In situ assembly of linked geometrically coupled microdevices

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Complex systems require their distinct components to function in a dynamic, integrated, and cooperative fashion. To accomplish this in current microfluidic networks, individual valves are often switched and pumps separately powered by using macroscopic methods such as applied external pressure. Direct manipulation and control at the single-device level, however, limits scalability, restricts portability, and hinders the development of massively parallel architectures that would take best advantage of microscale systems. In this article, we demonstrate that local geometry combined with a simple global field can not only reversibly drive component assembly but also power distinct devices in a parallel, locally uncoupled, and integrated fashion. By employing this simple approach, we assemble and demonstrate the operation of check valves, mixers, and pistons within specially designed microfluidic environments. In addition, we show that by linking these individual components together, more complex devices such as pumps can be both fabricated and powered in situ.

colloids | microfluidics | micromachines

Over the past decade, there has been significant interest in microfluidic technology; however, its impact has and will remain limited without widespread use (1). To broaden application into areas such as the typical laboratory for research application or point of care for biomedical analysis, there is a need for simplified devices that retain complex function. One significant hurdle to this realization is the in-place fabrication and integration of individual fluidic microcomponents. Small pieces simply cannot be easily handled or connected in a manner comparable with macroscale device fabrication. To overcome this, nature has chosen self-assembly (2), a process where pieces simply cannot be easily handled or connected in a manner comparable with macroscale device fabrication. To overcome this, nature has chosen self-assembly (2), a process where

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Results and Discussion

Here, we describe our experiments with 3 devices, each designed to highlight a particular aspect of our approach: first, that assembly can be performed in confined geometries; second, that the approach can be used to power devices once fabricated; and third, that devices can be linked, and confining structure can play an important role in both device assembly and function. Finally, and in the context of this last device, we discuss the assembly process in some detail.

In-Place Assembly—The Check Valve. Assembly of pieces within enclosed geometries is necessary for those devices that require components larger than their inlets and outlets. One device that clearly demonstrates the utility of in situ construction is the
check valve, a fluidic rectifier where flow is allowed in one direction but not the other. To fabricate such a device at the microscale, individual components must be brought within the valve chamber and fused together in place. With the paramagnetic colloidal particles we employ in these studies, thin microfluidic channels provide a planar, pseudo 2D environment. As shown in Fig. 1, for check valve function, the confining geometry is chosen such that individual component particles can flow in and out of all connecting channels. With application of the bulk magnetic field, however, magnetic dipoles strongly attract, driving stable device assembly into a compact, lowest-energy morphology. As can be readily seen here, the 7-particle clusters formed are too large to pass either through the valve outlet or inlet. Of important note is the assembly process is a reversible one; as the field is switched off, the clusters will disassemble, turning off device function if desired. One significant advantage of the colloids we use here is that they are readily disassemble, turning off device function if desired. One significant advantage of the colloids we use here is that they are readily available with a variety of surface functionalities, including reactive groups that can be used for irreversible assembly binding (19) if continued device operation is useful after field switch-off. And although only 2 of these valves are shown, their construction could be performed in a parallel fashion because of the global nature of the driving field.

In Fig. 1, function of the individual valves is demonstrated by fluid movement in the center channel; flow to the right closes the top valve and opens the bottom—flow to the left closes the bottom valve and opens the top. Although the single surrounding field has been used for assembly of both, it is important to note that individual valve action is uncoupled; flow blocks 1 channel but simultaneously opens the other. Efficiency of the valves is influenced by multiple factors. Because the colloidal building blocks are spherical, they do not completely block flow at a potential issue for some applications that cubic, space-filling colloidal building blocks (20) with embedded functionality could solve. In addition and because of the dynamic nature of the assembly method, field rotation leads to a net torque on the colloidal assembly. Apparent in the accompanying Movie S1, this rotation induces a local flow that prevents a tight seal with the channels they are designed to block with a measured value of $V_{0} = (V_{0} + V_{c}) = 64\%$.

**Power Across Length Scales—Mixing.** Rapid assembled-cluster rotation may be a disadvantage for this particular valve design, but associated fluid movement can be useful for other applications. It is well-known and a significant area of research in microfluidics that mixing in microscale geometries is difficult because of the laminar nature of the fluid flows, the associated lack of turbulence, and the resulting reliance on diffusion (21, 22). One design that has been used to mix in relatively large microfluidic devices is to use multilayer soft lithography to create pumps and valves and mix fluids by circulating them within a circular channel (23), an approach that has been used, for example, in screening for protein crystallization (24). This technique, however, relies on the supporting pressurization equipment associated with operating many of these pumps simultaneously that limits very high-level parallelization.

Shown in Fig. 2 is an active mixer created through the assembly of small colloidal building blocks in a confining geometry in a manner similar to those used for the check valves. In this system, 2 separate streams, one an aqueous colloidal solution and the other without colloids, are brought together at a mixing junction before expansion into a standard square channel. To demonstrate the utility here, we use a relatively slow-diffusing tracer consisting of nonmagnetic 0.76-$\mu$m polystyrene particles. This represents a good system because lateral concentration profiles can be directly determined by particle counting and not inferred from a bulk measurement. Without magnetic field application, lateral concentration profiles were measured (Fig. 2) at the channel start and at distances significantly down the channel length (data not shown). Here, the curves of relative tracer concentration were fit to the simple solution for 1-dimensional diffusion (25) given a step concentration initial condition:

$$C(x, t) = \frac{C_0}{2} \text{erfc} \left( \frac{x}{\sqrt{4D_1t}} \right) = \frac{C_0}{2} \text{erfc} \left( \frac{x}{\sqrt{4D_2y/\tau}} \right),$$

where $C_0$ is the initial concentration, $D_1$ is the diffusivity in the channel, $D_2$ is the diffusivity in the outside fluid, $y$ is the distance from the channel edge, and $\tau$ is the characteristic relaxation time.
with \( C_0 \) the initial tracer concentration, \( D \) the diffusion coefficient, \( x \) the lateral position, \( y \) the distance down the channel, and \( v \) the fluid velocity. Using the measured value of \( v = 3.6 \, \mu \text{m/s} \), we fit the unmixed concentration profiles (Fig. 2) and find \( D = 0.73 \, \mu \text{m}^2/\text{s} \), in good agreement with a value of \( 0.64 \, \mu \text{m}^2/\text{s} \) based on the particle radius and predicted from the Stokes–Einstein relation. Upon field actuation and rotation of the assembled cluster at \( \sim 10 \, \text{Hz} \), efficient mixing is readily observed in the region directly after the chamber. Quantifying the resulting concentration profile and using the diffusion values determined from the unmixed case, we predict, using Eq. 1, that channel lengths \( > 15 \, \text{cm} \) or times \( > 10 \, \text{h} \) would be required to achieve a comparable level of tracer dispersion via diffusion alone.

**Coupling Function to Local Geometry—Pumping.** The assembled mixer clearly demonstrates that a global field can be used to dynamically control microsystems and transport power across length scales to drive a microscale device. As is well known for such systems, viscous effects dominate over inertial effects, giving rise to the laminar flow characteristics; however, we see from these studies that the magnetic forces that arise from the applied field can be significant. To quantify their relative strength we use the Mason (Mn) number (26), where

\[
\text{Mn}^{-1} = \frac{\mu_0 M^2}{32 \pi \nu v_0} = \frac{\text{magnetic forces}}{\text{viscous forces}}. \tag{2}
\]

For the rapidly rotating clusters of Fig. 1 composed of 4.5-\( \mu \text{m} \) particles (of volume \( \nu_0 \)) we estimate rotation rates of \( \omega \approx 10 \, \text{s}^{-1} \). Using literature values for the magnetization \( M \) (27) at the low applied field strengths of \( \sim 5 \, \text{mT} \), where these experiments were conducted, we find \( \text{Mn}^{-1} \approx 1,000 \), emphasizing the strength of magnetic forces under these conditions. Such a clear dominance over fluid forces at these scales suggests that significant additional functionality is available with a modified approach.

To take advantage of this for useful microscale device operation, we need to harness assembly rotation in a manner that efficiently extracts rotational torque and imparts this to useful force propagation in desired directions. To do this, we employ a rack-and-pinion arrangement commonly associated with automotive steering mechanisms that couples pinion rotation to translation along the teeth of the complementary rack. The general concept is illustrated in Fig. 3, where a rotation of a square “wheel” leads to a smooth translation along a “road” composed of a series of truncated catenaries where \( \gamma = -\cosh(x) \) and the angle at which these catenaries meet corresponds to the interior angle of the square wheel (28). Mathematical solutions for the roads corresponding to wheels of arbitrary structure can also be generated and correspond to inverted cycloids for wheels constructed from assembled spheres; however, these have sharper profiles, features that replicate poorly during the soft lithography process at the necessary resolutions corresponding to the colloidal particles we employ here.

To demonstrate this approach, we integrate a microfluidic wall “rack” of slightly smoother structure than theoretically desired and a colloidal assembly “pinion” to create a piston capable of forcefully pushing fluid down a microfluidic channel. Although other designs are feasible, the rack in Fig. 4 is of finite length, requiring a reverse of the device rotation for continuous operation. To fix net system pumping in 1 direction as the field is switched between clockwise and counterclockwise rotation, we integrate the piston with active check valves composed once again of field-assembled colloidal particles. Here, a different geometry and diamond-shape structure was chosen to prevent assembly rotation and simplify design, with only 1 valve required at each device end. Available as Movie S2, real-time video of device actuation clearly demonstrates the parallel operation of multiple devices, the linked function of these devices, and the effectiveness of this approach. With the addition once again of nonparamagnetic tracer particles for flow visualization, we obtain at our low field strength flow rates of on the order of 1 nL/hr within the channel. Here, we see that the net flow is proportional to the rotation rate of the pinion, results that
demonstrate the strong coupling between field-induced rotation and colloidal assembly translation and function.

Here, it should be noted that, if the magnetic field is switched off, clusters fully disassemble and particles diffuse away by means of Brownian motion. Perhaps one of the most interesting observations of the behavior of these devices is their stability; once assembled they are, if not in their absolute ground state, in an extremely stable local minimum. This is due to a favoring of specific cluster shapes by microfluidic wall interaction and the potential barrier that a particle must overcome to be translated into another position at the cluster exterior. Based on the magnetic dipole interaction and by comparing the number of potential barriers that a particle must overcome to be translated as assembled they are, if not in their absolute ground state, in an energetic ground states through dynamic coupling to local geometry offers a greater variety of available components for microscale device development.

Conclusions

Microdevice fabrication and actuation using reversibly assembling colloidal systems and bulk magnetic fields provides a number of significant advantages over macroscopic techniques. The ability to easily and without direct contact link external energy sources to microscopic operation by local geometry coupling, without the loss of discrete device function, provides a promising route to practical and portable microsystem fabrication and operation. With the potential for massive parallelization, complex devices can clearly be assembled from simple, controllable, and modifiable building blocks within tightly confining microgeometries that influence the shape of the contained assembly by favoring the formation of dynamically stable clusters. The significant flexibility of this single technique has been demonstrated by the in situ powering and integration of multiple microfluidic devices including valves, mixers, and pumps. Although these results were obtained with associated instrumentation that is certainly macroscopic in size and not amenable to portable applications, the actual magnetic fields used were relatively small and could instead be generated with significantly smaller hardware (29, 30). Also, the components were assembled at microscopic sizes; however, the physics associated with magnetic-field based manipulation are scalable to smaller dimensions. Resolution in fabricating the surrounding matrices instead plays a significant role, and methods other than the soft lithography (31) used here, including those for glass or silicon, could be used instead because device function is not limited to elastic channel structures.

Materials and Methods

The microfluidic systems were assembled in polydimethylsiloxane (PDMS) by using standard soft-lithography techniques (32). The channels created by using this approach were planar and fabricated such that channel height was typically little more than the particle diameter. For our investigations, Dynabeads (www.dynalbiotech.com) of diameter 4.5 μm were used; these readily available particles are superparamagnetic because of the presence of Fe₃O₅ and therefore exhibit magnetic properties only in the presence of a magnetic field. To create the magnetic fields, 4 coils of 25-mm diameter with 1,000 windings were placed pairwise around the device along the axes of the sample plane. Through these coils, currents between −1 and 3 A were applied in an offset and sinusoidally varying fashion at ~100 Hz, each with 90° phase shift to its neighbors, resulting in ~5 mT to induce both particle attraction and assembly rotation (33) within the microfluidic system (see Fig. 5). The coils were placed far enough apart that microfluidic devices ~4 cm in diameter could easily be studied. In this setup, an optical trap was included for ease of particle manipulation and to control the number of paramagnetic colloids within confining environments. For tracer diffusion studies, 0.76-μm polystyrene particles (DS03R, Bangs) were used at low concentration; by using image processing (IPS, Visiometrics), these were individually counted and converted to normalized concentration for analysis.

ACKNOWLEDGMENTS. This research was supported by the Alexander von Humboldt Foundation and the Deutsche Forschungsgemeinschaft.