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A Robotic Module for Stochastic Fluidic Assembly of 3D Self-Reconfiguring Structures

Jonas Neubert *Student Member, IEEE*, Abraham P. Cantwell, Stephane Constantin, Michael Kalontarov, David Erickson, and Hod Lipson *Member, IEEE*

***Abstract*— Stochastic self-reconfiguring robots are modular robots that possess the ability to autonomously change the arrangement of their modules and do so through the use of non-deterministic processes. We present a concept for a robotic system in which the stochastic behavior of turbulent flow in a chamber is used during assembly and disassembly operations. The thermorheological properties of Pluronic® are used to implement flow routing for controlling the assembly process. This is the first use of thermorheological valving in three dimensions. A novel reversible module connection mechanism using a low melting point alloy which is soldered in a fluid environment is presented. Together with our approach to self-alignment, these are the innovations required to allow scalable self-directed assembly in three dimensions.**

I. Introduction

Modular robots are robotic systems composed of a set of building blocks that can be assembled in various arrangements to yield different morphologies and functions. Such systems have attracted the attention of researchers due to the potential advantage of mass fabrication of modules, re-usability of modules, and fault tolerance as well as ease of repair by replacing faulty modules.

The subset of self-reconfiguring modular robots adds the theoretical benefit of self-assembly of target structures and autonomous self-reconfiguration. Such a robotic system could be deployed to a remote location without prior knowledge of the task at hand and, upon arrival, self-assemble into a robot morphology determined by environmental variables. Later, the ability to self-reconfigure could be used to autonomously repair the robot or assume a new morphology to achieve a second task.

Various self-reconfigurable modular robots have been proposed and demonstrated. However, as of now, adding new modules into an existing structure remains a challenge. Three well-known self-reconfigurable modular robotic systems are M-TRAN [1], PolyBot [2] and Molecubes [3]. These systems rely on a supply of new modules in predefined positions. A method for re-assembly of a destroyed modular robot that uses camera vision is presented in [4] but so far only works with up to three parts.

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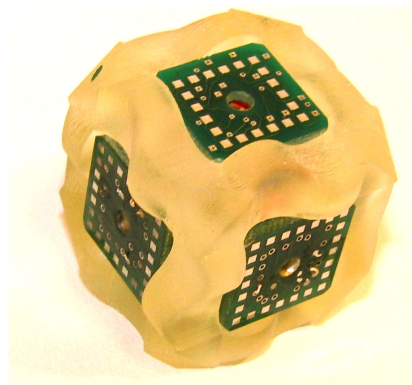
J. Neubert, A. P. Cantwell, S. Constantin, and H. Lipson are with the Computational Synthesis Laboratory, Cornell University, Ithaca, NY, 14853 USA (e-mail: jn283@cornell.edu, apc33@cornell.edu, sc445@cornell.edu, hod.lipson@cornell.edu, phone: 607-254-8940).

M. Kalontarov and D. Erickson are with the Erickson Laboratory, Cornell University, Ithaca, NY, 14853 USA (e-mail: mk579@cornell.edu).



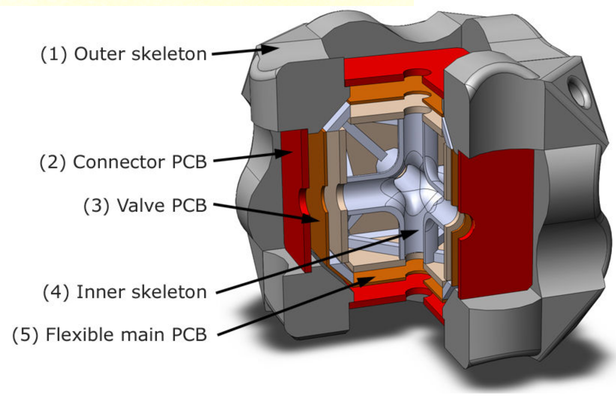


Fig. 1. Module design. (a) Photograph of a self-assembly module showing skeleton and surface printed circuit board (PCB). The module skeleton is manufactured using Objet 3D printing. (b) Illustration detailing interior of the module showing three layers of PCB as well as interior channels.

A further challenge in modular robotics is the scalability of systems. The most complex self-reconfiguring robotic system by the number of active modules to date is PolyBot which consists of only 56 modules. This highlights a more general trend in the area of modular robotics: While simulations of large scale modular robotic systems are frequently used to analyze systems of hundreds of modules, implementations of the same systems are hampered by limitations and uncertainties encountered in the physical world [5].

In recent years stochastic assembly systems have received increased attention in the field of modular robotics because they show the potential to overcome these problems. In stochastic self-assembly systems, there is no path planning for connecting modules. Instead modules are brought into contact through a random motion. For each randomly caused contact it is then decided whether the modules bond together or not, resulting in a quasi-deterministic assembly process. Key benefit of this approach towards self-assembly is that no computation or actuation is required from modules before they connect. Under the assumption that assembly originates from an initial seed from which attaching modules can draw power, modules require no independent power supply and can be completely passive. Stochastic self-assembly has the potential of reducing complexity and size of modules and at the same time opens the door to massive parallel assembly of structures.

Stochastic assembly has been demonstrated previously at different scales, for example by [6], but lacking reconfiguration. Self-assembly of a system that also support self-reconfiguration has been presented in 2D by [7]. The first demonstration of a 3D self-reconfigurable and self-assembling system using passive modules was by [8]. With the system presented in this paper we wish to extend this work towards a larger number of smaller modules. We present a stochastic modular robotic system employing fluidic assembly that uses modules with a side length of only 29mm.

II. Concept

The assembly process in our system occurs locally between any free floating module and an already assembled structure. Initially, a seed is required, which we refer to as the base of the assembly system. This base is powered externally and has computational capabilities in excess of those of single modules even though this is not strictly required. It is shaped in a way that allows one or more modules to connect to it.

All modules are initially free floating in a chamber filled with fluid. Modules have no onboard power supply and are therefore passive while in disassembled state. A propeller causes turbulent motion in the assembly chamber resulting in chaotic motion of all free modules. To start the assembly process, fluid flow is directed through the assembly chamber exiting through ports in the base. Agitated by the turbulent motion but directed by the overall flow, modules will, at random intervals, come into the vicinity of the base. Given sufficient proximity of a module and the base, the module will self-align and dock to the base.

The number of ports in the base is equal to the number of modules which can connect to it and each port can be opened and closed independently. Through selective opening of ports, a free floating module can be attracted to a desired location on the base. Up to this point in the assembly process this resembles a 2D fluidic assembly system, which our group previously presented [9].

Once a module approached and docked to the base, an electrical and mechanical bond is formed supplying the module with power and information. Modules are cube shaped with a curved edge as shown in Fig. 1. Their interior contains channels to route fluid flow from and to any of their six faces. Each of their six ports contains a valve so that after docking to the base, the module can partake in the selective attraction of new cubes. At all times will the modules in the already assembled structure be powered and have the ability to communicate with each other or the base.

Modules with three or less faces connected to the structure can be repelled from the structure for reconfiguration or disassembly. This occurs by reversing the direction of flow and breaking the bond between the modules.

Some of the central issues requiring attention are design of the bonding mechanism between modules, alignment between modules, and design of the valves on the modules. These will be described in depth in the following section. Other aspects of the design, for example implementation of a communication bus and protocol, while still being of importance for the functionality, are not included in this paper since they present no novelty.

III. Technical Implementation

A. Module Connection using Fields Metal

In any reconfigurable system the connection between modules needs to be reversible. In modular robotics systems the most frequently encountered module connection methods are magnetic, for example in [8] and [10], and latched connections, for example [3]. Latched and electromagnetic connections do not scale down favorably. Permanent magnets do scale but with passive free-floating modules there is no way to prevent clumping of modules before connection to the structure. In our system, modules are effectively soldered together. Instead of conventional solder, we use an alloy of 32.5% Bi, 51% In, and 16.5% Sn referred to as Fields Metal which melts at approximately 60°C. Fields Metal is deposited onto contact pads of a printed circuit

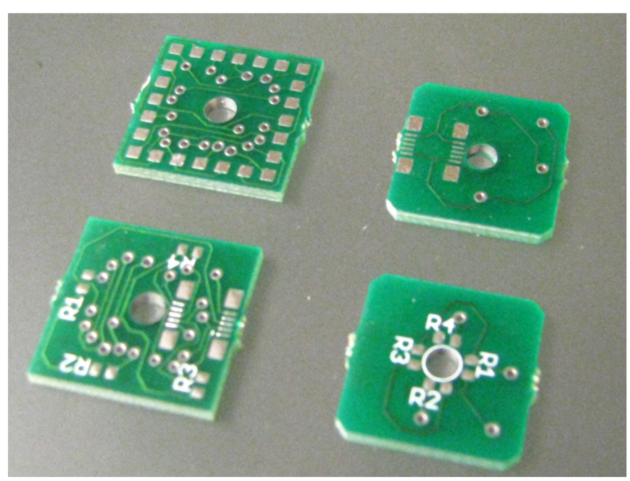


Fig. 2. Photograph of (left) connector PCB with connector pads and (right) valve PCB (without resistors). Upper boards show outer face, lower pictures show face directed towards inside of the cube. The central hole is the 2.8mm diameter port for fluid flow.

TABLE I
QUALITATIVE PROPERTIES OF VARIOUS PLURONIC MIXTURES

% weight F127	% weight F68	observations
15	0	Mixes into transparent liquid[1] within half a day[2]. Becomes a very soft gel at approx. 45°C above which viscosity decreases.
15	5	Mixes into transparent liquid[1] within half a day[2]. Shows some soft gel behavior around 55-60°C above which viscosity decreases.
15	10	Same observations as for 15%,5% mixture
15	15	Mixes into transparent liquid[1] within one day[2]. Turns into a soft gel at 45°C and into hard gel at 60°C.
20	5	Mixes into transparent liquid[1] within one day[2]. Fast gel transition into hard gel at 40°C.
20	10	Mixes into transparent liquid[1] within one day[2]. Fast gel transition into hard gel at 45°C. Stiffness peaks at approx 70°C and decreases for higher temperatures while remaining in hard gel state.
20	15	Mixing took several days [2], turns into clear liquid with small inclusions[1]. Flows viscously at room temperature, fast transition into hard gel at 40°C.
20	20	Pluronic does not fully dissolve within one week. Very viscous soft gel at room temperature.

Qualitative observations on heating of various aqueous mixtures of Pluronic. The remaining percentage is DI water. "Soft gel" is a high viscosity fluid exhibiting flow upon manual stirring and shaking. "Hard gel" is a highly viscous gel that shows no flow upon manual mixing or stirring. Heating is at a rate of approximately 5°C per minute, hysteresis effects are not recorded.
[1] At room temperature.
[2] While standing at approximately 5°C.

board (PCB) on the outside face of the module, the "connector PCB" in Fig. 1. Once a cube is available for docking (and held in place by fluidic forces), resistors on the opposite side of the circuit board are heated and result in melting of Fields Metal on the powered cube. After cooling, the solidified Fields Metal forms both a mechanical and electrical bond.

The PCB contains four 1Ω resistors only, arranged as two parallel sets of two in series to achieve an effective resistance of 1-Ω across the complete array. The PCB is industry standard fiberglass circuit board with a thickness of 1.6mm. The board dimensions are 13mm x 13mm with a hole of diameter 2.8mm in the center as shown in Fig 2. In our current setup each face is provided with a 2V DC line

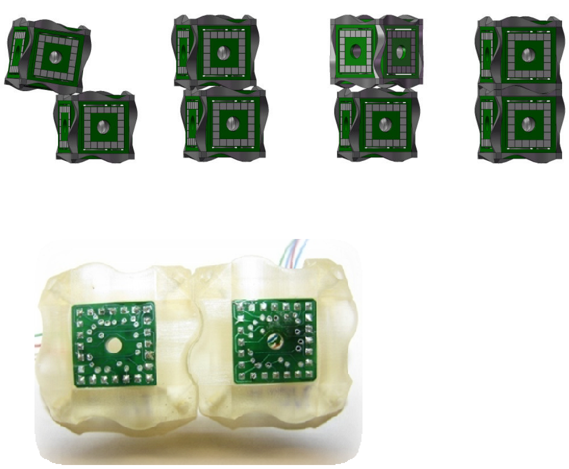


Fig. 3. Self-alignment of two cube-shaped modules during approach. Top: 3D renderings of different forms of misalignment occurring are (from left to right) large linear misalignment small linear misalignment and rotational misalignment. Bottom: Photo of two perfectly aligned modules which were used to confirm electrical bonding.

which is supply limited to 1A. This consumes approximately 2W of power while heating.

B. Thermorheological Valving

According to the concept detailed above, to redirect flow within the assembly chamber, the already assembled structure requires the capability to selectively open and close ports on its surface (and in fact also inside the structure). Due to the small size of our modules and space requirements imposed by other functionality, the port sizes are of 2.8mm diameter. The height of the valve cannot exceed half the width of our module, i.e. 14.5mm and needs to in fact be smaller than this to leave sufficient space for mounting and flow routing inside the module. A valve with overall dimensions on this scale is to our knowledge neither commercially nor otherwise available.

We designed and tested a valve with no moving parts based on thermorheological properties of certain fluids. This valve requires no mechanical actuation but relies solely on heating the fluid in its vicinity. In a non-conductive fluid, this is readily achieved through resistive heating.

In aqueous solution, block copolymers of type $E_mP_nE_m$ combining poly(ethylene oxide) with an average block length of *m*, and poly(propylene oxide) with average block length of *n*, show the property that while liquid at room temperature they form a gel of varying strength when heated. This behavior is referred to as thermorheological effect. A selection of such block polymers is available under the trade name Pluronic® from BASF and is commonly used in medical applications. A number of studies have been published describing the effect of heating solutions of Pluronic® in deionized (DI) water on viscosity, for example [11], [12]. Based on this previous information and our own trials whose results are summarized briefly in Table 1, we selected a mixture of 20% (by weight) of Pluronic F127, 10% Pluronic F68, and 70% DI water. We will refer to this

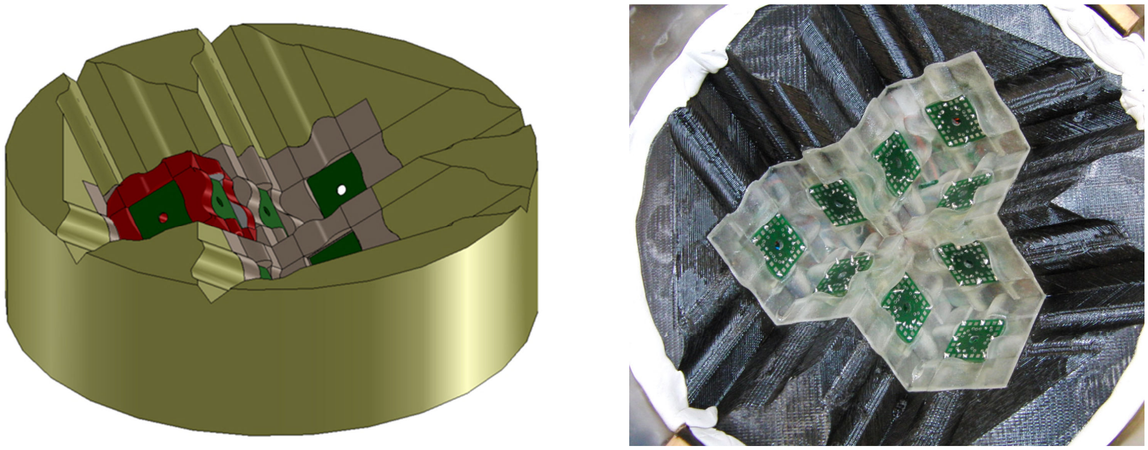


Fig. 4. Self-alignment of two cube-shaped modules during approach. Left: A 3D rendering of our specially shaped tank base to facilitate fast docking of the first cubes. Right: A photograph of the same base in the tank (the Pluronic water has been drained to avoid refractive distortion of the image).

solution as "Pluronic water" from here on. Pluronic F127 is $E_{101}P_{56}E_{101}$ using the notation previously introduced [14], Pluronic F68 is $E_{79}P_{28}E_{79}$ [15]. Both are available commercially as powder for a price of US$2.15 per kg.

Our trials show that the conductivity of all mixtures of Pluronic in deionized water is in the order of 10^6S to 10^7S. Such low conductivity provides sufficient insulation of electrical connections to allow immersed circuits to operate normally. Our trials did, however, also show that the timing function of microcontrollers appears to be affected by immersion in Pluronic which was overcome by sealing these with epoxy of type Loctite® Hysol® 120.

The fact that Pluronic water is both thermorheological and non-conductive, makes it ideal for valving applications. In different mixture it has previously been used in this context to facilitate self-assembly on the micro-scale [16].

We scaled thermorheological valves up to the millimeter scale for use in our modular robot. The entire valve is contained on one PCB. The valve PCB consists of four 1Ω resistors in parallel to achieve a 0.25Ω resistance across the

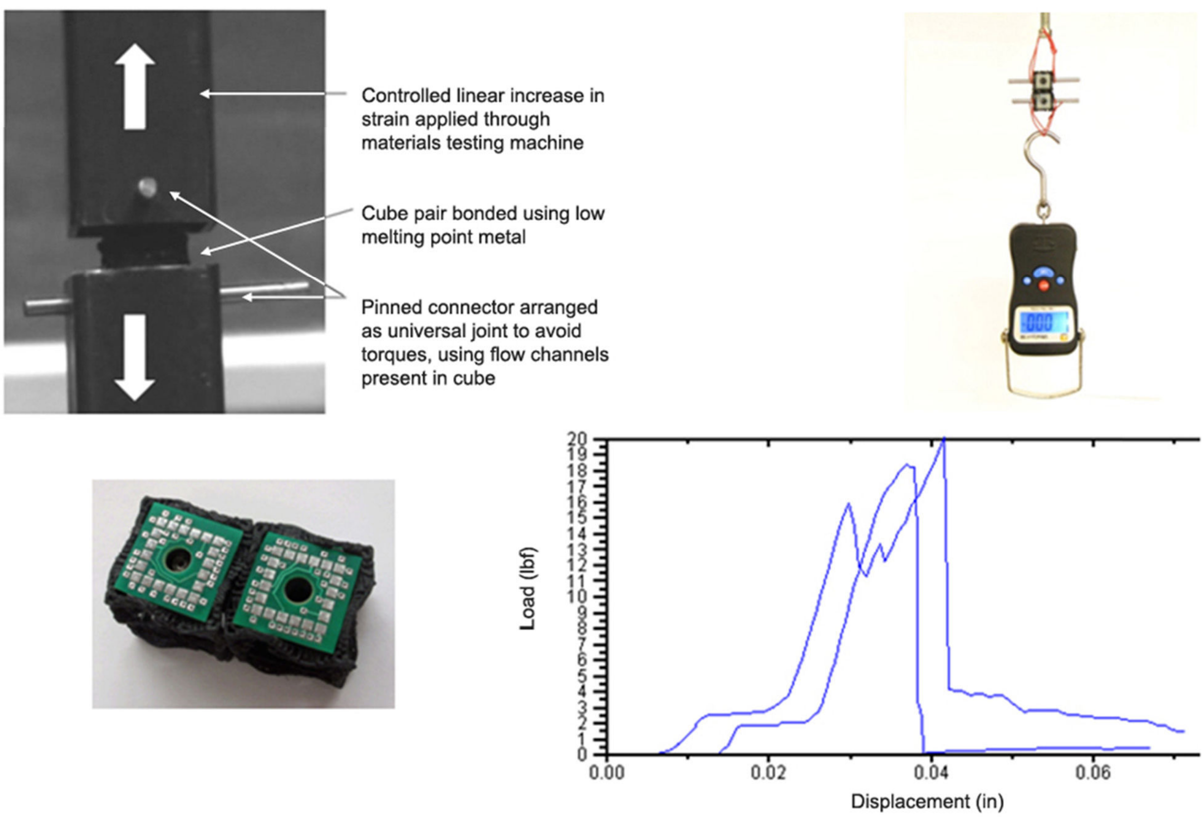


Fig. 5. Tension testing of cube bond. Two prototypes were attached to each other using heated Fields Metal (bottom left). Using an Instron tension testing machine (closeup photograph in top left) the stress/strain curves in the bottom right were obtained showing a maximum load before failure of approximately 9.5kg. This was confirmed by applying load through a scale as shown in the top right.

resistor array. These resistors are mounted on PCB with a thickness of 1.6mm. The board dimensions are 14mm by 14mm with a hole of diameter 2.8mm in the center as shown in Fig. 2, the location of the board in the module is shown in Fig. 1. In our current setup, each face is provided with a 2V DC line which is supply limited to 2A. For all modules in the structure, power is supplied through the structure from the base. The approximately 4W of power dissipated by this circuit are converted into heat. The resistors are exposed directly to Pluronic water which upon heating turns into a gel and blocks the hole in the circuit board.

On the sub-millimeter scale it is sufficient to heat a small section of tube and shear forces will block this thermorheological valve. With our adaptations thermorheological valves are now available as an actuator for larger scale modular robotic systems.

C. *Self-Alignment of Modules during Approach*

When relying on stochastic processes one cannot expect modules to arrive in the exact orientation and location as required. Misalignment is expected when one module approaches the already assembled part of the structure and during the docking process. Therefore, self-alignment needs to occur (Fig. 3 illustrates different forms of misalignment expected). We solve this challenge in a twofold manner.

As a first measure to ensure correct alignment of cubes, the cube skeleton possesses a curved edge. This edge is formed in such a way that contact between the two face circuit boards only occurs once the two (or more) connecting modules are fully aligned as shown in Fig. 3. For linear misalignments of up to half a cube's side length and all

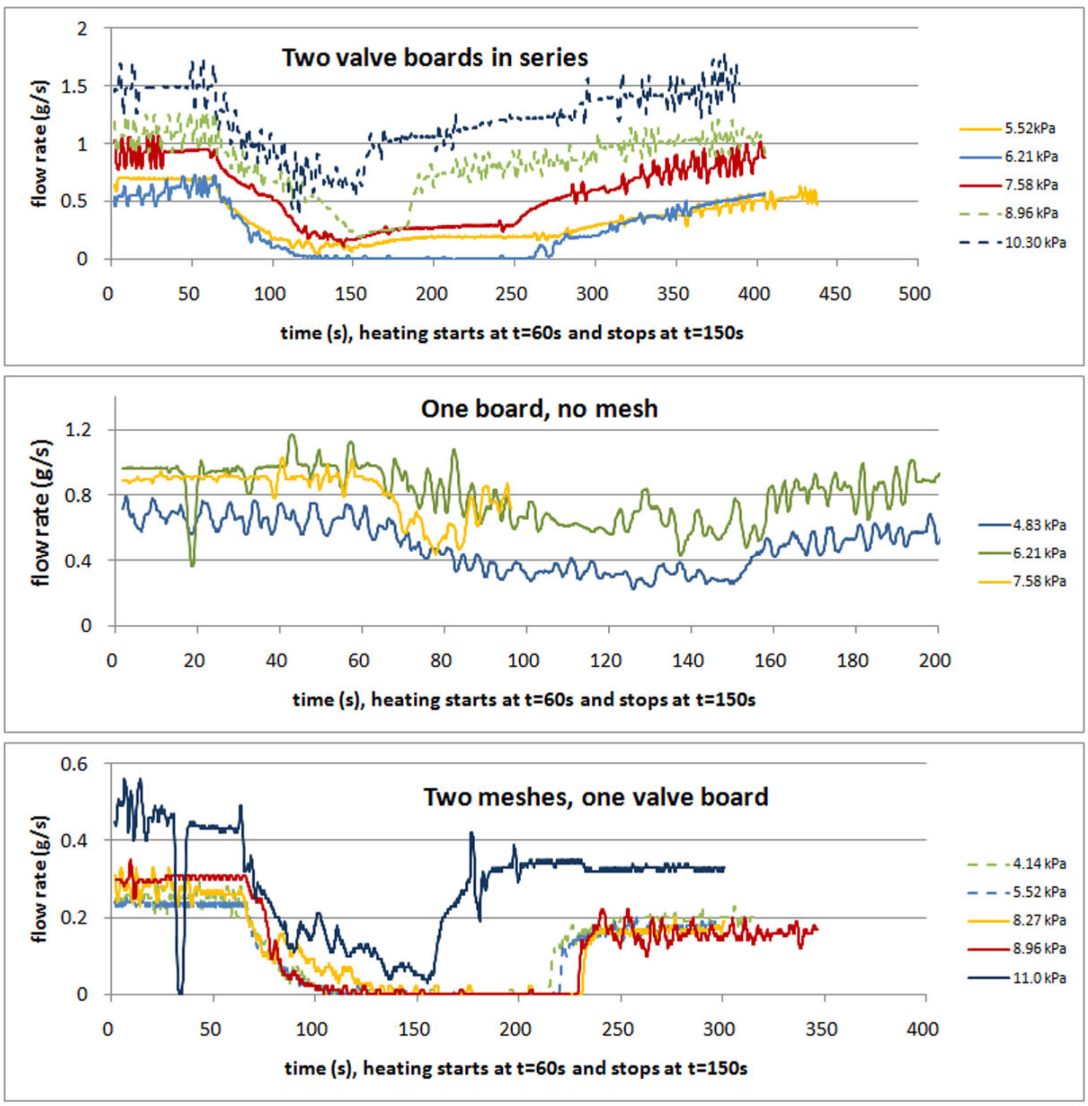


Fig. 6. Evaluation of thermorheological valve with mixture of 20% (weight) Pluronic F 127 and 10% F 68. Current through the heating resistors switches on after 60s, is then pulsed to keep the liquid temperature in vicinity of the valve at approximately 65°C -75°C. With one valve circuit board and two meshes across the flow pressures up to 9.0kPa the flow could be stopped, for 11.0kPa the flow rate could be reduced significantly. For a single valve board with no mesh the flow in the open position is much higher but the valving performance is degraded. Two valve boards in series with no mesh across the flow have similarly high flow in the open position but can stop flow at pressure differentials of up to 6.2kPa and lead to a significant reduction of flow rate at all other pressures measured.

radial misalignments, the curved edge guides the modules into alignment under forcing by the fluid flow.

Secondly, the shape of the already assembled structure plays a role in how well the self-alignment process can be guided. Similar to [7] who list probabilities of approach between two stochastically moving groups of modules, one could generate a list of the probability of correct self-alignment between a free cube and different structures. For example, it becomes quickly apparent in trials, that self-alignment occurs much more readily when a cube approaches a "pocket" of three surfaces, than when approaching only a flat surface. While one cannot guarantee such situations throughout the assembly process, we chose to give the base of our chamber from which assembly starts, such a preferred shape as shown in Fig. 4.

IV. Experimental Results

A. Strength of Bond

It is of central importance for successful self-assembly that the mechanical and electrical bonding between modules is reliable enough that every cube is connected in a functioning fashion to at least one neighbor. While this leaves sufficient room for errors, we already showed in experiments outside the test chamber that given good alignment, the electrical connection works reliably. Further, we tested the strength of the bond with the setup shown in Fig. 5. The supported load by a single pair of modules manually placed together was in excess of 7kg for all trials.

B. Valve Performance

Our main technical innovation so far has been the use of thermorheological valving on the millimeter scale and the design of a valve on a PCB. We expect that in our final assembly system we will require a pressure differential of approximately 7kPa-14kPa across any given valve to ensure sufficient overall flow through the assembly chamber. This is the case because the main cause of fluid flow and hence module motion in the chamber is agitation from a propeller and not the flow through the chamber.

Fig. 6 shows results of three separate experiments. After 60s of continuous flow, the valve was heated (switched to closed). A single valve only significantly reduces flow up to 4.8kPa differential which is not sufficient for our application. An arrangement with a fine metal grid mesh placed across the flow to facilitate heat conduction into the fluid, however, stops flow for pressure differentials up to 9.0kPa at the expense of reduced flow in the valve open position. Two valves in an array with no mesh stop flow at pressure differentials up to 6.2kPa but significantly reduce flows up to 9.0kPa. The latter two options are both feasible and the selection depends on the more frequent valve position during assembly. If an assembly strategy primarily keeps valves closed, the option using metal meshes would be preferred, for strategies with the valves mostly open, the double-PCB option would be preferred.

V. Conclusion

We presented a system for stochastic fluidic assembly that actively uses fluid properties and is thereby able to dramatically reduce the module complexity. Both our bonding method and thermorheological valving present new technologies in the field of modular robotics and open the way to reliable small-scale modules for stochastic assembly systems with large numbers of modules.

References

[1] E. Yoshida, S. Murata, A. Kamimura, K. Tomita, H. Kurokawa, and S. Kokaji, "A motion planning method for a self-reconfigurable modular robot," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2001, pp. 590–597.

[2] M. Yim, D. Duff, and K. Roufas, "PolyBot: a modular reconfigurable robot," *IEEE International Conference on Robotics and Automation*, 2000, pp. 514-520.

[3] Zykov V., Mytilinaios S., Desnoyer M., Lipson H. (2007), "Evolved and Designed Self-Reproducing Modular Robotics", *IEEE Transactions on Robotics*, vol. 23. No. 2, pp. 308 – 319.

[4] M. Yim, B. Shirmohammadi, J. Sastra, M. Park, M. Dugan, and C. J. Taylor, "Towards Robotics Self-reassembly After Explosion," in *Video Proc. of the IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS)*, San Diego CA, 2007.

[5] M. Yim, W.-M. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G.S. Chirikjian, "Modular Self-Reconfigurable Robot Systems," *IEEE Robotics & Automation Magazine; vol. 14, March 2007, pp. 43-52.*

[6] R. Jackman, S. Brittain, A. Adams, M. Prentiss, and G. Whitesides, "Design and fabrication of topologically complex, three-dimensional microstructures," *Science*, vol. 280, pp. 2089–2091, 1998.

[7] E. Klavins, S. Burden, and N. Napp, "Optimal Rules for Programmed Stochastic Self-Assembly," *Robotics: Science and Systems II*. MIT Press, 2006. pp. 9-16.

[8] P. White, K. Kopanski, and H. Lipson, "Stochastic self-reconfigurable cellular robotics," in *Proc. IEEE International Conf. on Robotics and Automation*, New Orleans, 2004, pp. 2888-2893.

[9] M. T. Tolley, V. Zykov, H. Lipson, D. Erickson, "Directed Fluidic Self-Assembly of Microscale Tiles" *Micro-Total Analysis Systems (uTAS)*, Tokyo, Japan, Oct. 2006, pp. 1552-1554.

[10] S. Miyashita, M. Kessler, and M. Lungarella, "How morphology affects self-assembly in a stochastic modular robot," *IEEE International Conference on Robotics and Automation*, Pasadena, 2008, pp. 3533-3538.

[11] V. Lenaerts, C. Triqueneaux, M. Quartern, F. Riegfalson, and P. Couvreur, "Temperature-dependent rheological behavior of Pluronic F-127 aqueous solutions," *International Journal of Pharmaceutics*, vol. 39, 1987, pp. 121-127.

[12] B. Fussnegger, "Poloxamers (2): Lutrol F 127 (Poloxamer 407)" *Excipients & Actives for Pharma*, vol. 40, 2000, pp. 7-9.

[13] C. Chaibundit, N.M. Ricardo, F.D. Costa, S.G. Yeates, and C. Booth, "Micellization and gelation of mixed copolymers P123 and F127 in aqueous solution.," *Langmuir*, vol. 23, 2007, pp. 9229-36.

[14] BASF, "Pluronic® F127 Block Copolymer Surfactant", BASF, 2004. Available: http://www.pharma-ingredients.basf.com/pdf/Statements/ Technical Informations/Pharma Solutions/EMP 030737e_Lutrol F 68.pdf

[15] BASF, Lutrol F 68 Poloxamer 188 Poloxamers Ph.Eur., Poloxamer USP/NF, BASF, 2008. http://www.pharma-ingredients.basf.com/pdf/Statements/ Technical Informations/Pharma Solutions/EMP 030737e_Lutrol F 68.pdf

[16] M. Krishnan, M.T. Tolley, H. Lipson, and D. Erickson, "Hydrodynamically Tunable Affinities for Fluidic Assembly," *Langmuir*, vol. 25, 2009, pp. 3769-3774.