C for 2−3 h. Peeling the PDMS off the master gave a negative relief of the structures on the master. The negative relief was used as a PDMS master for molding the gears. The surface of the PDMS master was made hydrophilic by exposing it to an air plasma; this process introduced silanol groups (Si−OH). The PDMS was then treated with a silane containing fluorinated functional groups. The chlorosilane reacted with the silanol groups on the surface of the PDMS and made the surface hydrophobic. Treating the PDMS surface with hydrophobic groups was necessary to prevent irreversible bonding between the PDMS master and PDMS prepolymer.[30] The gears were fabricated by pouring PDMS prepolymer between the PDMS master and a glass slide, and applying a small pressure (P ~ 1000 kPa) until the master and slide were in physical contact, and the prepolymer was excluded from the area of contact.[24] For fabrication of ferromagnetic gears, PDMS prepolymer that was mixed with approximately 15% magnetite (by weight) was used. After curing the prepolymer, the PDMS master was removed easily from the gears, since the master was not attached covalently to the PDMS gears; removal of the master left the gears attached to the glass substrate. The diamagnetic gears were colored by soaking them in a solution of methylene chloride and a dye, and then washing the gears several times with ethanol.[24]

Patterning of the Gears. The gears were patterned with hydrophilic and hydrophobic patches by manually covering regions of the surface

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(25) We used a mixture of perfluorodecalin and perfluoromethyldecalin. The two liquids have similar densities, boiling points, and surface tensions. Experiments that were performed either in a mixture of the two fluids, or in only perfluorodecalin, gave the same results.
(26) The units for interfacial free energy can be expressed as a force per unit length (mN/m) or as energy per unit area (J/m^2).
(27) Surfaces of PDMS were unpatterned (i.e., they were completely hydrophobic) unless otherwise indicated. Hydrophobic surfaces generated positive menisci at the PFD/air interface; these surfaces were attracted to other unpatterned surfaces.
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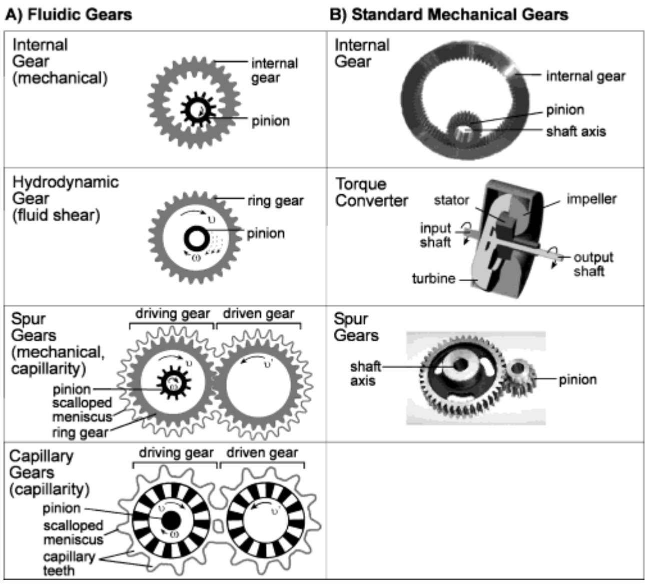

Figure 2. Summary of the gears described in this paper: "fluidic gears" (A), which operate at the fluid/air interface, and their conventional mechanical counterparts (B). (A) "Fluidic gears" can have either physical teeth or "capillary teeth"; both of these types of teeth generate menisci in the shape of a scalloped contour at the fluid/air interface. Gears that operate by mechanical interactions (internal and spur gears) have physical teeth that are covered with a film of fluid; the transmission of mechanical force is mediated through this film. Smooth rings that are patterned with hydrophilic and hydrophobic patches are called "capillary gears"; the alternating patches generate "capillary teeth" that prevent slip between adjacent gears. Fluidic gears do not require support and orientation by bearings and shafts, but instead they self-assemble, and are held in proximity to each other, by capillary forces. (B) Standard mechanical gears[52] require teeth that physically interlock, except for the case of the torque converter, which operates by shear forces. Standard gears require shafts for support and orientation and, thus, do not self-assemble.

that were to remain hydrophobic with nail polish (Peelers). A permanent marker was used to mark the top surface of the gear in the regions that were uncovered with nail polish (i.e., the regions that were to become hydrophilic) so that one could differentiate the hydrophilic and hydrophobic regions once the patches of nail polish were removed. The patterned gears were oxidized to make the uncovered regions hydrophilic; the patches of nail polish were removed using tweezers to reveal the hydrophobic regions.[31] Only the outer perimeters of the rings, and not the inner perimeters, were patterned with hydrophilic and hydrophobic patches during fabrication of the "capillary gears".

Results and Discussion

Gear Interactions. There are three types of mechanisms for transmitting torque at a fluid/air interface: mechanical interactions, hydrodynamic shear, and capillary forces (illustrated in this work by the interactions between overlapping patterned menisci). We refer collectively to gears that operate at the fluid/air interface as "fluidic gears" (Figure 2). Fluidic gears have differently shaped physical teeth, or no physical teeth at all (i.e., "capillary teeth"), depending on their intended mechanism of action. Both physical teeth and capillary teeth generate menisci in the shape of a scalloped contour at this interface. Figure 2 summarizes the different types of gears associated with each mechanism of torque transfer (A); diagrams of equivalent mechanical gears are also shown (B). Nomenclature of these gears is given in Table 1.

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Table 1. Nomenclature of Fluidic and Standard Mechanical Gears

capillary gear	a gear without topography on its surface, but that is patterned with hydrophilic and hydrophobic patches that generate capillary teeth
capillary teeth	hydrophilic or hydrophobic patches that generate raised menisci in a fluid
driven gear	a gear that rotates due to transfer of torque from a driving gear
driving gear	a gear which is powered by a driving shaft or pinion that transfers torque to another gear
impeller	a driving rotor (equivalent to a driving gear)
internal gear	gear having teeth on the inside of the rim
pinion	a small gear that engages a larger gear
pitch	number of teeth per diameter of the gear
ring gear	a gear that surrounds a pinion
scalloped meniscus	meniscus around the teeth of a gear that is in the shape of a scallop
shaft	a rotating cylindrical rod, attached to gears, that transfers power or motion
spur gears	gears which are coplanar and have teeth that are straight and parallel to their axes
stator	the stationary part of a motor
torque converter	a unit that transmits power via recirculating fluid in a closed housing
turbine	an engine driven by a moving fluid that pushes against the blades or paddles attached to a central shaft (equivalent to a driven gear)

A. Mechanical Forces. Conventional gears that operate by mechanical transfer of torque require teeth that interdigitate physically. In these conventional systems, mechanical forces are transmitted by contact of one gear with a second. At fluid interfaces, the teeth of the gears are covered with a film of fluid, and the transmission of mechanical force is mediated through this film.[32,33] Two types of gears that operate by this mechanism at a fluid/air interface are internal and spur gears. (Spur gears also operate by capillary/meniscus overlap forces and will be addressed in the section "Capillary/Mensici Overlap".)

An internal gear has teeth along the inner perimeter of its rim; the internal gear is diamagnetic and a magnetic pinion[34,35] rotates along this inner perimeter (Figure 3). The underlying bar magnet rotating clockwise causes the magnetic pinion also to rotate clockwise. The pinion first comes into contact with the internal gear by capillary attraction,[36] since both gears have hydrophobic surfaces that generate positive menisci (Figure 3B). When the pinion rotates, it transmits a tangential force to the internal gear; this interaction is predominately mechanical. The motion of the gears depends on whether the axes of rotation of the gears are fixed, as well as on the viscous forces acting on them. If the internal gear is fixed, then the angular motion of the pinion requires it to travel counterclockwise along the inner perimeter of the internal gear. If the internal gear is unfixed and the pinion is fixed, the internal gear will move clockwise. If both gears are unfixed, how much each of the gears moves will depend on the viscous drag acting on each of them, since these viscous forces oppose the rotation of the gears. When both of the gears are unfixed at a PFD/air interface, the viscous forces

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(33) Bloyce, A.; Michler, T. *Heat Treat. Met.-UK* **2002**, *29*, 33−38.
(34) A pinion is defined as a small gear that engages a larger gear. In this text, gears can be engaged either by physical contact (mechanical) or by mediation through a fluid (hydrodynamic or capillary).
(35) In this text, we present magnetic pinions having the shape of either a ring (e.g., Figures 3, 4, 6, and 9) or a disk (e.g., Figures 7 and 8). There is no functional difference between these two types of pinions, as both of these pinions rotate at the same angular velocity as the rotating bar magnet.
(36) The dependence of the operation of these gears on capillary forces is discussed in the section "Pitch: Toothed Gears".

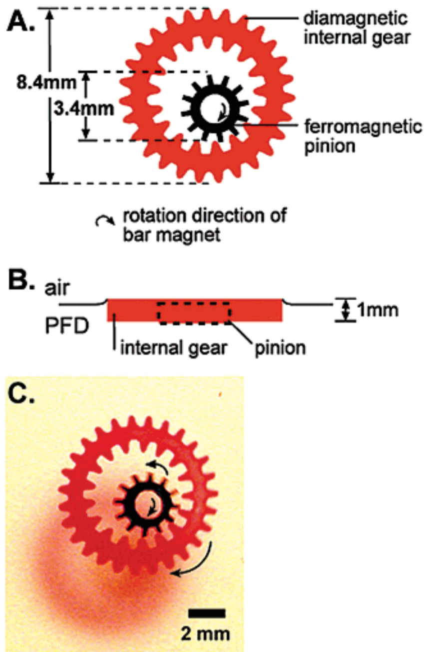


Figure 3. (A) Schematic diagram of an internal gear, which operates mainly by mechanical interactions. The ring gear is diamagnetic and the pinion is ferromagnetic. (B) Side view diagram of an internal gear at a PFD/air interface. The surfaces of the gears are hydrophobic and make positive menisci at the interface. Diamagnetic gears having thicknesses of 1 mm are approximately 0.9 mm submersed in PFD; ferromagnetic gears are almost all submersed in the fluid except for their top surfaces. (C) Photograph of an internal gear in motion at a PFD/air interface. Both the pinion and the ring gear are unfixed. The arrows show the direction of rotation of each of the gears.

acting on the gears are low, and the gears rotate freely—the pinion rotates clockwise and travels counterclockwise along the perimeter of the internal gear; the internal gear rotates clockwise (Figure 3C).

B. Hydrodynamic Shear. Hydrodynamic flows result from the rotation of a gear at fluid/air interfaces. When a ferromagnetic gear or ring (driven by a magnetic field) rotates, it produces two kinds of flows: (i) a shear motion to the side of the gear (Figure 4A-i) and (ii) a vortex that pumps fluid from the underlying bulk to the fluid/air interface (Figure 4A-ii).[14,15] The hydrodynamic shear is largely responsible for driving the diamagnetic gears.

We first consider a construct consisting of an outer diamagnetic ring gear and an inner magnetic pinion[37] (Figure 4B); we refer to this construct of two elements as a "hydrodynamic gear". Since the fluid is the medium through which torque from the pinion is transmitted to the diamagnetic gear, the moving fluid causes the outer gear to rotate, as shown by the arrows in Figure 4A-i. The magnetic pinion therefore shears the fluid around it, and drags the diamagnetic gear. In addition, the vortex produced by the pinion is radially symmetric; we believe that this symmetry causes the pinion to self-center within the ring gear. For a magnetic pinion with radius R_0 and angular velocity ω, the pinion will drive the ring gear with radius R_1, with an angular

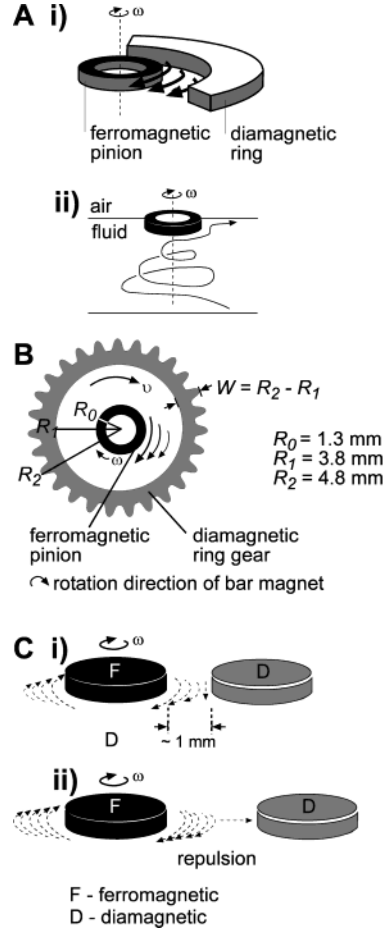


Figure 4. Gears that transfer torque by hydrodynamic shear. (A) (i) Schematic diagram of a ferromagnetic pinion, which is driven by a magnetic field, shearing the fluid against its side. The flow lines are depicted by the arrows. This shearing action creates the necessary forces for driving the diamagnetic gears and disks in (B) and (C). (ii) Schematic diagram of a ferromagnetic ring pumping fluid from the bulk of the fluid to the fluid/air interface; the flow lines underneath the ring are also shown. This pumping action is symmetric and causes the ferromagnetic pinion to self-center within the ring gear in (B). (B) A "hydrodynamic gear" consists of two components: a ferromagnetic pinion and a diamagnetic ring gear; the pinion drives the ring gear through shear forces (depicted by the arrows) transmitted through the fluid. (C) (i) Fluid drive. Torque can be transferred from a magnetic disk to a diamagnetic disk significantly only if the axes of the disks are held at a *fixed* distance away from each other. (ii) Self-assembly of the system in (C-i) does not result in the transfer of torque due to the large hydrodynamic forces (i.e., the shearing motion generated by the ferromagnetic gear) that repel the diamagnetic disk.

velocity, υ, determined by eq 1,[38]

$$\upsilon = \frac{\omega}{c}\frac{R_1 T_1}{(2R_1 W + W^2)}\left(\frac{x^2}{1 - x^2}\right) \quad (1)$$

where W is the width of the ring gear, T_1 is the thickness of the ring gear, $x = R_0/R_1 < 1$ is the ratio of the radius of the pinion to the inner radius of the ring gear, and c is a dimensionless constant. The magnitude of the hydrodynamic torque varies linearly with the angular velocity of the pinion. As the radius of the pinion (R_0) increases, the pinion has a larger surface area in contact with the fluid. As a result, a large pinion can shear more fluid around it, and produce a larger hydrodynamic force than a small pinion. Since this shear acts upon the sides of the

(37) In this text, we present magnetic pinions that drive diamagnetic rings by hydrodynamic shear that have either physical teeth (e.g., Figures 6 and 9) or no physical teeth (e.g., Figures 7 and 8). There is no difference between the effects of these pinions, since both types of pinions rotate at the same angular velocity as the rotating bar magnet, and both drive the diamagnetic rings by hydrodynamic shear (thus they do not require physical contact with the rings to operate).

(38) Please see section "Derivation of Eq 1".

ring gear, as the thickness of the ring gear (T_1) increases, the ring gear has a larger surface area to which the fluid can shear against; thus, υ increases with T_1. A ring gear with a large inner radius (R_1) has a lower angular velocity than a ring gear with a small R_1, because the hydrodynamic force experienced by a ring gear decreases as R_1 increases (the hydrodynamic shear produced by the pinion decreases as $1/r$). The viscous drag on the ring gear is due to the bottom surface of the gear shearing against the fluid. A ring gear with a large width has a lower angular velocity than a ring gear with a small width (if both gears have the same R_1 and are powered by the same pinion), since the larger gear has larger area and experiences more drag than the smaller.

A second configuration for transmission of torque through hydrodynamic shear could be a ferromagnetic gear (or disk) that is positioned beside, and on the same plane, as a diamagnetic gear (or disk) (Figure 4C-i). This mechanism of transferring torque through shear is known as "fluid drive" in other circumstances, and is similar to the mechanism responsible for the operation of torque converters.[39] In this configuration, the gears must be separated by fluid, and be placed near ($d = \sim 1$ mm for gears with $r = \sim 5$ mm), but at a fixed distance from, each other. We were unable to cause the gears to self-assemble[40] into this configuration: an unfixed ferromagnetic gear that is in the vicinity of an unfixed (laterally mobile) diamagnetic gear does not transmit torque significantly by hydrodynamic shear (Figure 4C-ii). The rotation of the magnetic gear at angular velocities typical of those we used ($\omega = 100-1000$ rpm) results in a repulsive hydrodynamic force between the two gears, due to the high pumping action of the magnetic gear.[17] In this configuration, the capillary attraction is not strong enough to keep the gears close to one another, and no torque is transmitted by hydrodynamic shear.

Transmission of torque is possible, however, in this type of configuration, albeit not by hydrodynamic shear, by using diamagnetic ring gears (which are powered by a magnetic pinion) instead of magnetic gears (or disks). Diamagnetic ring gears that are powered by a magnetic pinion do not produce as high hydrodynamic repulsion as magnetic gears. The diamagnetic ring gears must also have teeth that overcome slip: either physical teeth that interact mechanically and through overlap of menisci (spur gears), or capillary teeth that interact only through overlap of menisci (capillary gears). Both types of teeth create more attractive capillary forces than those created by smooth, unpatterned disks; these forces are necessary for balancing the hydrodynamic repulsion.

Derivation of Eq 1. The relationship between the angular velocity of the pinion, ω, and the angular velocity of the ring gear, υ, as shown for the hydrodynamic gear in Figure 4B, is expressed as eq 1. To explain the form of eq 1, we describe the different torques acting on the ring gear. The fluid in the annulus is pumped due to the rotation of the pinion. For example, when a cylinder of radius R_0 rotates inside a second concentric stationary cylinder of radius R_1, the velocity field[41] is $u_\theta(r) = \omega[r - R_1^2/r]/[1 - (R_1/R_0)^2]$. The motion of the gears is analogous to that between two cylinders, and since $\upsilon \ll \omega$, the fluid exerts a shear stress on the ring gear given by eq 2, where μ is the viscosity of the fluid.

$$\text{shear stress} = \frac{\mu\omega R_0}{(R_1^{\,2}/R_0) - R_0} \tag{2}$$

Here, we let $x = R_0/R_1$. The corresponding torque on the ring gear, τ_1, is obtained by multiplying eq 2 by $2\pi R_1^2 T_1$, thus giving eq 3.

$$\tau_1 = \mu\omega\left(\frac{x^2}{1 - x^2}\right)2\pi R_1^{\,2}T_1 \tag{3}$$

From the area of contact between the ring gear and the fluid below it, there is also a torque, τ_2, resisting motion of the ring, which we estimate as proportional to the product of a shear stress, $\mu\upsilon$, a moment arm, R_1, and an area of contact, $\pi(2R_1W + W^2)$. This product yields eq 4.

$$\tau_2 = \mu\upsilon R_1\pi(2R_1W + W^2) \tag{4}$$

At steady state, the torque producing motion of the ring gear must balance the torque resisting the motion. Thus, equating eqs 3 and 4 gives, within a multiplicative constant, eq 1. The dimensionless constant, c, can be determined experimentally. Note that we have neglected the small torque from the fluid at radial distances greater than R_1.

To test eq 1, we first performed a series of experiments in which we measured the rotation speed of the ring gears for ring gears having the same inner radii, R_1, but varying widths, W. These experiments were repeated for different ω (450 and 760 rpm) and radii of the pinion ($R_0 = 1.75$ and 1.35 mm). The dimensionless ratio, ω/υ, is plotted against W in Figure 5A-i. Clearly, ω/υ becomes much greater as W increases.

Next, we took into account the different sizes of the pinions and the area of the ring gear in contact with the fluid. We plotted $(\omega R_1T_1/\upsilon A)[x^2/(1 - x^2)]$ against W, where $A = 2R_1W + W^2$; this scaling collapses the data as shown in Figure 5A-ii. The constant, c, was determined to be ~ 1 from this plot.

In addition, we verified eq 1 by performing a second set of experiments where the widths of the ring gears were constant but R_1 was varied. Figures 5B-i and 5B-ii were plotted similarly to those in Figure 5A; these plots show that the data also collapse and give a similar constant of $c \sim 1$.

C. Capillary/Menisci Overlap. Gears made in PDMS (undoped or doped) can be patterned two ways: (i) with physical teeth and (ii) with alternating hydrophobic and hydrophilic surfaces. Both of these types of structures generate patterned menisci at the fluid/air interface; the interaction of complementary menisci from two different gears enables the transfer of torque between gears. We have designed both spur gears and capillary gears that operate by this mechanism.

1. Spur Gears. Spur gears are coplanar-paired gears that rotate in opposite directions and have teeth that are straight and parallel to their axes. We have examined spur gears that are made up of a driving gear (here, a diamagnetic ring gear that is powered by a magnetic pinion, Figure 6A-i) and a driven gear (a diamagnetic ring gear, Figure 6A-ii). When a driving gear comes into contact (in this illustration, mechanical contact) with another diamagnetic ring gear (the driven gear), their teeth

(39) Society of Automotive Engineers. Transmission Committee. Design Standards Subcommittee. *Design Practices: Passenger Car Automatic Transmissions (Ae-18)*; Society of Automotive Engineers, 1994.

(40) The disks transferred torque only when the axes of rotation of the gears were fixed by pinning the centers of the gears onto the floor of the dish.

(41) Batchelor, G. K. *An Introduction to Fluid Dynamics*; Cambridge University Press: New York, 1967.

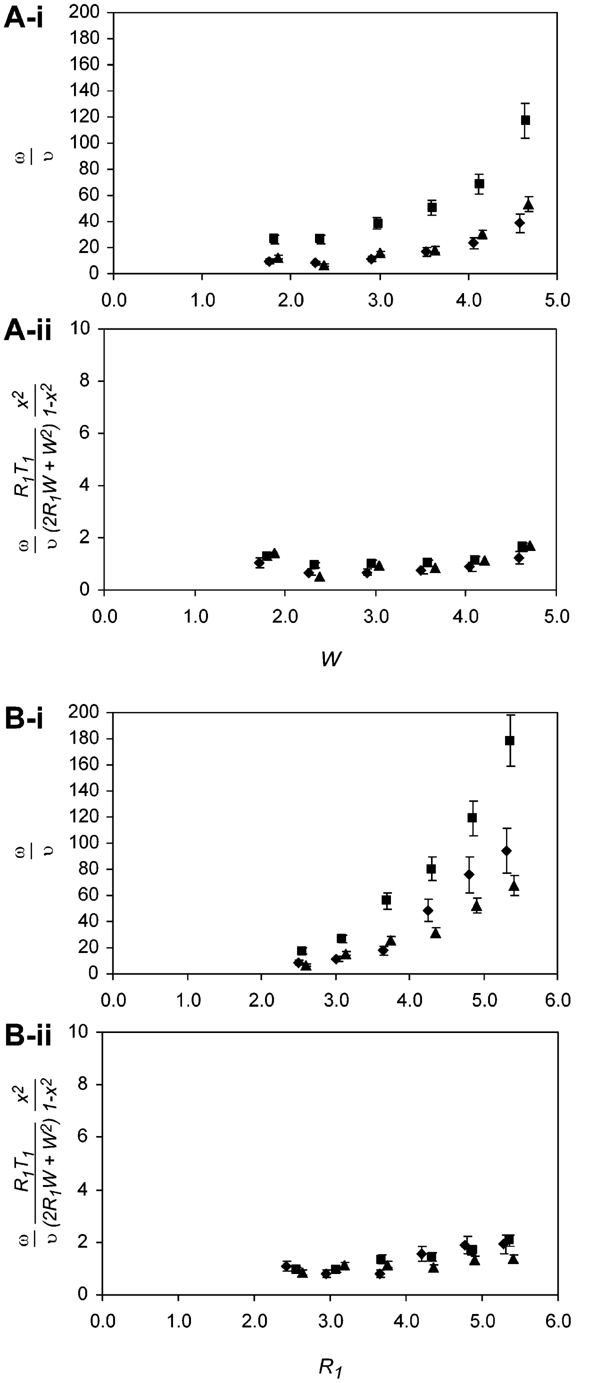


Figure 5. Plots for testing the form of eq 1. The symbols represent different sets of experiments for different ω and radii of the pinion, R_0: ◆, $\omega = 450$ rpm, $R_0 = 1.75$ mm; ▲, $\omega = 760$ rpm, $R_0 = 1.75$ mm; and ■, $\omega = 760$ rpm, $R_0 = 1.35$ mm. Data points are horizontally offset for clarity. Error bars represent ± 1 standard deviation (number of measurements $N = 20$). (A) Experiments with ring gears having the same inner radii, R_1, but varying widths, W. (i) Time for one revolution of the ring gear (in dimensionless units, ω/υ), plotted against W. (ii) Scaling the data by taking into account the different sizes of the pinion and the width of the ring gears collapses the data. (B) Experiments with ring gears having the same W, but different R_1. (i) The ratio of ω/υ plotted against R_1. (ii) Scaling the data by taking into account the different sizes of the pinion and the width of the ring gears collapses the data, in a manner similar to (A-ii). Both (A-ii) and (B-ii) give $c \sim 1$.

engage and the driven gear rotates in the opposite direction, but with the same magnitude of angular velocity as the driving gear (Figure 6A,B).

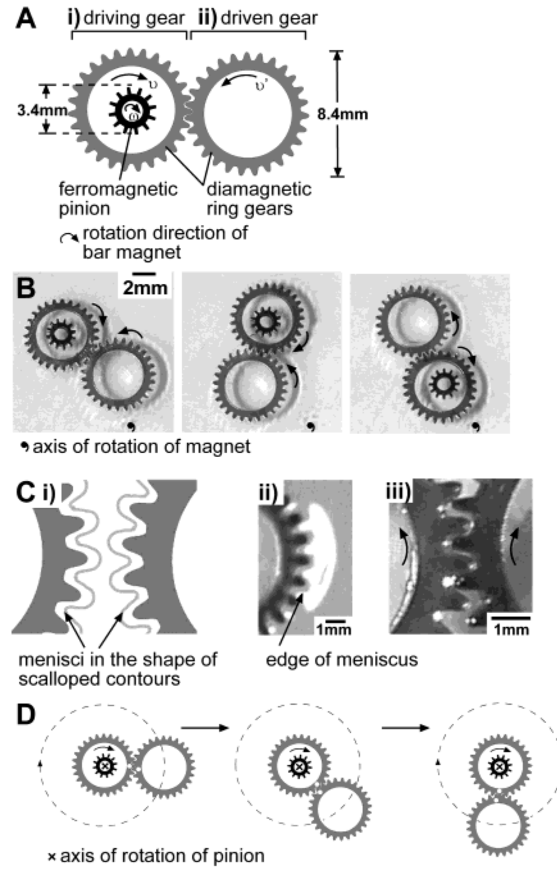


Figure 6. Spur gears. (A) Top view schematic diagram of a driving gear (i) and a driven gear (ii). The driving gear is made up of a ferromagnetic pinion within a diamagnetic ring gear. The diamagnetic ring gears are attracted to each other by capillary interactions. (B) Photographs of spur gears rotating at a PFD/air interface. The arrows indicate the direction of rotation of the gears. The (›) marks the axis of rotation of the bar magnet (drawn in Photoshop; this chiral shape was chosen to indicate that the orientations of the frames do not change as the gears rotate). (C) (i) Schematic diagram of the ring gears showing the menisci around the teeth of the gears, which are in the shape of scalloped contours. The teeth of the gears, and thus the menisci, are complementary to one another. (ii) Photograph showing the shape of the meniscus around the teeth of a ring gear. The edge of the meniscus was visualized by reflecting light off the PFD (reflected areas are white in the photograph) around the teeth of the gear. (iii) Photograph of the teeth of the ring gears interdigitating as the gears are rotating. (D) Motion of the ring gears sticking irreversibly and rotating as one unit about the axis of the pinion. The gears are marked with white circles to help the reader follow the positions of the teeth.

The teeth on the gears have two functions—they generate patterned menisci in the shape of a scalloped contour that cause the gears to self-assemble (Figure 6C); they also transfer force mechanically when teeth on different gears engage. The gears remain engaged and rotating as long as the attractive capillary force between them is stronger than the hydrodynamic repulsion of the driving gear (reflecting the vortex around the driving gear), so that the gears stay in physical contact. Another necessary condition for operation of the gears is that the mechanical force of the driving gear (which depends on the angular velocity of the gear) must be greater than the capillary force; otherwise, the gears will stick irreversibly and rotate as one unit about the axis of the pinion (Figure 6D).[42]

We designed spur gears with rounded teeth so that the teeth would interdigitate and push off of one another smoothly when they are engaged. Spur gears with rectangular teeth tended to stick irreversibly rather than rotate freely because the teeth of adjacent gears wedged together.

The assembly and disassembly of the spur gears can be controlled externally by varying the hydrodynamic repulsion of the driving gear, i.e., by varying the angular velocity of the bar magnet (and, thus, of the magnetic pinion). Assembly of the gears required angular velocities of the pinion, $\omega < 1000$ rpm. At $\omega > 1000$ rpm, when the hydrodynamic repulsion of the driving gear was higher than the capillary attraction of the ring gears, the ring gears disassembled; decreasing the hydrodynamic repulsion resulted in reassembly of the gears.

2. Capillary Gears. Disks can generate patterned menisci even without physical teeth; for simplicity, we still refer to disks as "gears"—even though they lack teeth—provided they can transmit torque. We have examined a system comprising a diamagnetic ring gear that is powered by a ferromagnetic pinion and a second diamagnetic ring gear (Figure 7A-i). The diamagnetic rings do not have physical teeth or other topography on their surfaces, but are instead patterned with alternating hydrophilic and hydrophobic regions;[31] these surfaces generate a regular angular pattern of raised menisci in the shape of a scallop around the gear (Figure 7A-ii). We refer to the hydrophilic and hydrophobic patches as "capillary teeth" and gears with capillary teeth as "capillary gears".

Capillary gears attracted each other by capillary interactions between menisci of the same type. Both hydrophobic and hydrophilic PDMS surfaces generated positive menisci at the PFD/air interface, since PFD wets both hydrophobic and hydrophilic PDMS; these menisci varied, however, in their shapes because of the difference in surface free energies between hydrophilic and hydrophobic PDMS. Because hydrophilic PDMS has a higher surface free energy than hydrophobic PDMS, PFD preferentially wets hydrophilic PDMS in order to lower the energy of the interface.[43] Thus, hydrophilic and hydrophobic PDMS generated menisci having different shapes even though both of these surfaces generated positive menisci; the hydrophobic regions generated shallower positive menisci than that of the hydrophilic regions (Figure 7A-ii). Menisci of the same type preferentially overlapped; the observation that large positive menisci preferentially overlap with other regions having large positive menisci agrees with previous reports.[44]

The alternating overlap of similar menisci as the gears rotated facilitated the transmission of torque (Figure 7B-ii). The overlap of menisci that are bridging the gears (i.e., the capillary teeth) was the mechanism by which a force, tangential to the outer rim of the driving gear, could be transmitted to the driven gear; the bridging menisci and the variation in the strength of the

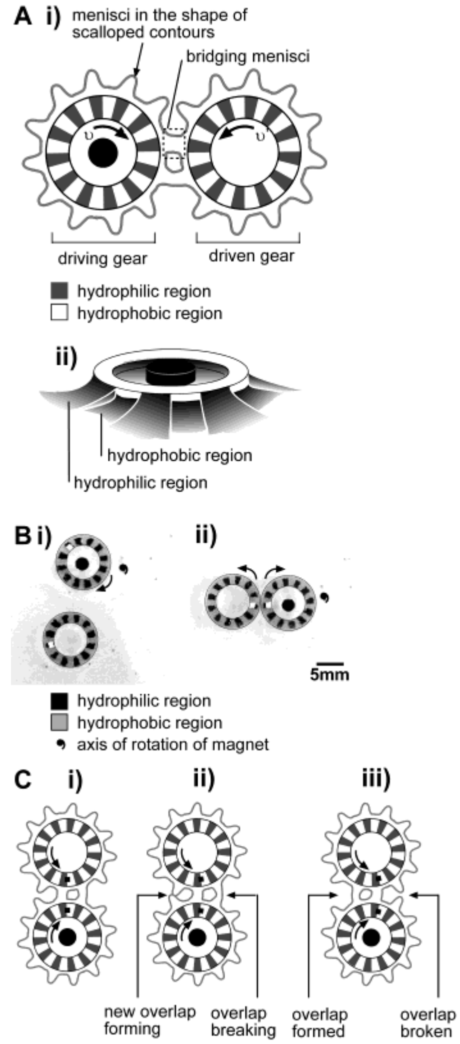


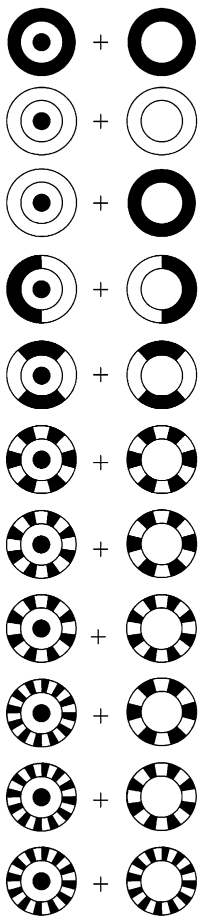
Figure 7. (A) (i) Schematic diagram of capillary gears that interact at the PFD/air interface by overlap of patterned menisci. The (outer) ring gears are diamagnetic and the (inner) pinion is ferromagnetic. The gray regions are hydrophilic and generate positive menisci at the PFD/air interface; the white regions are hydrophobic and also generate positive menisci, but ones that are shallower than the menisci at the hydrophilic regions. The patterned menisci are in the shape of a scalloped contour; the contour is shown graphically by the gray lines around the perimeter of the gears. Menisci of the same type overlap favorably and form bridging menisci between the rims of the gears. (ii) Side view of a capillary gear showing the heights of the different menisci. The heights of the menisci are exaggerated in order to show the different effects between hydrophilic and hydrophobic regions. (B) Photographs showing the self-assembly (i) and the transfer of torque (ii) between two capillary gears. The gears are marked (using Photoshop) with white squares to help the reader follow the positions of the teeth. The contours of the gears are also marked (using Photoshop) to facilitate visualization of the gears. The (•) marks the axis of rotation of the magnet (drawn in Photoshop; this chiral shape was chosen to indicate that the orientations of the frames do not change as the gears rotate). (C) Schematic diagrams depicting the changes in the shapes of the bridging menisci as the gears are in contact and rotating. The gears are marked with black squares to help the reader follow the positions of the teeth. (i) Capillary gears with two sets of hydrophilic faces initially in contact; bridging menisci are formed between these faces. (ii) As the gears rotate in their respective directions, a new overlap begins to form (LHS) and an overlap begins to break (RHS). (iii) A new overlap has formed (LHS) and an overlap has broken (RHS).

(42) The motion of the gears sticking irreversibly and rotating as one unit about the axis of the pinion is similar to the motion of the "hydrodynamic gear", where the diamagnetic ring gear rotates symmetrically around the magnetic pinion.

(43) This observation is different from that of surfaces of PDMS at the PFD/H_2O interface, where hydrophilic regions are wetted preferentially by water (thus generating negative menisci), and hydrophobic regions are wetted preferentially by PFD (thus generating positive menisci). The difference in wetting between the PFD/air and PFD/H_2O systems lies in the origins of the forces that make up the surface free energies of each component. Approximately 70% of the surface free energy of water originates in its polar interactions, predominately in hydrogen bonding; wetting by water is therefore strongly affected by changes in polarity of the interface [Folkers, J. P.; Laibinis, P. E.; Whitesides, G. M. *J. Adhes. Sci. Technol.* **1992**, *6*, 1397−1410.; Folkers, J. P.; Laibinis, P. E.; Whitesides, G. M. *Langmuir* **1992**, *8*, 1330−1341]. On the other hand, the surface free energy of PFD is predominately comprised of dispersion interactions (and contains no polar component). Hydrophilic PDMS presents Si−OH groups on its surface; maximizing the exposure of this surface to H_2O groups reduces the liquid−solid interfacial energy (γ_{SL}) of this interface. Hydrophobic PDMS contains Si−CH_3 groups; maximizing the exposure of this surface to hydrophobic −F groups (from PFD) reduces γ_{SL} of this interface. Thus, in the PFD/H_2O system, hydrophilic PDMS is preferentially wetted by water and not PFD.

(44) Wu, H.; Bowden, N.; Whitesides, G. M. *Appl. Phys. Lett.* **1999**, *75*, 3222−3224.

Table 2. Number of Teeth Required for the Continuous Transfer of Torque in Capillary Gears ($d = 10$ mm)[a]



A	B	Notation	Transfer of Torque
		-	no
		-	no
		-	no
		$[1]_A;[1]_B$	no
		$[2]_A;[2]_B$	no
		$[6]_A;[6]_B$	no
		$[8]_A;[6]_B$	no
		$[8]_A;[8]_B$	yes
		$[12]_A;[6]_B$	no
		$[12]_A;[8]_B$	no
		$[12]_A;[12]_B$	yes

[a] □, hydrophobic region; ■, hydrophilic region.

capillary interaction (i.e., in the interfaces between the hydrophilic and hydrophobic regions of the gears) prevented the surfaces of the two gears from slipping against one another. To illustrate how the shapes of the menisci change as the gears rotate, consider two capillary gears with two sets of interacting hydrophilic regions (Figure 7C-i). The menisci at these regions overlap, and bridging menisci form (between the rims of the gears). As the gears rotate, a new pair of lobes on the menisci begins to overlap, as shown on the left-hand side (LHS) of Figure 7C-ii. The bridging menisci on the right-hand side (RHS) of Figure 7C-ii begin to pinch off; the width of the overlap formed by the bridging menisci decreases in order to minimize the surface area of the menisci and thus the surface free energy of the system. These menisci eventually pinch off as this set of hydrophilic regions rotate away from each other (Figure 7C-iii).

3. Pitch: Capillary Gears. The pitch, or the number of teeth per diameter of the gear, is an important factor in determining whether torque can be transferred continuously between gears. (We refer to the "continuous transmission of torque" as transfer of torque without slip.) Table 2 summarizes the number of "teeth", *n* (that is, hydrophilic regions), that was required for torque to be transferred between capillary gears having an outer diameter of 10 mm. Here, we denote the number of hydrophilic regions in brackets, $[n_{hydrophilic}]_A$. For example, $[1]_A;[1]_B$ means that both gears A and B have one hydrophilic region (and therefore each gear has one hydrophobic region, due to symmetry). We refer to a capillary gear as having "teeth" only if the gear contains both hydrophilic and hydrophobic regions. Disks that are completely hydrophilic or completely hydrophobic do not have teeth; we refer to these as rings.

In the case of two rings, both being completely hydrophilic and having no hydrophobic regions, or both being completely hydrophobic and having no hydrophilic regions, there is no continuous transmission of torque. At low angular velocities of the pinion ($\omega < 100$ rpm), the hydrodynamic forces are weak and the attractive capillary forces are dominant; the rings stick irreversibly and rotate about the axis of the pinion, in a motion that is similar to that observed with spur gears (Figure 6D). At intermediate angular velocities ($\omega = 100-1000$ rpm), when the hydrodynamic repulsion is balanced with the capillary forces, the rings come into contact, but the driving ring rotates and travels around the outer perimeter of the driven ring. The driving ring does not cause the driven ring to rotate continuously in the direction opposite to the driving ring, because the interface between the rings allows them to slip. At high angular velocities of the pinion ($\omega > \sim 2000$ rpm), we suspect that hydrodynamic repulsion dominates and the driving ring repels the driven ring.[45]

A hydrophobic ring and a hydrophilic ring are weakly attracted to one another, because both surfaces generate positive menisci at the PFD/air interface. When these two rings come into contact, at both low and intermediate angular velocities, the driving ring rotates and slips around the perimeter of the driven ring; this weak interaction causes the driven ring to rotate slowly and sporadically.

Capillary gears must have a number of alternating hydrophilic and hydrophobic regions that generate menisci that act like teeth (and therefore overcome slip), in order for one gear to transmit torque continuously to another. We found empirically that the minimum number of teeth required for the smooth transmission of torque in capillary gears was eight—that is, $[8]_A;[8]_B$—for ring gears having a diameter of 10 mm.

Gears having a low pitch (i.e., $[6]_A;[6]_B$) did not operate smoothly because there was too much slip for the gears to transmit torque continuously. A low pitch implies a large surface area (or distance) between consecutive teeth, and thus a smaller number of transitions between hydrophilic and hydrophobic regions on a gear, than for a gear with a high pitch. The variations in the capillary force are necessary to hold the gears in position once similar menisci of the two gears overlap. When these interfaces are too far apart, as in the case with the $[6]_A;[6]_B$ gears, rotation of the driving gear allows it to slip against the surface of the driven gear until the teeth of the gears misalign (i.e., the hydrophilic region of one gear approaches the hydrophobic region of the other gear). The gears continue to slip until the teeth are again realigned, and this process repeats itself.

Gears having a high pitch (i.e., a large (~48) number of teeth per surface area of the gear) would generate menisci without

(45) We could not perform experiments with $\omega > 1500$ rpm, since the rotating bar magnet could not reach these angular velocities. At these high angular velocities, hydrodynamic repulsion should dominate over the capillary attraction between the gears; the driving gear should repel the driven gear similar to that in Figure 4C-ii.

significant lobes.[46] We believe that the interaction between these gears would be similar to that between two rings having smooth surfaces, i.e., rings that are either completely hydrophilic or completely hydrophobic.

Gears having different numbers of capillary teeth, $[n]_A \neq [n]_B$, were unable to continuously transmit torque, although some torque was transferred with the presence of slip; these observations described the $[8]_A;[6]_B$, $[12]_A;[6]_B$, and $[12]_A;[8]_B$ systems. In these systems, the hydrophilic regions overlapped preferentially, but the different sizes of the regions caused the gears to misalign as the gears rotated.

4. Pitch: Toothed Gears. The pitch is also an important factor for the operation of toothed gears at the fluid/air interface, since the teeth of the gears determine the shapes of the patterned menisci. For example, we designed magnetic pinions having 0, 6, 12, or 20 teeth, each pinion having the same radius, for driving the internal gear in Figure 3. The optimal configuration was with the magnetic pinion having 12 teeth, since only the outer part of the teeth of the pinion was in physical contact with the teeth of the internal gear. This number of teeth generated a capillary interaction between the teeth of the pinion and the teeth of the internal gear that was neither too strong nor too weak: when the pinion had no teeth, the pinion could not engage with, and thus could not mechanically drive, the internal gear; instead, the pinion rotated in the center of the internal gear.[47] When the pinion had six teeth, the teeth of the pinion tended to wedge in between the teeth of the internal gear, as the overlap of menisci between the teeth, and the strength of the interaction, of the gears was high; when the pinion had 20 teeth, the contour of the meniscus was almost smooth, and the capillary interaction between the pinion and internal gears was weak. In this latter configuration, the pinion disengaged from the internal gear and rotated in the center of the internal gear (similarly to the motion of a pinion with no teeth). Thus, the pitch of a gear can be used to increase or decrease the degree of interaction with another gear.

D. Multiple Types of Drive. Gears that are coupled through capillarity or shear can have interactions that are different from ones that are coupled mechanically. For gears in which torque is transmitted through capillarity or shear, the interface between gears allows slip, and the linear velocities of the rims do not have to match. Figure 8 shows a system in which gears 1 and 3 are driving gears and gear 2 is a driven gear. Gears 1 and 3 have physical teeth; these teeth cause the meniscus around them to have a scalloped contour. Gear 2 can either have a smooth rim patterned into hydrophilic and hydrophobic regions (capillary, A) or physical teeth (mechanical, B). Gears 1 and 3 are designed to have the same initial linear velocity, i.e., $v_1 = 2\pi\omega_1 R_1 = v_3$, where $\omega_3 = 2\omega_1$ and $R_1 = 2R_3$.

In the capillary-coupled system (Figure 8A), the linear velocity of gear 1 decreases upon contact with gear 2, since gear 2 acts as a load. The linear velocity of gear 3 does not change, so $v_1 = v_2 < v_3$. Because the interface between the gears allows slip, gear 3 remains aligned with the other gears, and helps to drive gear 2. The linear velocities of gears 1 and 3 do not have to match in order for all three gears to operate in this aligned configuration.

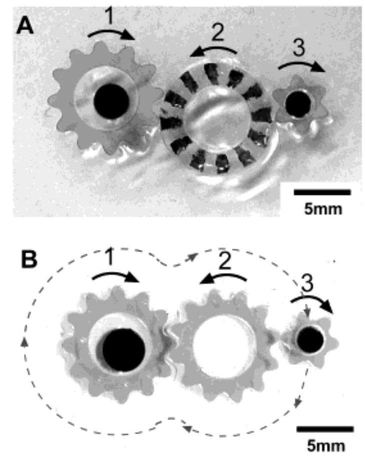


Figure 8. Multiple types of drive. (A) Capillary system. The schematic diagram shows different types of gears interacting through overlap of menisci. Gears 1 and 3 are driving gears; they are hydrophobic and have physical teeth. Gear 2 is diamagnetic and is patterned hydrophilic and hydrophobic; it does not have physical teeth. The gears are stable in this aligned configuration when the linear velocities of the rims do not match, since the interface between the gears allows slip. (B) Mechanical system. In a similar configuration, but with gear 2 having teeth, the system does not allow slip. Gear 3 therefore travels around the perimeters of gears 1 and 2 when the linear velocities of the rims do not match. In both (A) and (B), the ferromagnetic pinions are not centered within the ring gears due to the loads placed on the gears. The axis of rotation of the magnet was positioned underneath the pinion of gear 1.

In the mechanically coupled system (Figure 8B), $v_1 = v_2 < v_3$. Because this system is mechanically coupled, the interface between the gears does not allow slip, and gear 3 rotates faster than gears 1 and 2; it therefore travels around the perimeter of the other gears, following a path indicated by the dashed line in the figure. The angular velocities of the rims must be equal in order for all three gears to operate in this aligned configuration.

E. Complex Systems of Gears. We demonstrate the interplay of magnetic interactions, hydrodynamic shear, capillarity, and mechanical interactions by using a system in which the gears follow the contour of an arbitrary shape as they rotate; this system has no analogy in conventional, mechanically geared systems. Figure 9A shows two magnetic gears: (i) one outside (outer gear) and (ii) one inside (inner gear) of a diamagnetic, asymmetrical, closed polymer track. Although both gears rotate in the direction of the magnetic field (produced by the bar magnet), they travel around the track in opposite directions. The inner gear travels counterclockwise and the outer travels clockwise in the paths indicated by the dashed lines in the figure. The gears and the asymmetrical track attracted one other by capillary interactions between menisci on their hydrophobic surfaces.

The outer gear (Figure 9A-i) was attracted inward toward the axis of rotation of the magnet and traversed the whole perimeter of the asymmetrical track, as long as this axis was positioned inside the track. Here, capillary interaction between the gear and track was coupled with the attraction of the magnetic gear toward the axis of rotation of the magnet to stabilize the path of the gear. Hence, it was not necessary to generate additional capillary attraction by having teeth on the outer perimeter of the track.

(46) We did not test capillary gears having greater than a total of 12 teeth, since it was difficult to pattern these gears manually, but gears with physical teeth having a high pitch did generate menisci without significant lobes.
(47) This motion is the same as that produced by the driving gear in Figure 4A, i.e., when a magnetic pinion drives a ring gear by hydrodynamic shear.

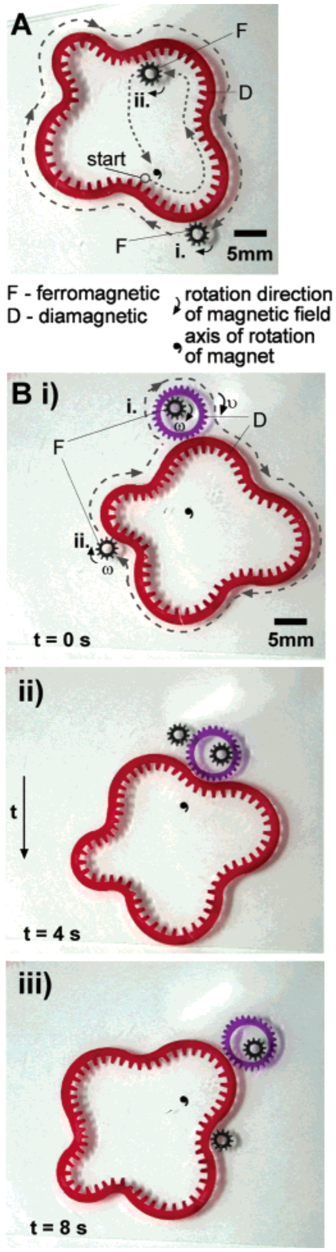


Figure 9. Photographs showing the paths (depicted by the dashed lines) of magnetic gears traveling around the perimeters of a diamagnetic asymmetrical track. The (•) marks the axis of rotation of the magnet (drawn in Photoshop; this chiral shape was chosen to indicate that the orientations of the frames do not change as the gears rotate). Surfaces of the gears and the track are hydrophobic; they are attracted to each other due to capillarity. (A) (i) The (outer) gear outside the track travels clockwise around the track. (ii) The (inner) gear inside the track travels counterclockwise from starting position ○, along the right side of the track. When the gear reaches the top of the track, attraction of the gear to the axis of rotation of the magnet causes the gear to detach from the track. The photograph in (A) shows the inner gear just as it has detached from the track. (B) Series of photographs showing (i) a diamagnetic ring gear (that is driven by a magnetic pinion) and (ii) a magnetic gear traveling around the outer perimeter of the track. The ring gear rotates at angular velocity υ, where $\upsilon \sim 10^{-1}\omega$, and ω is the angular velocity of the pinion.

Teeth were required on the inner perimeter of the track to increase the overlap of the menisci between the track and the inner gear (Figure 9A-ii); when the inner perimeter of the track was a smooth surface, the capillary attraction between the track and the gear was weak, and the inner gear detached from the track much more readily than when teeth on the track were present. When the inner gear traveled sufficiently far from the axis of the magnetic field, the gear detached from the track and returned to the axis.

In Figure 9B, a magnetic pinion within a diamagnetic ring gear (i) was introduced on the outside of the asymmetrical track; it also followed the perimeter of the track. Since rotation of the ring gear is due to the hydrodynamic shear produced by the magnetic pinion, the rotation rate of the ring gear, υ, was ~10× slower than the angular velocity of the magnetic pinion, ω. The unconstrained magnetic gear (ii) moved around the track more rapidly than did the ring gear, and therefore traveled around the surface the ring gear.

Conclusions

We have designed a self-assembling system of gears based on capillary interactions at a fluid/air interface. Previously, we used capillary interactions to induce self-assembly of systems at equilibrium.[1,2,24,31,48−51] Here, capillary interactions caused self-assembly of a dynamic system in which torque could be transmitted among the components.

We have identified three mechanisms for transmission of torque at the fluid/air interface. Two are more familiar—mechanical (based on interdigitated physical teeth) and hydrodynamic shear; one is less familiar—the interaction of scalloped menisci. The gears have differently shaped "teeth" depending on their intended mechanism of action. Physical teeth can serve at least two functions at a fluid/air interface: they can interdigitate mechanically, and they can generate scalloped menisci (by which the teeth can interact through overlap of menisci). Patterning the edges of a smooth rim into alternating hydrophobic and hydrophilic regions can also generate a different class of "teeth"—that is, "capillary teeth"—and scalloped menisci. Experimentally, using planar lithography, it is easier to fabricate gears with teeth than it is to pattern the smooth rim of a disk into hydrophilic and hydrophobic regions.

The systems described in this paper have two characteristic properties that would be difficult to obtain with systems of fixed gears: self-leveling, and—we assume—ultralow wear. These systems also enable interactions between gears that are difficult or impossible in conventional mechanically coupled systems: gears are not required to have matching linear velocities of the rims if they are coupled by capillary interactions, and the gears can follow the perimeters of arbitrary shapes. Because these systems are dynamic and externally driven, the assembly and disassembly of the components can be controlled by changing the angular velocity of the driving motor; these systems can serve as the bases for the assembly of reconfigurable devices. An externally driven system also implies that direct mechanical coupling or alignment of the driving motor and the driven gears is not required, and that multiple components can be driven using a single driving motor.

(48) Bowden, N.; Arias, F.; Deng, T.; Whitesides, G. M. *Langmuir* **2001**, *17*, 1757−1765.
(49) Bowden, N.; Tien, J.; Huck, W. T. S.; Whitesides, G. M. *In Supramolecular Organization and Materials Design*; Cambridge University Press: New York, 2002; pp 103−145.
(50) Bowden, N.; Terfort, A.; Carbeck, J.; Whitesides, G. M. *Science* **1997**, *276*, 233−235.
(51) Gracias, D. H.; Boncheva, M.; Omoregie, O.; Whitesides, G. M. *Appl. Phys. Lett.* **2002**, *80*, 2802−2804.
(52) Pictures of mechanical gears were adapted from the following sources: http://www.seisa.co.jp/english/e_uchihaguruma.htm, http://www.mit.edu/afs/athena/course/2/2.972/www/reports/torque_converter/torque_converter.htm, and http://www.howstuffworks.com/gear2.htm.

The systems we have described also have limitations that make them less useful than mechanical gear systems for applications that require a larger amount of torque to be transferred than this system can supply, or that require the gear system to be stable to perturbations. The rotational speed of the driving gear limits the amount of torque that a driving gear can transfer to a driven gear. As we noted, when the driving gear rotates at a rate that is higher than an upper limit, repulsive forces prevent the gears from assembling. When the driving gear rotates more slowly than a lower bound, the gears stick together and the resulting composite rotates as one unit. Thus, there is a range of torques that the system can transfer, and these torques are small. In addition, since the system operates by interaction with a magnetic field, removing the system from the region above the rotating, external magnetic bar will cause the gears to stop rotating. Small perturbations to the system, such as shaking, produce oscillations in the fluid that also disrupt the gears.

The self-assembling gear systems presented here are planar (2D), but these systems may be extended to three dimensions (3D) by gears interacting through fluid/air and fluid/fluid interfaces.[19] The extension of these gear systems to 3D would be interesting for two reasons: (i) multiphase systems can potentially lead to the formation of 3D asymmetrical devices having more functionality than 2D systems, and (ii) we expect to find complex interactions among components and interesting collective behavior emerging from 3D dynamic systems.

Although we showed assembly of components that were millimeter in size, the forces should scale to micrometer (μm)-scale components; we believe that dynamic assembly of μm-size gears should be possible.[49] These gear systems, especially if fabricated at the μm scale, may find applications in microelectronics and microelectromechanical systems (MEMS).

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