Peltier-Based Freeze-Thaw Connector for Waterborne Self-Assembly Systems

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***Abstract*— We present a novel type of inter-module connection mechanism for waterborne modular robotic systems. The proposed mechanism exploits the thermoelectric effect to cool down and freeze the water between two modules thus causes them to attach to each other. We validate the feasibility of this mechanism by embedding a Peltier heat pump ($m = 0.8\,g$) in two types of cm scale self-assembly systems, one in which the modules are free to move and one in which the modules are linked together by hinges. Our experimental results demonstrate that the proposed Peltier-based connector has (a) a high bond strength/weight ratio for a rather large range of temperatures and (b) is rather robust against misalignments between docking modules, making it a useful alternative to current connection mechanisms for small scale low autonomy self-assembly systems.**

I. Introduction

Manufacturing technologies and industries heavily rely on robots. For macroscopic objects industrial robots are not only economical but are also reliable, fast, and accurate. Such robots, however, hit a barrier – entailing lower yields and higher fabrication costs – as the assembled objects become too complex. One potential solution to this problem is to exploit processes of self-assembly, that is, processes in which the interaction of pre-existing components leads to organized structures without human intervention. Such components could be, for instance, identical mechanical units (modules). Self-assembly is of crucial importance in the biological realm at all scales, e.g. for the formation of the protein shells of viruses and for protein folding.

By taking inspiration from nature, many inroads have already been made to realize self-assembly systems. For instance, the possibility of using self-assembly for the fabrication of structures from a given set components (potentially of nano- or micrometer scale) has been suggested by Winfree [1], Rothemund [2] or Whitesides *et. al* [3]–[6]. In the related field of self-reconfigurable systems, research effort has been devoted to realizing robots that can rearrange the connectivity of their structural units and create new topologies to accomplish a task [7]. Special attention has been paid to the design and construction of basic building blocks of a typically small repertoire, binding or docking interfaces allowing transfer of mechanical forces and moments, electrical power, and the sharing of information between the modules [8]–[19].

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Most modular systems are "deterministically self-reconfigurable" implying that the exact location of the unit is known all the time. That is, the units are moved or directly manipulated into their target locations through deliberate active motion. In contrast to such systems, self-assembly systems are "stochastically self-reconfigurable" implying that (1) there are uncertainties in the knowledge of the modules' location (the location is known exactly only when the unit docks to the main structure); and (2) the modules have only limited (or no) computational (deliberative) abilities. To date, a few self-reconfigurable modular robots relying on stochastic self-assembly have been built [20]–[26]. Although in all these systems the units interact asynchronously and concurrently, a certain amount of state-based control is still required for the modules to move, communicate, and dock. Such docking/undocking is one of the main challenges towards the realization of self-assembly system (other two challenges are how to actuate the modules, so that they can move, and how to supply power to them).

In this paper, we address the docking/undocking challenge by presenting the design and construction of a novel kind of connection mechanism. The connector works by freezing water close to it so that when another module is in its neighborhood, the two modules stick to each other. We also show how this connector can be embedded in a stochastic modular robot. In the following section II, we provide a brief review of available connection mechanisms with a special emphasis on the ones used in the field of modular robotics. Then, in section III, we describe our Peltier-based freezing-thawing connection mechanism and validate its functioning as a connector. In section IV, we describe the experiments of proposed connector by embedding it into a group of modular robots. This is followed by a discussion (section V), some pointers to future work and a brief conclusion (section VI).

II. Connection mechanism

For a modular robot, the ability to attach to and detach from another module or to parts of the environment is of fundamental importance. With the connection mechanism introduced in this paper we tackle the following problems that arise especially at smaller scales ($<$1 cm): (1) The actuation that is necessary for mechanical connectors is not easy to scale down. (2) The connection strength has to be sufficiently strong to fulfill the robot's purpose. (3) The precise alignment of the connector is crucial for a successful binding for some connection types. (4) The electromechanical complexity of the connector has to be small enough to allow for mass fabrication.

TABLE I

CLASSES OF CONNECTORS (μm - cm SCALE)

type	sub-type	main problem	reference
surface tension	-	weak bond / controllability	Boncheva 2003 [6], Rothemund 2000 [2], Hosokawa *et al.* 2005 [27], Bowden *et al.* 1997 [4], Chengde Mao *et al.* 2002 [5]
permanent magnets	-	detachment	Hosokawa *et al.* 1994 [28]
	+ electrical actuator	heavy weight	Bishop *et al.* 2005 [24]
	+ SMA spring	duration to detach	Murata *et al.* 1999 [12]
electrical magnets	-	strength-to-weight ratio	Murata 1994 [10]
	+ electrical actuator	heavy weight	Kotay *et al.* 1998 [14], Zykov *et al.* 2005 [18], Bhat *et al.* 2006 [29]
mechanical (hook, latch, lock)	-	actuation / alignment	Penrose 1959 [30] [a]
	+ electrical actuator	heavy weight	Yim 1994 [13], Rus *et al.* 2001 [15], Jørgensen *et al.* 2004 [17], Murata *et al.* 1998 [11], Terada *et al.* 2004 [31]
	+ electrical magnets		Griffith 2005 [22]
	+ SMA		Fukuda *et al.* 1988 [8], Castano et al. 2002 [16]
Velcro	-	detachment	
	+ pneumatic actuator	energy consumption	Shimizu *et al.* 2005 [23]
	+ electrical actuator	heavy weight	Moeckel *et al.* 2005 [32]
Peltier	-	heat dissipation	López *et al.* 2007 [33] [b]

[a] turbulence was controlled

[b] as a microgripper

Table I lists various popular connection types for modular robots. In what follows, we will review some of them.

The exploitation of surface tension through the use of hydrophilic and hydrophobic materials provides a binding mechanism for modular robots in a fluidic environment that is often used for research on cm-scale stochastic self-assembly systems [4]–[6], [27]. The connection strength is weak compared to other mechanisms but is sufficient because the modules are lightweight. Additional properties make this mechanism useful: (1) no power has to be provided for attachment and detachment; (2) the alignment is done by the connecting force itself; and (3) the connection mechanism is easy to produce.

Permanent magnets are a second type of popular connection mechanism for modular robots. They have many useful properties: (1) they do not require any power for binding; (2) the relatively strong attractive force eases the alignment problem; and (3) they are rather straightforward to manufacture. However, because their attractive force is constantly active, a repelling force is necessary to revoke the connection. Some robots use a mechanism to push modules away from each other until the attraction force has no more effect, for example with a Shape Memory Alloy (SMA) [12]. Others rotate the permanent magnets so that they repel each other [24]. Permanent magnets are useful at the cm scale though their attractive force decreases with third power with respect to the size.

A third type of popular connection mechanism are electromagnets. They allow for selective connections and are simple to fabricate and implement. However, they need to be constantly powered to ensure the connection, and their strength-to-weight ratio decreases with size. It follows that for the use on a scale smaller than the cm scale they are not applicable.

Mechanical connectors such as latches, lock and key, as well as hooking mechanisms provide a high connection strength. The docking and undocking is usually driven by electrical motors. However, they are not a viable solution at small scales because of the high demands on the precision of the required alignment. Furthermore, it is a difficult engineering task to build and actuate small and robust mechanical systems.

Velcro has the advantage that the connection mechanism itself does not have to be actuated [23], [32]. A repelling force has to be provided only for the detachment (through an actuator). A further advantage of Velcro is that it does not have to be aligned precisely to connect and also works at small scales.

III. PELTIER-BASED FREEZE-THAW CONNECTOR FOR LIGHTWEIGHT SELF-ASSEMBLY ROBOTS

The size of 1 cm is a critical size for self-assembly systems. For objects in water around that size, viscosity is as important as inertia; for such objects, the Reynolds number (the ratio of inertial forces and viscous forces) is ≈ 1. It follows that objects smaller than that size are affected more by viscous forces whereas larger objects are affected more by inertial forces. In order to make a step towards smaller and more lightweight systems, we propose a novel connection mechanism: the water close to the docking interface of one module is frozen to ice building a local bridge to another module.

A. The Peltier connector

The core of our connector is the Peltier heat pump – a double-faced cooling-heating device that can transfer thermal energy from one side of the device to the other, with consumption of electrical energy. We used the Peltier device to freeze (and thaw) the water between two modules and thus realize binding (and unbinding) between modules. The polarity of the current applied to the device defines which side is cooled down or heated up. The device consists of different types of semiconducting materials that are connected in series to take advantage of the so-called thermoelectric or Peltier effect. This effect is the direct conversion of an electric voltage into a temperature difference and *vice versa*, and allows the element to work as a heat pump. Peltier devices are available in various sizes. For our purpose we used an 8×8 mm element that weighs 0.8 g (Fig. 1). Theoretically, the Peltier heat pump can induce a temperature difference of up to $72\ ^{\circ}C$ while consuming approximatively 2.60 W.

One particular advantage of this type of inter-module connection mechanism is due to the absence of mechanical parts which makes it scalable. The fact that the connector is devoid of moving parts makes it also intrinsically less prone to failures. One disadvantage is that in order to sustain the connections, energy has to be supplied permanently to the heat pump. For the detachment process, however, there is no need to supply energy because the ice melts when it is not cooled down; moreover, the flow of heat from the hot surface supports the thawing process speeding it up.

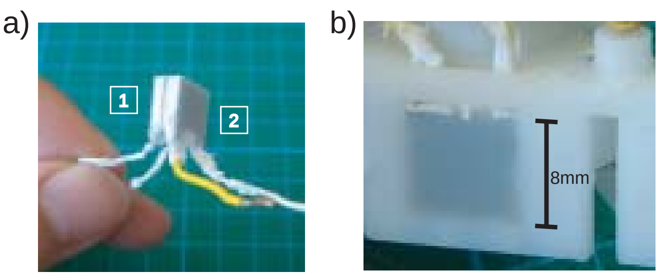

Fig. 1. Illustration of Peltier elements. a) Frozen Peltier elements (8×8 mm) sticking together. b) A Peltier element embedded into a module.

B. Feasibility study

To confirm the use of Peltier devices to build a connector, we conducted two experiments. First, we tested the connector's functionality for different water temperatures. Second, we measured how much force was required to separate two modules (once they had connected to each other) also for different water temperatures.

Table II shows the conditions for which a connection was realized as a function of the voltage V applied to the Peltier elements and the time T necessary to achieve a connection. On average it took about one minute to establish a connection. For low temperatures and high voltages the two Peltier devices bound quickly to each other, for higher temperatures, however, the required time increased (e.g. at room temperature for $V = 2\ V$, it took $T = 3\ min$).

Although the time for the connection takes more time than for most other types of interconnection, the duration and the energy required for freezing decreases with the square of the size of the element's active area (the smallest commercially available Peltier elements have an area of approximately $1\ mm^2$, and we assume that a reduction in size can solve the heat dissipation problem which comes with this device).

We measured the bond strength for several water temperatures by applying a force perpendicular to the binding side until the connection broke (Fig. 2). A voltage of $V = 2\ V$ was applied to two Peltier elements for 60 seconds to bond, and the two elements were separated by hand from each other. On average, the connector withstood a pulling force of 17.56 N (the standard deviation was $\sigma = 2.03$). Considering the weight cumulated of the two Peltier elements (1.6 g), it becomes clear that the bond strength/weight ratio is higher than for other known connection mechanisms (Table I). Moreover, we observe that the bonding force remaines roughly constant for different water temperatures. This is because the volume of ice that the two Peltier elements built up stayed relatively constant irrespective of the water temperature. A further advantage is that in order to connect, the two Peltier elements do not have to be aligned precisely. This property allows the system to be not only strong and scalable, but also robust to misalignments.

TABLE II

EXPERIMENTAL RESULTS OF ESTABLISHING A CONNECTION UNDER DIFFERENT CONDITIONS ($Voltage$ $[V]$, $Time$ $[seconds]$).

water temperature 0 °C

$V \setminus T$	30 s	60 s	120 s
0.5 V	×	√	√
1 V	√	√	√
2 V	√	√	√

water temperature 5 ° C

$V \setminus T$	30 s	60 s	120 s
0.5 V	×	×	×
1 V	×	×	√
2 V	√	√	√

water temperature 10 °C

$V \setminus T$	30 s	60 s	120 s
0.5 V	×	×	×
1 V	×	×	√
2 V	√	√	√

water temperature 15 °C

$V \setminus$ T	30 s	60 s	120 s
0.5 V	×	×	×
1 V	×	×	×
2 V	√	√	√

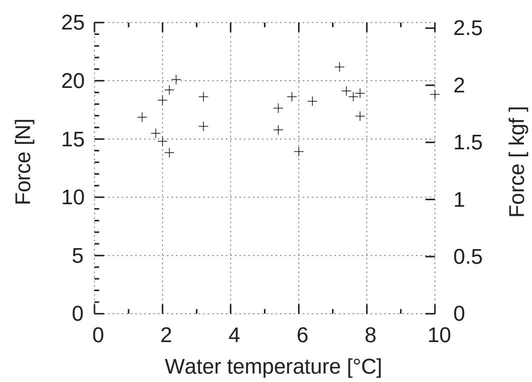

Fig. 2. Temperature - bonding strength comparison. X-axis: water temperature [°C], Y-axis: force to detach $[N,\ kgf]$

IV. IMPLEMENTATION OF THE PELTIER CONNECTORS TO SELF-ASSEMBLY ROBOTS

Followed by the feasibility of the connector idea (described in Section III), we embedded the Peltier-based connector into two types of stochastic modular robots.

A. Kite-shaped model

The experimental setup was composed of a power supply, a metallic ceiling, a water tank, and six modules immersed halfway in water (Fig. 3). Each module consisted of a kite-shaped wedge made of durable plastic (acrylnitrile butadene styrene; ABS) spanning angles of 60 degrees and 30 degrees. The modules (H: 13 mm, L: 30 mm) contained a permanent magnet oriented orthogonally to their main axis to attract or repel other modules (Fig. 4 a). A vibration motor was used to endow the modules with a minimal locomotive ability which allowed the modules to move randomly around – vaguely reminescent of Brownian motion. Rather than using batteries, electricity was supplied to the modules through a pantograph that drew current from a metal ceiling. This solution not only led to lightweight modules ($m = 6.0\ g$), but it ensured that all modules received approximately the same amount of energy in a particular experiment. When an

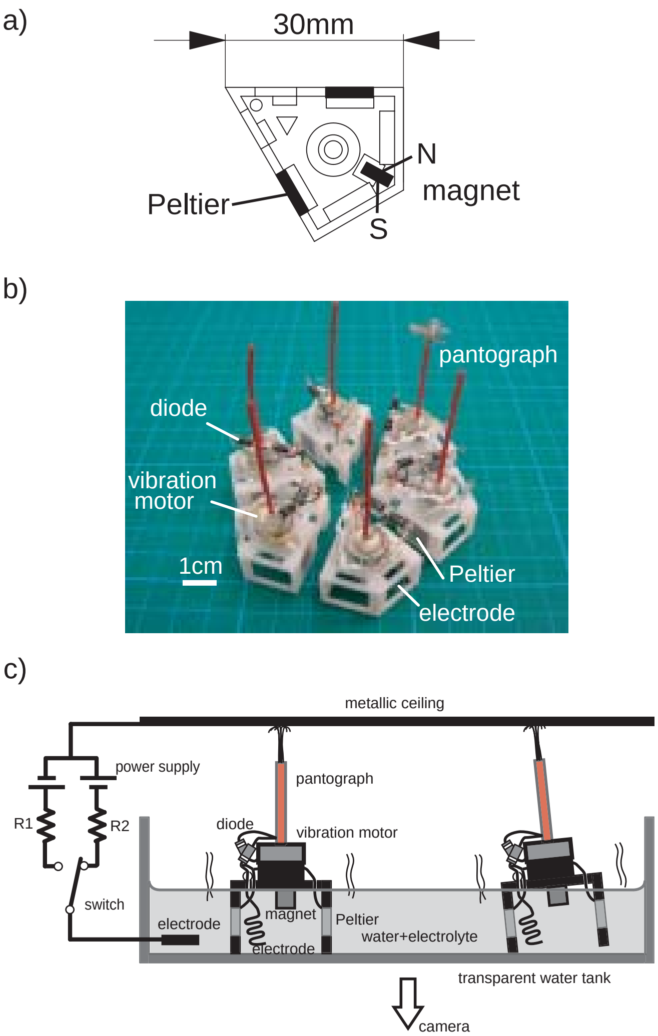

Fig. 3. Experimental setup. a) Schematic illustration of a module (bottom view). b) Picture of 6 modules. c) Experimental setup with 2 modules.

electrical potential was applied to the metallic ceiling plate, current flowed through the pantograph to the vibration motor returning to ground via the electrodes (platinum) immersed in the water (8 % concentration of electrolyte (salt) was added to the water to make it conductive). To speed up the connection between two modules, the water in which the modules moved was cooled down to approximately $-3\ ^{\circ}$C (due to the concentration of salt this was slightly higher than the freezing temperature). Two diodes were used to switch the direction of the current. Current flowed either through the Peltier element or the vibration motor depending on the direction of the voltage applied to the system (Fig. 3c, switch).

We first carried out experiments to test the reliability of the connector and to investigate the reconfigurability of our self-assembly system. The result is shown in Fig. 4. In the beginning of the experiment the modules were placed in the arena (Fig. 4 a) and arranged by hand to form a hexagonal shape (Fig. 4 b). Voltage was applied via the metallic ceiling (Fig. 4 c). After one minute, all six modules were connected to each other forming one unit (Fig. 4 d). We then flipped the polarity of the current supplied through the pantograph. The Peltier connectors stopped cooling and the vibration motors started to vibrate causing a disassembly of the hexagonal shape into 6 separate modules (Fig. 4 e). As a result of the vibrations of the motor, the modules moved around in the arena where they eventually got magnetically attracted by another module and started to form triangles (Fig. 4 f,g). The experiment was considered completed when the six modules had formed two triangles (Fig. 4 h). We conducted the

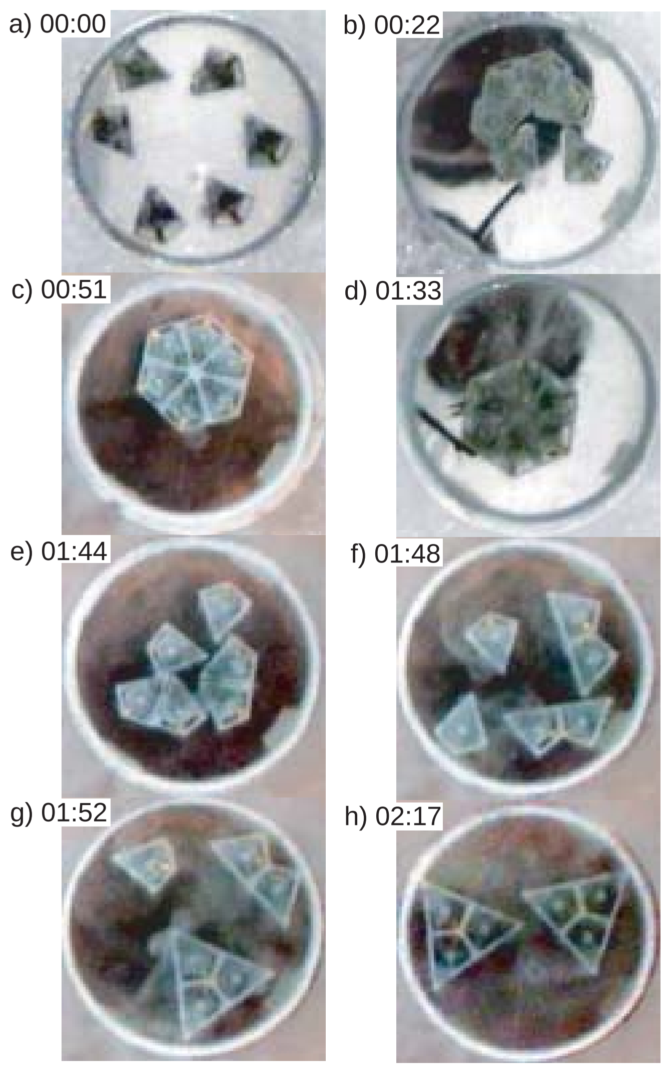

Fig. 4. Snapshots of the experiment.

experiment several times. For sufficiently long waiting times T, we always observed two different ways of convergence to the final states: one is in Fig. 4h (two 3-clusters), the other is three 2-clusters (not on the picture, yield problem [28]).

B. *Hinge-connected chain model*

The outcome of the experiments described in section IV-A led to the question of how to take our modular system to another level of operation. To answer this question, we added permanent magnets to each module. Because with many modules the outcome of this change was not easy to anticipate, we built a new type of module. Each module was physically linked through hinge joints to two modules forming a chain (Fig. 5, $m = 12.8\ g$). By taking inspiration from protein folding, we expected a drastic reduction of dimensionality of the search space. The main advantage of this implementation is that it avoids a crucial problem: the increased number of magnets generates also undesired configurations. Note that the positions of all the other magnets were replaced and rearranged. Only the center module (red colored, Fig. 5b) had a large magnet oriented orthogonally to the symmetry axis. The other small cylindrical magnets were oriented vertically – “S”outh poles attracting “N”orth poles and *vice versa*. As in the modules described in the previous section, diodes were used to direct the current flow. Depending on the polarity of the applied voltage, current only flowed either through the Peltier elements ($12\ V$) or through the vibration motors ($10\ V$).

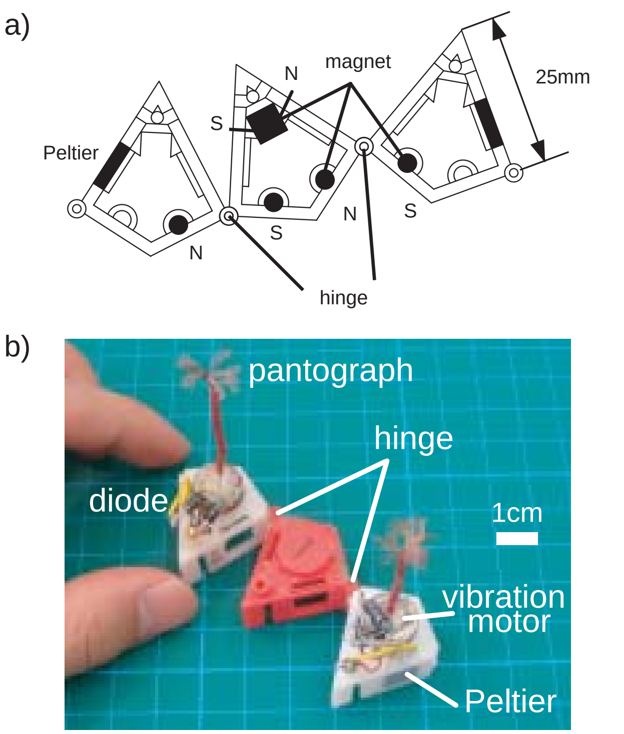

Fig. 5. Chain model. a) Schematic illustration of a chain. b) Picture of a chain. Three modules are connected by hinges.

Snapshots from a representative experiment are shown in Fig. 6. At the beginning of the experiment, we arranged by hand two chains of 3 modules each to form a hexagonal shape (Fig. 6b). Voltage was applied to the system so that the Peltier elements were powered (Fig. 6c). After one minute, an ice layer built up between the modules causing them to attach to each other yielding one single piece (Fig. 6d). We then inverted the polarity of the applied voltage and let the current flow to the vibration motors (Fig. 6e). The ice melted and the modules altered their configuration guided by the magnetic forces (Fig. 6f,g). The transformation was completed in a minute, and two magnetically connected triangle chains were obtained (Fig. 6h). The success rate of the reconfiguration

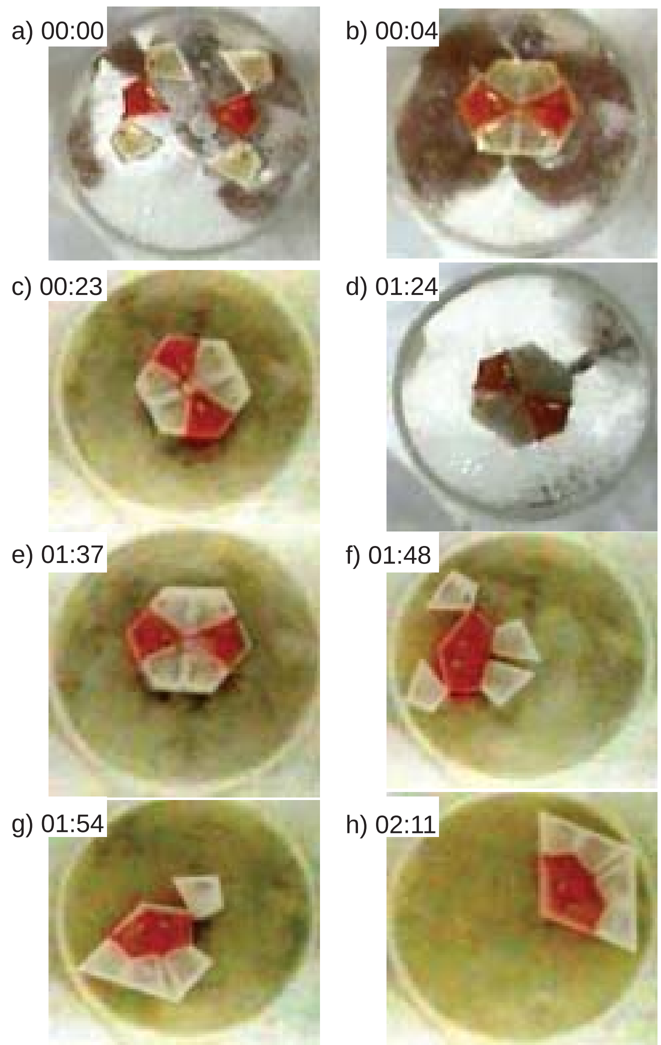

Fig. 6. Snapshots of the experiment with chain modules.

just described was not as high as expected. We suspect that this low yield rate was mainly due to a design problem: the position of the large magnet was too close to the edge of the module. Therefore a rather strong movement of the modules was required to induce a disassembly of the initial hexagonal configuration.

The main implication of the two experiments described in this section IV is that the restriction of the geometric constraint of modules, in other words, the “dimensionality reduction” of the reconfiguration problems enables the system to transit to a different level of functionality, bringing the modules to magnetically connected triangular clusters while avoiding undesirable formations (yield problem).

V. Discussion

An important goal of the growing field of self-assembly is the development of a better formal understanding of the specific mechanisms and general principles underlying it. It is clear that the discovery of principles which hold at all scales will require substantial input from various fields. At the molecular scale, biological systems are one of the examples that achieve robust self-assembly system through an intricate web of well ordered reactions. Attention must be paid to the fact that all components are passively interacting even if it looks as if they are actively reacting [34]. In order to achieve highly autonomous self-assembly modules, the realization of a sufficient number of degrees of freedom that are controllable is necessary for such small scale autonomous-distributed systems. In particular, because of the difficulty in including different types of attractive forces within the same system, realizing a new kind of connection mechanism endows the module with a better means of reacting in the environment. In this sense, the idea of a connector exploiting the thermoelectric effect may open yet another possibility for the state of the art of self-assembly systems.

VI. Conclusion

We presented a novel type of connection mechanism for small-scale modular robotic systems. The mechanism exploits the thermoelectric effect to cool down the temperature and freeze water close to the modules and induce a strong bonding between modules. To test the connector, we embedded it into water-based modular robots. The results obtained in this research demonstrate the utility of the proposed connection mechanism for lightweight self-assembling systems, and open a door towards more resilient self-assembly system at smaller scales.

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