Dynamically programmable fluidic assembly

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A major challenge in fluidic assembly is the dynamically programmable fabrication of arbitrary geometries from basic components. Current approaches require predetermination of either the assembly machinery or the component interfaces for the specific target geometries. We present an alternative concept that exploits self-assembly forces locally but directs these forces globally, allowing fabrication and manipulation of target structures without tailoring the substrate or interfaces. By controlling the flow in a microfluidic chamber, components are directed to their target locations where local interactions align and bond them. Following this approach, we demonstrate and quantify the experimental assembly of structures composed of two to ten components. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3048562]

There has been great interest recently in self-assembly[1–3] as an avenue for the fabrication of functional microscale[4] and nanoscale[5,6] devices. However, in order to assemble structures with arbitrarily specified (nonregular, nonrandom) geometry, bottom-up assembly approaches generally require selective intercomponent affinities for each pair of components using mechanisms such as free surface energy minimization with shape recognition,[4,7,8] electrostatic interactions,[9] and DNA base pairing.[10] These static affinities are analogous to the interlocking shapes that uniquely determine piece positions in a jigsaw puzzle. This "jigsaw puzzle" approach, however, has several challenges: First, the components must be redesigned specifically for each new target structure. Second, as the target structure's complexity increases, the number of distinct affinity patterns required also increases. This causes the selectivity of intercomponent affinities to decrease due to a fixed affinity pattern space. The result is an increased probability of assembly errors and a decrease in assembly rates due to the relative dilution of each component type. An alternative approach[11] assembles a target structure using a set of rails to guide components along predetermined paths. This approach shows promise in its ability to accommodate a large variety of target geometries; however any given rail architecture places constraints on the set of attainable target structures and manipulation paths. For example, railed substructures cannot easily be rotated to form larger structures or to be used in different configurations. Thus, the rail system itself must be tailored to the target assembly task.

Here we study an unguided assembly process that uses fluidic forces to assemble arbitrary structures from regular components, while avoiding the limitations of a purely stochastic or fixed-rail system. This increased flexibility comes at the expense of more complicated control requirements. Instead of propelling components along guided paths, our system creates the fluid flow conditions that attract components to where they are needed. At this point the regular geometric design of the components causes them to self-align and bond. Robust assembly procedures are used to overcome the stochasticity inherent in such an indirect assembly method. Thus, the assembly is directed and does not rely on stochastic agitation for component transportation. These features help to overcome the slow assembly rates and assembly errors that inhibit the scalability of current self-assembly processes to the fabrication of arbitrary structures while maintaining the capability of defining the target structure dynamically (i.e., without requiring component or system redesign). Thus our approach combines the opportunities—and challenges—of both the "pure self-assembly" and path-directed approaches.

We demonstrate our semidirected fluidic assembly process experimentally in two dimensions. Our components are 500×500 μm^2 silicon tiles with 30 μm thickness and a single passive latch on each side [Fig. 1(a)]. Two main features of the tile design facilitate assembly: a regular pattern on the tiles' sides causes adjacent tiles to self-align, while passive latches on each tile side [Fig. 1(b)] bond tiles together. We achieve indirect control of the positions of our microscale components by immersing them in an assembly fluid within a polydimethylsiloxane microfluidic chamber [Figs. 1(c) and 1(d)] and directing the fluid flow through the

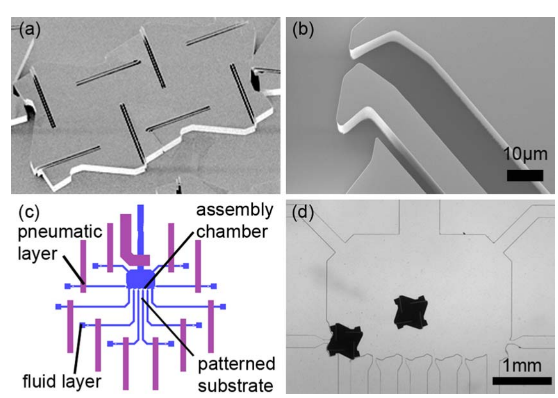

FIG. 1. (Color online) Experimental system. (a) Scanning electron microscope image of silicon tiles with patterned sides for alignment, held together by compliant latches. (b) Detail of latch design. (c) Computer aided design drawing of multilayer microfluidic assembly chamber with pneumatic valving and intersecting channels for injection and removal of fluid and tiles. (d) Optical micrograph of assembly chamber and two microtiles.

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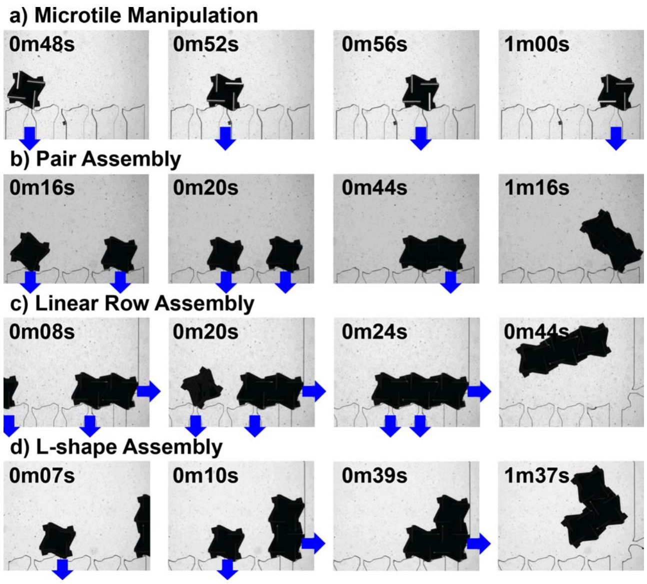

FIG. 2. (Color online) Microtile manipulation and assembly. Frames taken from video micrographs of (a) an automated microtile manipulation and [(b)–(d)] three assembly experiments. Timed valve actuation directs pressurized flow into the microfluidic chamber and out the indicated openings. Fluid flow applies hydrodynamic forces to the microtiles, causing them to move and assemble. Alignment patterns and compliant latches cause adjacent tiles to self-align and bond together. The valving sequences determine the final structures.

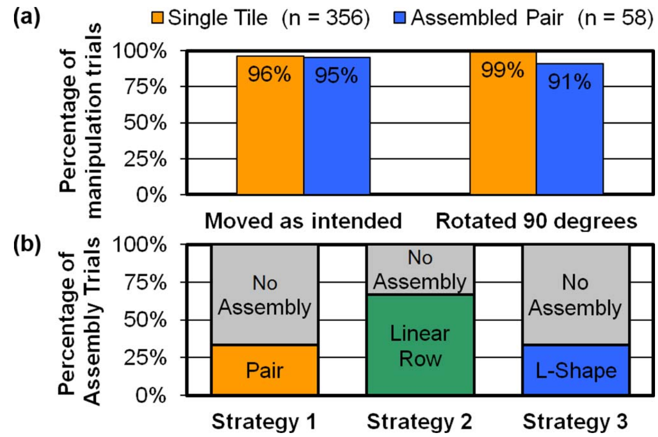

FIG. 3. (Color online) Experimental results. (a) Microtile manipulation: percentage of automated manipulation experiments in which a single tile or assembled tile pair moved and rotated as anticipated. (b) Deterministic assembly: resulting structures at the end of 30 consecutive automated assembly experiments for each of three different open-loop assembly strategies (valving sequences).

chamber (see Supplementary Material[14] for details). We control the flow conditions by regulating the pressures at eight active openings where microfluidic channels join the assembly chamber—four along the bottom and two on each side. (As the chamber is mounted horizontally, *bottom* is an arbitrary designation.) A geometric pattern along the bottom of the chamber causes the microtiles to seat in specific locations adjacent to each of the openings, thus forming a "patterned assembly substrate." The remaining three larger openings are used for the introduction of tiles into and extraction of debris out of the chamber.

On- and off-chip valving, achieved using soft lithography,[12] allow digital control of the pressure (high, low, or closed) at each active opening. This is essentially a form of *boundary condition phenomenological superposition distributed manipulation*, as defined by Varsos and Luntz.[13] The resulting fluid flow applies hydrodynamic forces and torques to a microtile within the chamber, causing it to be attracted to an opening location on the assembly substrate. Subsequently, the opening and closing of other valves attract other microtiles and bind the components together to form subassemblies. These subassemblies can then be rejected from their seated position and reoriented in the same way as individual components. Thus, with appropriate sequencing of valve openings, a set of subassemblies can be made to form deterministically into an arbitrary structure.

Using the correct sequence of valve states, we assembled and manipulated elementary structures, which form the fundamental building blocks for more complex assemblies. We demonstrated the repeatable automated assembly of two-tile constructs and both three-tile polymorphs using open-loop valving control (see Supplementary Material,[14] movie S4). As a first step, we introduced a single tile into the chamber and marched it along the substrate from one inlet/outlet position to the next [Fig. 2(a)]. This was achieved by opening the valve at the destination position on the substrate to atmospheric pressure and pumping fluid into the chamber from a combination of the remaining openings. Using this automated open-loop control strategy, the tiles moved one position in the desired direction 96% of 356 attempts [Fig. 3(a)]. During 99% of these motions, the tiles rotated 90° when moving from one outlet to the next. Experiments in the manipulation of assembled tile pairs showed similar trends [Fig. 3(a)].

The next step toward the assembly of complex shapes was to bring two tiles together and induce them to latch. An automated open-loop valving sequence was developed to attract two tiles to the substrate, bring them toward one another, and induce them to latch together [Fig. 2(b)]. The tiles always began in the same initial positions, but their orientations were not tightly controlled. Valving configurations for this 60 s sequence were changed on a 4 s cycle. The tile pair was subsequently moved to verify assembly. This control sequence (strategy 1) resulted in an assembled pair 10 out of 30 consecutive experiments [Fig. 3(b)]. In the remaining experiments, no assembly occurred.

As a demonstration of the next layer of assembly, we fabricated three-tile structures in the two possible polymorphs: a linear row and an L shape. In each case we began with a single tile and a latched pair assembled using valving sequence such as that used in strategy 1. For linear row assembly (strategy 2), we began with the assembled pair horizontal on the substrate and attracted the third tile next to the assembled pair (Fig. 2(c)). The L-shape assembly sequence (strategy 3) began with a vertical assembled tile pair and attracted a third tile to be attached at the base [Fig. 2(d)]. In both cases any structures assembled at the end of the sequence were released from the substrate to test for assembly. Strategy 2 assembled a three-tile row 20 of 30 consecutive trials while strategy 3 assembled an L shape 10 of 30 trials [Fig. 3(b)]. More importantly, strategy 2 *never* resulted in the assembly of an L shape and strategy 3 never resulted in the assembly of row. Thus, we found our strategies to be *deterministic* in the sense that they never resulted in false assemblies. In all of the cases where strategies 2 and 3 were not successful, the end products were the same as the initial components: a latched pair and a single tile [indicated by No Assembly in Fig. 3(b)]. Of course, the success rates of any of these three strategies could be increased arbitrarily high by simply repeating the valve sequence (at the cost of longer assembly times).

The latches used in these experiments were designed for relatively low assembly and disassembly energies. This allowed the tiles to latch easily but also meant that many assemblies came apart in experiment, reducing the assembly success rates. We also tested stiffer latches, which permanently bonded tiles together (Supplementary Material,[14] Fig. S1). However, the stiffer latches also made assembly more difficult and complicated the iteration of experiments.

Alternative valve control strategies are possible to facilitate the assembly of larger structures and to increase assembly rates. While the valving timings and sequences of the open-loop controllers employed here could be further tuned to improve assembly speed and robustness, another approach is also promising: closed-loop feedback control. An automated controller with image processing could be used to identify—and correct for—assembly errors and improve the system's efficiency and reliability. We demonstrated this closed-loop approach with user-controlled valving guided by visual feedback. In this manner we assembled symmetric structures composed of four to ten components (Fig. 4), as well as a number of pairs of complementary mirror-image structures (Supplementary Material,[14] Fig. S2).

In the extension of our assembly approach to larger structures, it is important that our system scales well with large numbers of components. One important condition for scalability is the capability of parallel assembly. For large target structure sizes, fabricating by adding components sequentially takes a prohibitively long time. However, such a structure may be feasibly manufactured by dividing the work among multiple assembly sites working in parallel and then bringing together the produced subassemblies. Our system lends itself well to this kind of parallel assembly. In experiment we have demonstrated that our system manipulates assemblies nearly as effectively as single components [Fig. 3(a)]. One could imagine a hierarchical approach in which the six-tile-wide substrate of our experimental system was expanded to a network of intercommunicating assembly sites with new components attracted where they are needed. Subassemblies would then be passed on from one site to the next and assembled repeatedly into structures of increasing size until the final structure was completed.

The system presented here forms the basis for a dynamically programmable fluidic assembly technique in which regular microscale components are assembled hierarchically into arbitrarily complex target geometries. Applications for such a technique include the fabrication of a wide range of micro/nanoelectromechanical system (MEMS/NEMS) devices. Additionally, since our assembly mechanism does not rely on the unusual properties of the materials used, a wide range of component materials and assembly fluids is possible. For example, silicon microtiles such as those used here could be augmented with sensors, actuators, and electrical interfaces, assembled in a nonconductive fluid. Alternatively,

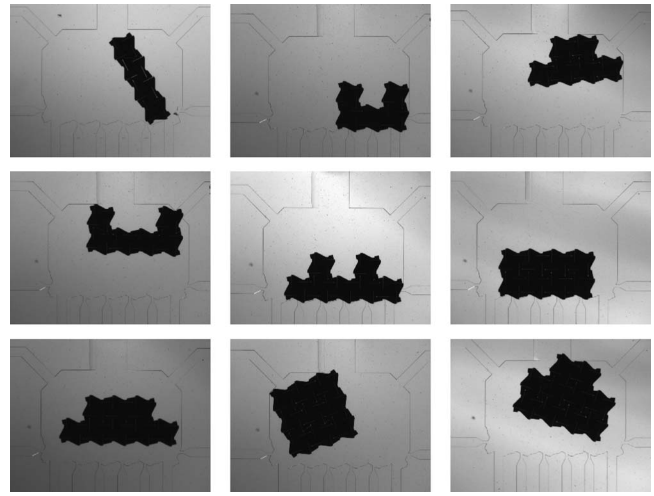

FIG. 4. Larger assemblies. Frames from video micrographs of the assembly of symmetrical structures composed of four to ten components. Valve switching was controlled manually with visual feedback [see Supplementary Material, movie S5 (Ref. 14)].

simple tiles could be fabricated *in situ* by polymerizing photocurable resin.[11] Combinations of different types of tiles are also possible. This makes our technique particularly appealing for the assembly of devices that require exotic materials with incompatible fabrication processes such as lab-on-chip/bioanalysis systems.

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[14] See EPAPS Document No. E-APPLAB-93-068850 for text detailing experimental materials and methods with figures of alternative latch design experiments (S1), assembled complementary shapes (S2), and microtile fabrication steps (S3), as well as movies of deterministic assembly experiments (S4) and visual feedback experiments (S5). For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.