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Fluidic Manipulation for Scalable Stochastic 3D Assembly of Modular Robots

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Abstract—**One of the grand challenges of self-reconfiguring modular robotics is the assembly of a functional system from thousands of components. However, to date, only systems comprised of small numbers of modules have been demonstrated. One approach to scaling to large numbers of modules is to simplify module design by relieving the modules of the typical power, control, and actuation requirements necessary for locomotion. Assembly is accomplished by taking advantage of stochastic environmental motions to move the modules into place. Here we present an experimental system in which we assemble 3D target structures stochastically from simple, 15 mm-scaled components by manipulating the fluid flow in a 1.3 L tank. We also demonstrate fundamental assembly and repair operations experimentally, and discuss initial assembly statistics.**

I. Introduction

SELF-RECONFIGURING modular robots offer many potential advantages over traditional robotics including the abilities to adapt their morphology to a given task and self-repair when damaged. The repeated use of a small set of units also potentially leads to reduced costs due to economies of scale and re-usability. However, in order to realize these advantages, the system must be able to scale to large numbers of small modules. While this feat is accomplished routinely in natural systems, to date, only robot systems comprised of less than approximately 50 modules have been demonstrated. These systems typically assemble using deterministic processes where modules move directly to their target positions. However, this puts severe power, control, and actuation demands on the modules, potentially over and above those required to fulfill their role in the final assembly.

Taking inspiration from nature, we follow a stochastic approach to modular robot assembly in which structures are assembled by taking advantages of ambient environmental motions. Stochastic modular robotic assembly has been previously demonstrated in two dimensions on an air table [1]-[3]. Gilpin *et al*. [4] followed a related approach that began with an ordered lattice and employed stochastic environmental motions to remove unwanted modules. We have previously demonstrated 3D stochastic assembly in a fluid environment [5], [6]. However, the large scales of these systems (8-13 cm), and their reliance on oil as an assembly fluid (due to exposed electronics), led to intractably slow assembly rates and made it difficult to demonstrate the assembly of more than a few components.

In order to scale to larger numbers of modules while reducing their size, it is possible to further simplify the modules by removing all components that are active during assembly. However, this simplification comes at the cost of a more complex assembly substrate capable of module manipulation. Using this approach, we have previously demonstrated the 2D assembly of 10-module structures from 500 μm x 500 μm x 30 μm tiles on a microfluidic chip [7]. These modules were self-aligning and attachment forces were provided by a passive latching mechanism on each tile edge. Further experiments also explored the possibility of printing the microtiles with electronic components [8].

Here we present an experimental system for expanding this scalable fluidic assembly approach to three-dimensional assembly. This system is composed of 15 mm scaled cubic modules which are assembled within a 1.3 L assembly tank (Fig. 1). The following sections describe the module, assembly tank, and control software design, followed by initial structure assembly and repair experiments.

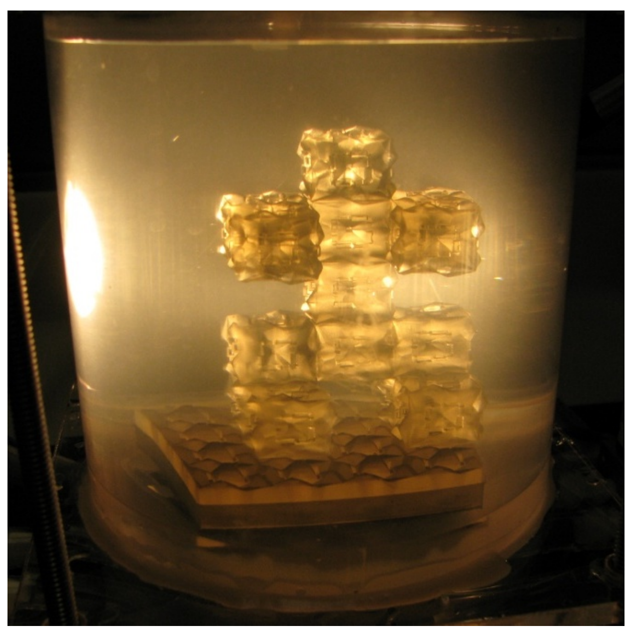

Fig. 1. 3D stochastic fluidic assembly system. Modules are assembled on an active patterned substrate on the bottom of a fluidic tank. Stochastic fluid motion is employed for module transportation. Fluid flow in and out of the substrate is modulated by a set of computer-controlled valves to direct structure assembly.

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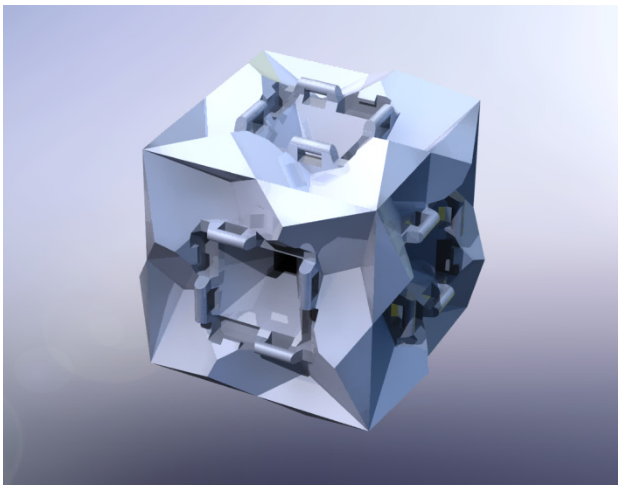
II. System Design

A. Modules

As mentioned above, the modules were designed to be as simple as possible in order to accommodate scaling to large numbers and small dimensions. Thus, there are no module components that must be active during assembly. In fact, we use single-material modules here in order to demonstrate the fluidic manipulation and assembly of target structures. Since the assembly process relies only on the modules' shape, we make the assumption that they can later be embedded with a variety of components necessary for their role within the robotic system (sensors, actuators, etc.).



(a)

(b)

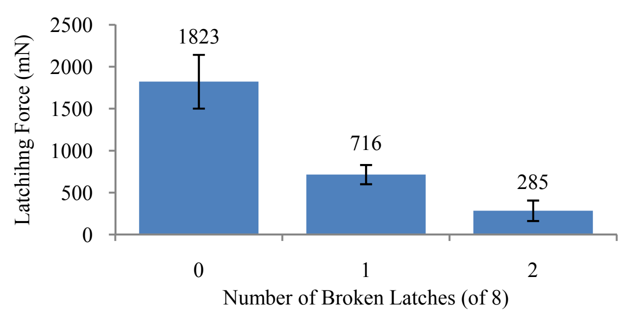
Fig. 2. Module design. (a) Computer aided design of (b) 3D printed module with a length of 15 mm. A set of extruded features on each face fit into complimentary cuts on adjacent modules in any orientation to promote alignment on a rectilinear lattice. Four latches on each face lock into complimentary protrusions to hold latched cubes together.

The modules were printed in an Objet EDEN260V 3D printer out of their FullCure720 Transparent acrylic-based photopolymer material [9]. The modules have a four-fold rotationally symmetric pattern of protrusions and depressions on each side in order to align any two modules' sides when they approach with any orientation to the nearest regular lattice configuration (Fig. 2). In addition, four latches on each face mate with four complementary shapes on an adjacent face to hold assembled cubes together.

We evaluated this latch design by measuring the total latching force between two modules. For these measurements we pressed the faces of two modules together manually, and suspended a weight from one cube while holding the other cube in the air (Fig. 3(a)). We increased the weight (by adding water to the suspended bottle) until the two modules became detached. Over 10 randomly-selected face pairings, the latching mechanism provided an average latching force of 1.8 N, and a maximum force of 3.4 N.

Due to the mechanism's redundant design, we expected its performance to degrade gracefully with damage. We tested this by measuring the force between modules with broken latches (Fig. 3(b)). We indeed found that there was still a force between the two cubes, although the average latching force was reduced to 0.7 N with one broken latch, and 0.3 with two.

(a)

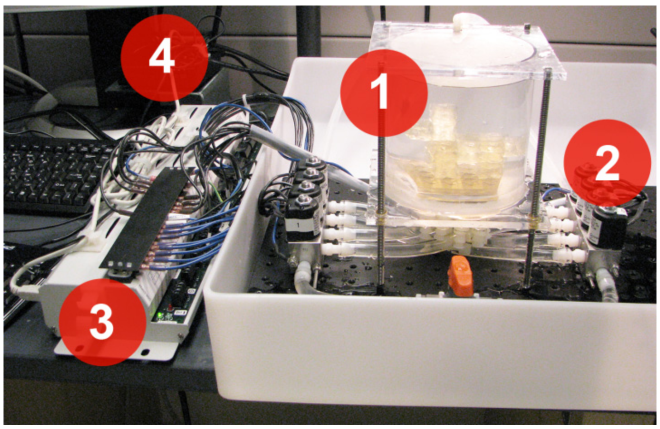


(b)

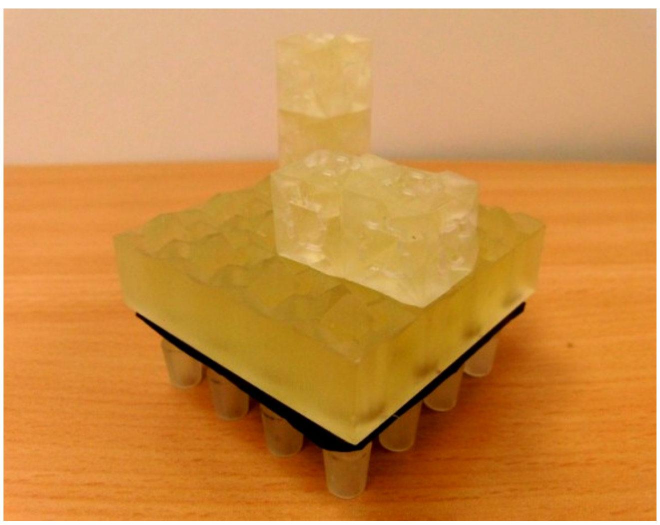
Fig. 3. Latching force measurement. (a) The strength of the latches was measured experimentally by increasing the amount of weight suspended from a latched cube until the bond broke. (b) The redundant latch design led to graceful degradation of the average latching force with one or two broken latches.

B. *Experimental Apparatus*

Our stochastic fluidic system assembles the modules described in Section II, *A* by manipulating the fluid flow in a 1.3 L assembly tank. The experimental apparatus that accomplishes this is composed of five parts: the assembly tank, a pump, a set of solenoid valves for flow control, relays and controller board, and a controlling PC (Fig. 4(a), Table I). The pump is used to circulate the assembly fluid (tap water) through the experimental apparatus. The valves (via the PC and controller) are used to switch the flow path through the assembly tank in order to indirectly manipulate the modules.



(a)



(b)

Fig. 4. Experimental Apparatus. (a) The experimental apparatus consists of 1) the assembly tank, 2) the control valves, 3) valve relays and USB controller board, 4) PC and keypad, and 5) fluid pump (not pictured). (b) 3D printed active substrate component with 16 ports shaped to complement cube faces.

Module assembly occurs on a patterned substrate on the bottom of the assembly tank. The substrate consists of a four by four array of ports patterned to match the cube faces, but without the latching mechanism (Fig. 4(b)). A pyramid at the centre of each port inserts into an indent in the center of each cube face to further improve alignment. Each port also has four fluid channels (one at each corner) that connect to a single channel on the outside of the tank. Two valves (normally closed) associated with each port can be opened to connect the port to either the high or low pressure end of the pump. Thus each port can be made to act as a source, a sink, or can be deactivated. An additional source provides stochastic circulation in the tank that transports the modules.

The tank itself is not sealed such that it is kept at atmospheric pressure. This facilitates the introduction/ removal of modules and assembles into/out of the tank. Finally, a hand-operated valve on a separate flow line connecting the high and low pressure ends of the pump allows for the regulation of the amount of flow through the tank.

TABLE I
SYSTEM COMPONENTS

Component	Manufacturer	Part	Quantity	Value
Assembly Tank	Custom	-	Volume (L)	1.3
Gear Pump	Oberdorfer Pumps Inc.	N991-F41	Flow rate @ 25 psi (m^3/s)	$1.2\text{x}10^{-4}$
Pump Motor	Baldor Electric Co.	17E537 W460 G1	Power (W)	249
Solenoid Valves	Peter Paul Electronics Co. Inc.	52X05 570GB	Flow Coefficient (Cv)	0.292
Solid State Relays	Measurement Computing Co.	SSR-OAC-05	Max Switching Time (ms)	8.33
USB Controller Board	Measurement Computing Co.	USB-SSR24	Relay Module Capacity	24
PC	CompuLab	Fit-PC2	x86 Processor Speed (GHz)	1.6

With the regulation valve closed, we would expect the flow rate at each port acting as a sink to decrease linearly with the total number of sinks open. We tested this experimentally by recording the time taken to pump one liter of water through the substrate with one to four valves open (Fig. 5). Our results indicate that this is indeed the case.

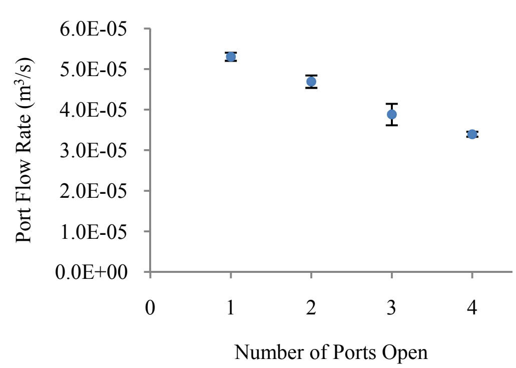


Fig. 5. Sink flow rate vs. number of ports open. As expected, we found the flow rate through each port acting as a sink to decrease with the number of ports open.

C. *Control Software*

A custom valve control program was written in C++ to switch the states of the valves independently using a keypad or mouse and give feedback on their states (Fig. 6). An option to switch chosen valves on and off at a specified frequency was also included. This program calls the library functions provided by the controller manufacturer to energize the appropriate relays to switch the desired valves on or off.

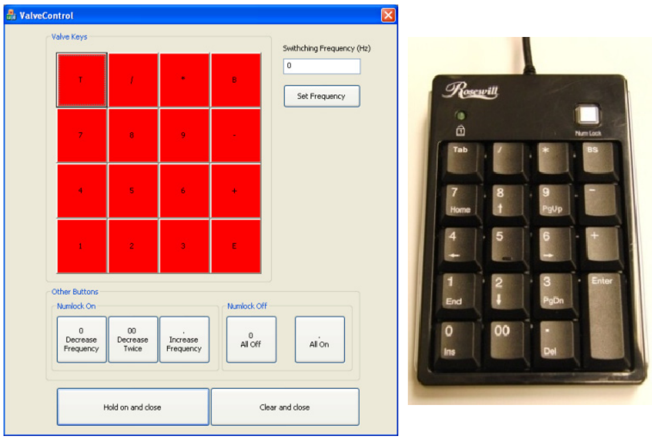


Fig. 6. Custom valve control software. A custom valve control program (left) communicates with the USB valve relay controller to switch the valves in response to user commands from a keypad with a similar physical layout (right). Additional buttons are used to set the valve switching frequency.

III. Experimental Procedure

A. *Manipulation Experiments*

The first set of experiments was conducted to evaluate the ability of the stochastic assembly system to manipulate individual modules, in spite of the stochastic fluid motion (Fig. 7(a)). In order to evaluate this, a single module was first introduced into the tank. A port on the substrate was then turned into a sink by opening the appropriate valve to connect the port to the low pressure end of the pump. Once the stochastic motion in the tank brought the module close enough to the sink to be attracted, the valves were then switched to turn the sink port into a source while turning a neighboring port into a sink in an effort to attract and align the module to the new port. This process was repeated to juggle the module among the four ports in the center of the active substrate until it became stuck and had to be rejected off the entire substrate. The total number of successful port moves was recorded as well as the fraction of these moves that the cube and substrate patterns caused the cube to align properly with the substrate.

B. *Assembly Experiments*

The second set of experiments evaluated the ability of the system to assemble 3D structures. Pairs of modules were first assembled by introducing four modules into the tank and opening two sinks (Fig. 7(b)). Once two modules were attracted to adjacent sinks, the control software's frequency option was used to repeatedly open and close the sinks, which had the effect of vibrating the cubes. The switching frequency was then adjusted from 0 to 40 Hz until the cubes were latched together. The flow was then reversed to release the structure from the substrate and test for assembly. If assembled, the total latching times were recorded. L-shaped three-module structures were assembled in a similar manner, by adding a third cube to an assembled pair (Fig. 7(c)).

Since the same fluidic forces used to manipulate modules can also be used to manipulate assemblies, a 3D structure can be assembled by re-orienting a 2D structure assembled on the substrate upright and adding new modules to its side. To demonstrate this concept, we used fluid forces to position a previously-assembled L-shaped structure vertically on the substrate and added a new module as in the previous experiments (Fig. 7(d)).

C. *Structure Repair Experiments*

A third set of experiments was conducted to evaluate the ability of the system to repair damage on a complex, 14-module structure (Fig. 7(e)). A pre-assembled, anthropomorphic 14-module structure with a piece missing (corresponding to damage) was first inserted into the assembly tank in a known position with the missing piece at the substrate. The substrate port at the location of the missing component was then opened as a sink in order to attract one of three surplus free modules. Once a module was attracted to the correct location, the valve switching frequency was adjusted as previously to vibrate the module to the correct orientation and cause it to attach to the structure.

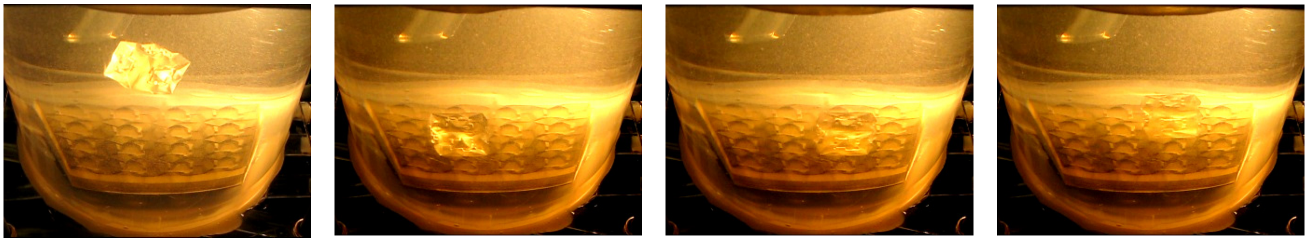
IV. Results and Discussion

A. *Manipulation Experiments*

We found our system was able to manipulate modules quite effectively in the stochastic environment, and that the modules aligned very well with the substrate. Switching the valves as described in the previous section moved the modules an average of 19 times in the intended direction before they had to be rejected off the substrate. Furthermore, the modules aligned spontaneously with the activated substrate port 72% of the time, without the need for any applied vibration.

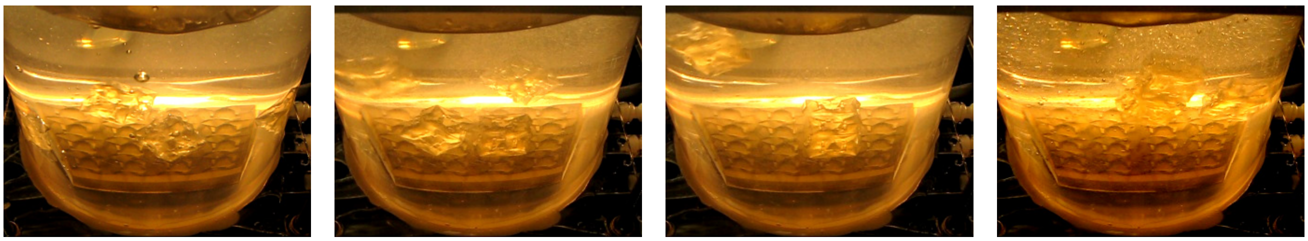
B. *Assembly Experiments*

The assembly experiments demonstrated the ability of our stochastic system to assemble 3D structures. By attracting cubes together on the substrate and switching the corresponding valves on and off at the correct frequency for a sufficient amount of time, it was generally possible to induce adjacent cubes to latch. Table 2 lists the average time required to assemble the two, three, and four-module structures. Note that unlike the planar three-module case, the 3D four-module experiment began with an assembled substructure (since a substructure was a requirement).



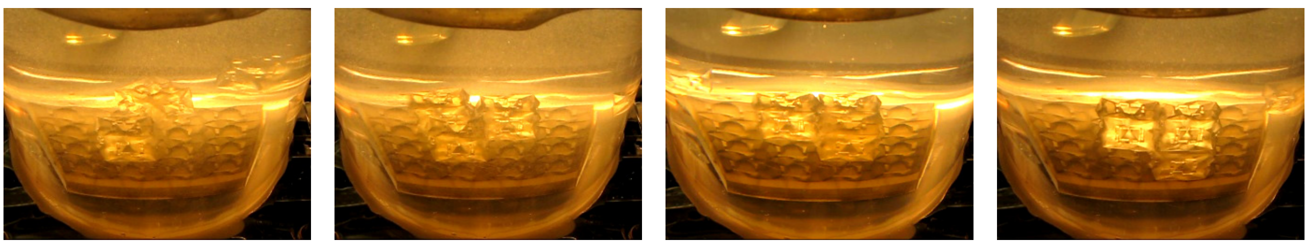
t = 17s t = 26s t = 29s t = 31s

(a) Module manipulation



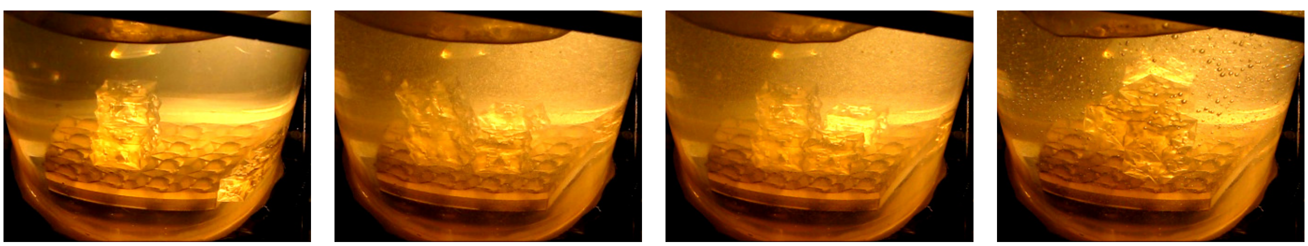
t = 11s t = 6m01s t = 6m15s t = 6m59s

(b) Two module assembly



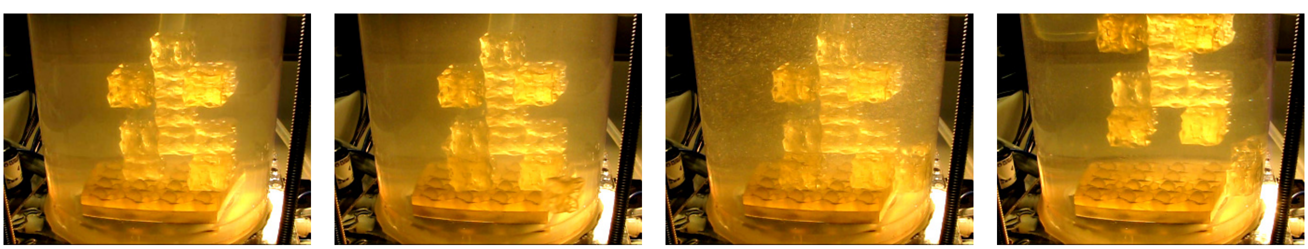
t = 7m06s t = 7m09s t = 7m56s t = 8m47s

(c) Three module assembly



t = 0s t = 1m15s t = 1m17s t = 2m23s

(d) Four module assembly



t = 0s t = 17s t = 3m28s t = 4m41s

(e) Structure repair

Fig. 7. Manipulation, assembly, and repair experiments. (a) Sequence of frames from a video demonstrating the effective manipulation of a module by circulating it among four substrate ports. (b) Attraction and assembly of two modules to the substrate. Rapidly switching the sink valves on and off causes the modules to vibrate and eventually snap into place. Reversing the flow releases the assembled pair from the substrate. (b) A similar approach is used to assemble three modules in an L-shape. (d) Starting with an upright L-shape, assembled as in (c), a fourth module is attracted and assembled to create a 3D structure which is then released from the substrate. (e) A "damaged" anthropomorphic assembly which has lost a toe module is repaired through stochastic fluidic assembly. Once the missing piece is replaced, the structure can be removed from the assembly tank. See Movie M1 for a more detailed view of these experiments.

Experimenting with various vibration frequencies to induce modules to latch together led to an interesting observation: At lower frequencies, the modules have larger motions (thus can correct for larger misalignments) but are less likely to latch together if aligned (since they move more slowly and thus have less kinetic energy when they collide). By contrast, at higher vibration frequencies, aligned modules are more likely to latch but misaligned modules are less likely to align. Thus, increasing the vibration frequency has an effect reminiscent of annealing where if it is done at the correct rate, the modules tend to align nicely on the cubic lattice before latching together.

It is also interesting to compare these experimental results with our previously developed model-based simulation of the stochastic fluidic assembly system [10]. In [10], we used this simulator to predict the time required to assemble one cube next to another on the centre of the bottom of a cylindrical fluidic chamber. The mean time to assembly was found to be 104 s in simulation, whereas here we found it to be 346 s experimentally. However, it should be noted that the cubes in simulation had flat sides and that in our experiments the majority of the time was spent vibrating the modules to induce them to latch together.

TABLE II
EXPERIMENTAL ASSEMBLY TIMES

Experiment	Number of Experiments	Average Assembly Time (s)	Standard Error (s)
Two module assembly	5	346	60
Three module assembly	3	398	46
Four module assembly	1	125	-
Structure repair	2	350	75
All experiments	11	341	37

C. *Structure Repair Experiments*

As seen in Table 2, it took an average of 350 s to replace the missing component on the structure inserted into the assembly chamber at a known position. Importantly, the vibration used to latch the replacement piece in place did not disassemble the original structure. However, in many cases the structure became dislodged from the substrate and had to be manually re-positioned. This is due to the fact that an insufficient number of controllable substrate ports were available to manipulate a structure of the given size.

V. Conclusions

We have presented an experimental system for the scalable 3D assembly of modular robot components. This system aims to increase the scalability of modular robots to large numbers of small modules. Our approach to this end is to reduce the complexity of the modules required for assembly as much as possible in order to maximize the amount resources a module spends on achieving its functions within the assembled robot. We do this by assembling the modules in a stochastic fluidic environment which takes care of module transportation. We then manipulate the fluid flow at an active assembly substrate using external valving to direct component assembly.

Following this approach, we have demonstrated the assembly of two-, three-, and four-module structures. We have also demonstrated the repair of a 14-module 3D structure inserted into the tank. Further experiments are necessary to explore the range of the system's capabilities and demonstrate the assembly of functional modules.

Nonetheless, these experiments represent the first steps toward a large-scale system where subassemblies are manufactured on many separate assembly substrates and brought together through a combination of directed and stochastic processes to form complex machines. This assembly approach is reminiscent of what occurs in nature and would likely share some of natural assembly's advantages, such as versatility, robustness, and evolvability, as well as its challenges, such as inefficiency and unpredictability.

Acknowledgment

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