Stochastic Self-Reconfigurable Cellular Robotics

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***Abstract* — Current implementations of self-reconfigurable robotics rearrange modules through a planned, deterministic reconfiguration path. Reconfiguration is achieved using active module locomotion or manipulation. Here we propose a form of self-reconfigurable robotics based on passive, stochastic self-organization. Solid-state cellular units exploit 'Brownian motion' in their environment and require no local power or locomotion ability. This form of reconfiguration avoids many of the barriers that prevent self-reconfigurable robotics from extending to large numbers and small scales. We demonstrate working prototypes and discuss preliminary analytical and computational models for analyzing the scalability of this concept.**

Keywords – modular self-reconfigurable robotics, self-assembly.

I. Introduction

Self-reconfigurable robots can change their morphology autonomously to accomplish diverse tasks. These robots can rearrange the connectivity of their structural modules to create new topologies, and thus can attain a larger variety of configurations than are available to a fixed-morphology robot.

The potential of self-reconfiguring robotics is widely recognized and a number of design concepts have been developed and demonstrated in the last decade. Fukuda and Kawauchi [2] developed CEBOT, cellular robots that join with others to form structures to perform some task. Yim [13] developed modular robots that can be manually reconfigured to form different structures that have various means of locomotion, and has since developed a number of self-reconfigurable systems such as PolyBot [12]. Pamecha and Chirikjian [8] developed a self-reconfiguring structure made up of metamorphic modules that have the ability to form structures by rolling over each other in a plane. Rus and Vona [9] developed Crystalline, modules that can form robotic systems by collapsing and expanding the body of each module. Rus *et al* have also studied different forms of self-organizing robotics through their experiments with the prototypes of Molecules [4][5], modules that have a pair of two degree-of-freedom atoms and can successfully form 3-D shapes. Murata et al [6][7] created Fracta, a modular robot that can form into different 3-D shapes by rotating themselves about each other. Tomita *et al* [10] further develop this concept of modules that can climb over one another. Yoshida *et al* [14] present a miniaturized self-reconfigurable robot.

In those and other current reconfigurable systems, modules are rearranged through a planned, *deterministic* reconfiguration path accomplished through deliberate *active* motion. Modules rearrange either by locomoting independently, or by being manipulated into place by other motorized units of the robot. Such explicit reconfiguration processes offer many advantages, but place severe power and mechanical actuation challenges on the design of each module. In particular, these requirements limit the scalability of such systems to smaller scales, where power storage is difficult and mechanical locomotion and actuation possibilities are limited.

In this paper we propose a form of self-reconfigurable robotics based on *passive, stochastic* self-organization. We seek simple, solid-state units (no moving parts) that can take advantage of Brownian motion in their environment to alleviate the need for local power and independent locomotion ability. This form of reconfiguration avoids many of the barriers that prevent self-reconfigurable robotics from extending to large numbers and small scales. As scales reduce, deterministic active locomotion becomes increasingly difficult, whereas stochastic passive motion becomes easier. Biological and physical systems at the micro- and nano-scales rely extensively on such parallel stochastic self-assembly and reconfiguration based on passive motion, and this tendency is progressively pronounced as scales decrease. To date, artificial systems based on stochastic self-assembly of structures have been demonstrated at the millimeter scale [3] and at the nano-scale [11], but are not reconfigurable: they assemble – like a puzzle – according to predesigned templates. This approach is also difficult to scale to complex, non-periodic, arbitrary 3D configuration and is very sensitive to matching errors.

While the underlying process we propose is stochastic, we still wish to deterministically control the overall global configuration and behavior of the system, and so new structural and control issues must be addressed. In this paper we present a macro-scale prototype system and preliminary analytical and computational models with which we have begun investigating the challenges and opportunities of this robotic substrate.

II. Concept

A stochastic robotic system reconfigures inside an environment that enables Brownian motion. At the macro-scale, such environments exist in zero-gravity space or in agitated fluid surroundings. At the micro and nano scales, almost any fluid environment facilitates such motion. After or between reconfigurations, a system may

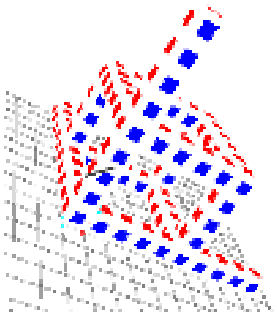

Figure 1. **Concept illustration.** Cellular units can form and reconfigure into 3D structures.

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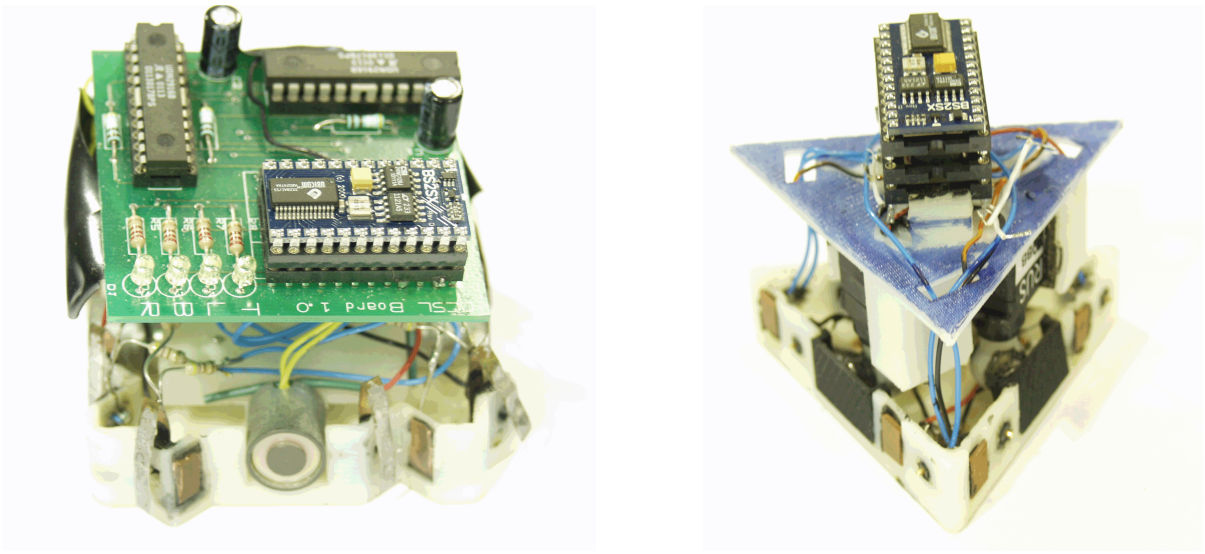


(a) (b)

Figure 2. **Two prototype units** (a) square, using electromagnets (b) triangle, using swiveling permanent magnets

operate outside of this kind of environment.

Units of a stochastic modular robotic system have the following characteristics:

- **Units are unpowered**, and become active only once they bond to the main structure.
- **Units have no locomotion ability**. The potential location of a unit is determined by active bonding sites and the statistical mechanics of Brownian motion.
- **Unit interfaces are identical**, and their function differentiates depending on their final context.

Structures can reconfigure by activating new bonding sites on their exterior and waiting for a floating unit to bond, or by rejecting connected units into the environment. The likelihood of bonding depends on statistical mechanics properties of the motion and attraction basin of active bonding sites. Depending on the specific design of individual modules, they can share power and information and cooperate to achieve global sensing, actuation and computation. Power for this system comes from the substrate on which it is grown, or from the environment in which it is embedded.

III. IMPLEMENTATION

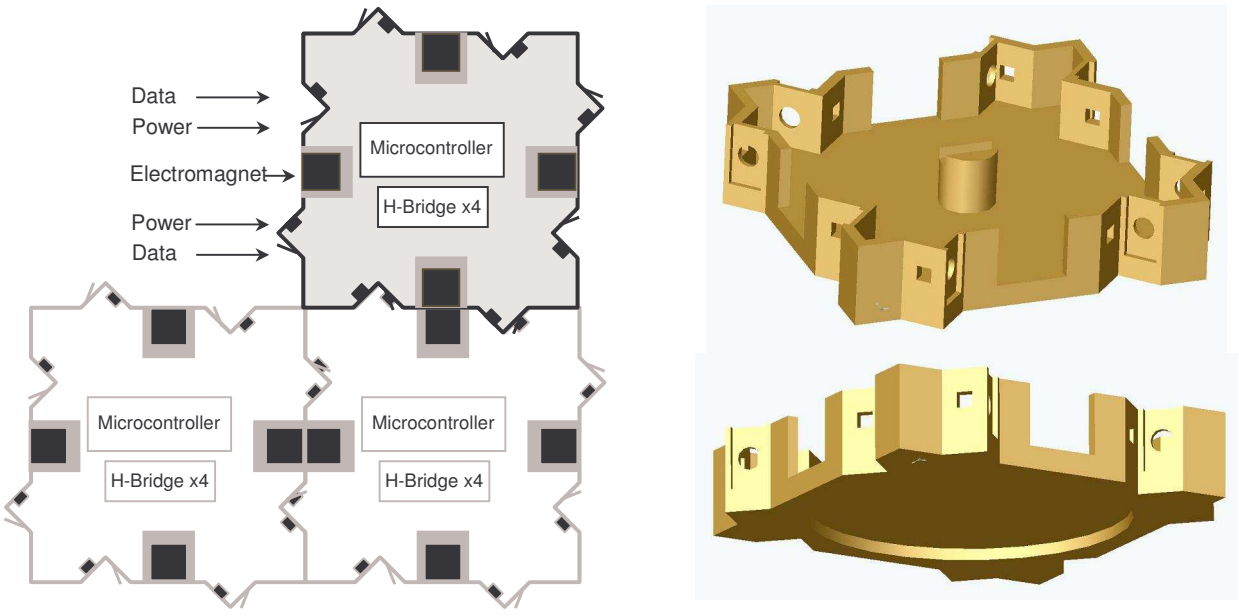
We chose to begin investigating this concept at a macroscopic scale and in two-dimensions. The environment selected was planar, consisting of a 30×30cm (1 square foot) air table atop an orbital shaker. The shaker oscillated at 1Hz to simulate macroscopic Brownian motion. Three cellular units shuffled in this space with nearly frictionless motion, elastically bouncing off each other and off the table boundaries. Three units are the minimum required to demonstrate meaningful geometric reconfiguration. In one set of experiments we used square modules (Figure 2a), that self-assembled into an *L*-shape and then into a line. In a second set of experiments we used triangular units (Figure 2b), that self assembled into a line and then changed their sequence within the line.

Design details

The schematics of the design of the square unit and its base are shown in Figure 3. The base unit is 6cm square and supports all of the components of the robot from the circuitry to the electromagnets. A circular indentation on the bottom of the base allows formation of an air cushion under the robot, permitting it to float freely. Each side has a slot to allow the electromagnet to protrude and connect to another robot's electromagnet. Triangular notches were used to ensure that the robots line up perfectly and that the robots separate (rather than slide sideways) when the polarity of the electromagnets is reversed. Our electromagnets attract the other electromagnets whether they are powered or not, but the attractive force drops proportional to the square of the distance. The force that is necessary to bond one robot to another is equal to the total spring force applied by the leaf spring contacts when the two robots are completely bonded.

A critical part of the design is the means for transmitting power and information from one robot to another. An alternating male/female pattern of contacts consisting of leaf springs and copper plates was used. Beryllium-copper sheet roughly 3mm wide and 0.1mm thick is bent in half lengthwise in order to create a cantilever spring that requires very little force to compress and yet will not fail due to yielding or fatigue. A tradeoff exists between the stiffness of the bond and the quality of the contact, and it must withstand multiple connections and sustain multiple impacts. Through repeated tests, a design was obtained that yielded robust and consistent performance. Capacitance filtration was used to allow smooth wakeup of the microcontroller and to remove spikes introduced at the instant of bond formation.

The robot control circuitry comprises a printed circuit board that holds a set of H-bridges and a Basic Stamp II microchip. There are a total of four H-bridges that are used to electronically switch the polarity of the electromagnets. The H-bridges receive a logic signal from the controller, which in turn determines which sites to activate depending on the current configuration state. Information is transmitted via serial



(a) (b)

Figure 3. **Design of a unit cell** (a) Layout and I/O schematics, (b) base geometry

connections made by the data contacts and is used to link the states of adjacent robots i so as to achieve local autonomous decision-making based on global state.

The triangular units used in the second set of experiments involve a similar design but used permanent magnets whose polarity is reversed by swiveling them about a vertical axis using a servomotor. The permanent magnets used are significantly stronger than the electromagnets, and therefore have a larger attraction basin and do not require the elaborate alignment pattern. However, the design involved moving parts and therefore is less compatible with the long-term objective of this project.

IV. Experimental Results

We carried out two experiments, demonstrating self-assembly and reconfiguration of three robots into various formations.

In the first experiment, the square units were programmed to configure into an L-pattern and then reconfigure into a line. One of the units was selected as the 'base' unit, and was externally powered. We also restricted the configuration such that the third unit would only assemble to the second unit, rather than both second and third units attaching directly to the base. This constraint was enforced to verify that the second unit, once attached to the base, is indeed active, and that the configuration information propagates through the system.

Figure 4 (top) shows a sequence of snapshots from the configuration and reconfiguration processes. The significantly long time to required configure into the final state is due to the tight geometric constraints of the arena boundary, and is an artifact of our particular setup. More general statistical data is provided in Table I. Figure 4 (bottom) shows a sequence of snapshots from the configuration and reconfiguration process for the triangular units. These units reconfigure much faster because of the stronger magnetic forces and smaller unit size, allowing more freedom for shuffling and more uniform Brownian motion.

To obtain a more rigorous statistical estimate of the bonding rate of this system and its potential scalability, we carried out 40 additional experiments, measuring the mean time to form a bond under two ratios of passive to active bonding sites. The results are shown in Table 1 and were measured in an arena with one square-foot area. The discrepancy between the measured rates and the time to reach the final reconfiguration in Figure 4 may be explained by the boundary conditions imposed by the tight arena geometry on the final shape.

TABLE I. Bonding Statistics for Square Units

Density [units/sqf]	2	3
Active bonding sites [sites/sqf]	4	4
Passive bonding sites [sites/sqf]	4	8
Mean time to bond [sec/sqf]*	60.8 ± 8.8	38.8 ± 11.3
Average bonding rate [bonds/sec/sqf]	0.016	0.026

* Std. dev. and average based on 20 experiments each, at 1Hz agitation

V. Analytical Model

The rate of structure configuration is dependent on bonding statistics. An analogy can be drawn between the growth of an unconstrained structure and the statistical mechanics of crystal formation. There are two key differences, however. Atoms forming a crystal are not permanently bonded at any location, and are somewhat free to move within the structure to minimize energy, and thus fill any internal cavities and relieve dislocations. In our system bonds are permanent (at least until reconfiguration is initiated), and so undesired cavities are difficult to fill. Nonetheless, a simple model can be developed.

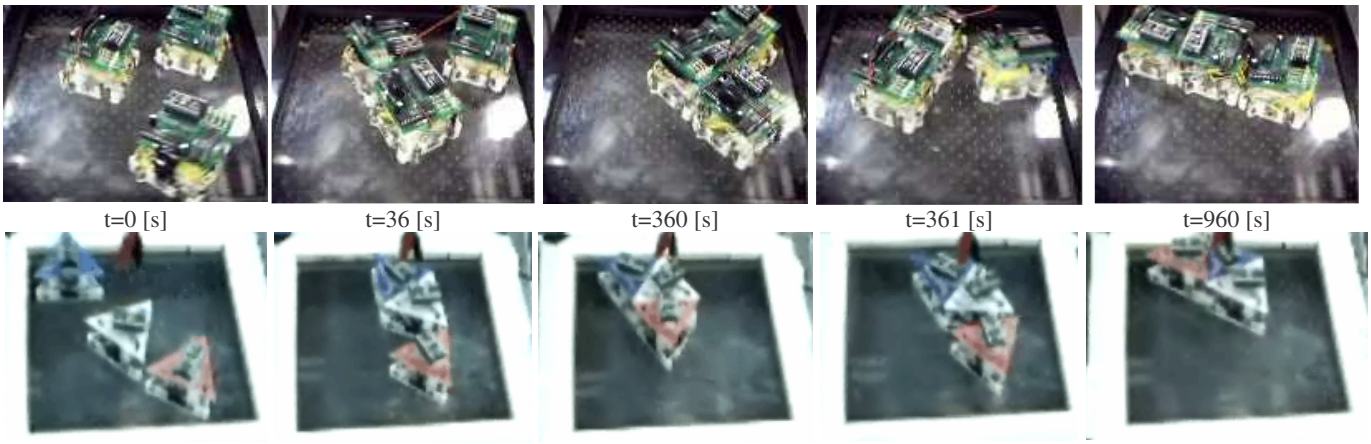


Figure 4. **Stochastic self-reconfiguration**: (top row) square units with electromagnets; (bottom row) triangular units with swiveling permanent magnets. All units have *no locomotion ability*, and all units except seed are *unpowered*.

A differential relationship can describe the dependency between a structure with F units and rate of its growth dF/dt as proportional to the number of active bonding sites. If the number of active bonding sites is proportional to the surface area of the structure (the perimeter of the area in our 2D case), and we assume the perimeter to be proportional to the square root of the area, then

$$\frac{dF(t)}{dt} = \alpha\sqrt{F(t)} \tag{1}$$

where α is some bonding rate coefficient (see below). Solving this differential equation yields a polynomial solution,

$$F(t) = \frac{\alpha^2}{2}t^2 \tag{2}$$

The coefficient α combines various factors that influence the structure formation rate. We observed some of these factors to be:

- **The density** of the free units in the surrounding environment. The density of free units determines the ratio between active bonding sites on the main structure and the complementary potential bonding sites on the passive free units. This ratio directly influences the probability of initiating a bond. In our experiments the density of bonds ranged from 1:1 to 1:2 (active : passive).
- **The energy** of free units. The energy affects the velocity of the units in the environment, the mean distance covered in Brownian motion and the impact with which bonds are initiated. This ratio directly influences the probability of initiating and retaining bond. In our experiments the average velocity was 60±40 mm/s and the mass was 100gr.
- **The attraction** of the bonding sites. Depending on the attraction field created by the active bonding site, this factor also influences the probability of forming and retaining bonds. In a static state the square units attract a passive bond up to 15mm away or 14° of misalignment.
- **The retention** of the bonding mechanism. Based on mechanics of the bonding mechanisms, a bond needs to be able to hold a unit in place. A bond that is not retained may lose a unit due to the environmental agitation, or may hold the unit improperly and thus preclude geometric scaling. In our experiments, no bonds were lost.

The actual factors are difficult to predict analytically and depend on intricate physics of the bonding process, including dynamics, friction, and elasticity of the connectors, magnetic field (in our case) and fluid mechanics of the environment. Table 1 lists two such factors measured *empirically* in our system for two different densities.

This simple model predicts that robot reconfiguration process will accelerate with size. This prediction is quantitatively verified in the computational simulations below, for unconstrained geometries. However, the model ignores the complexities introduced by non-uniform geometry, and so more elaborate computational models are needed.

VI. Computational Model

We investigated the scaling of the configuration process by computationally simulating the formation of various structures under various physical conditions, and configuration control schemes.

The 2D simulator, shown in Figure 5, simulates the kinematics of large numbers of square units in a circular arena. The radius of the arena can be increased as necessary to reduce boundary effects. Each unit has a position, orientation, and linear and angular velocities. The units bounce elastically off each other and the arena boundary while conserving total momentum and energy. However, the specific spins of each unit after collision are set randomly. Figure 5a shows traces of the motion of the free units; these traces are omitted from the other figures for clarity. Units can be fixed in the main structure or freely floating. Fixed units (with zero linear and angular velocity) are drawn in bold.

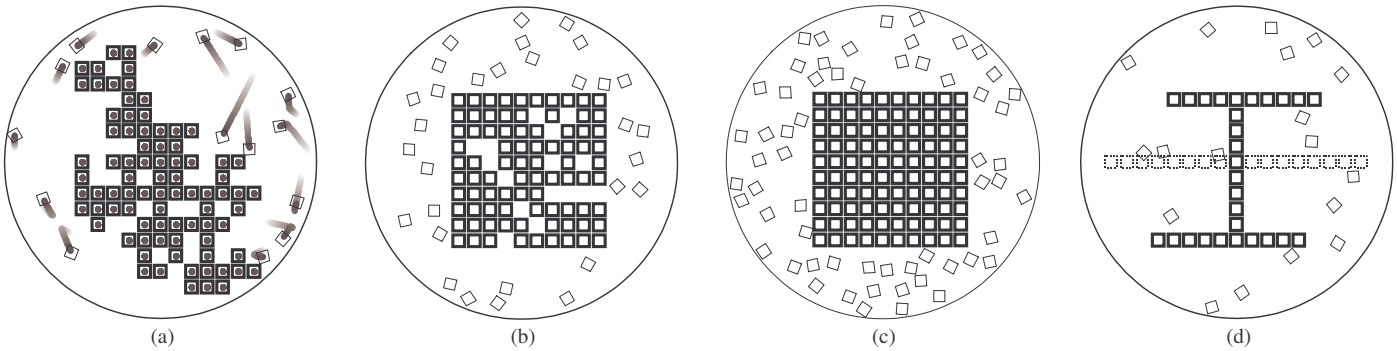


Figure 5. **Simulations of configuration formation**: (a) unconstrained growth, showing motion traces; (b) 10x10 square structure, unmoderated; (c) 10x10 square structure, using layerd construction; and (d) Reconfiguring from a line to an H-shaped structure with diameter equivalent to a 10x10 square.

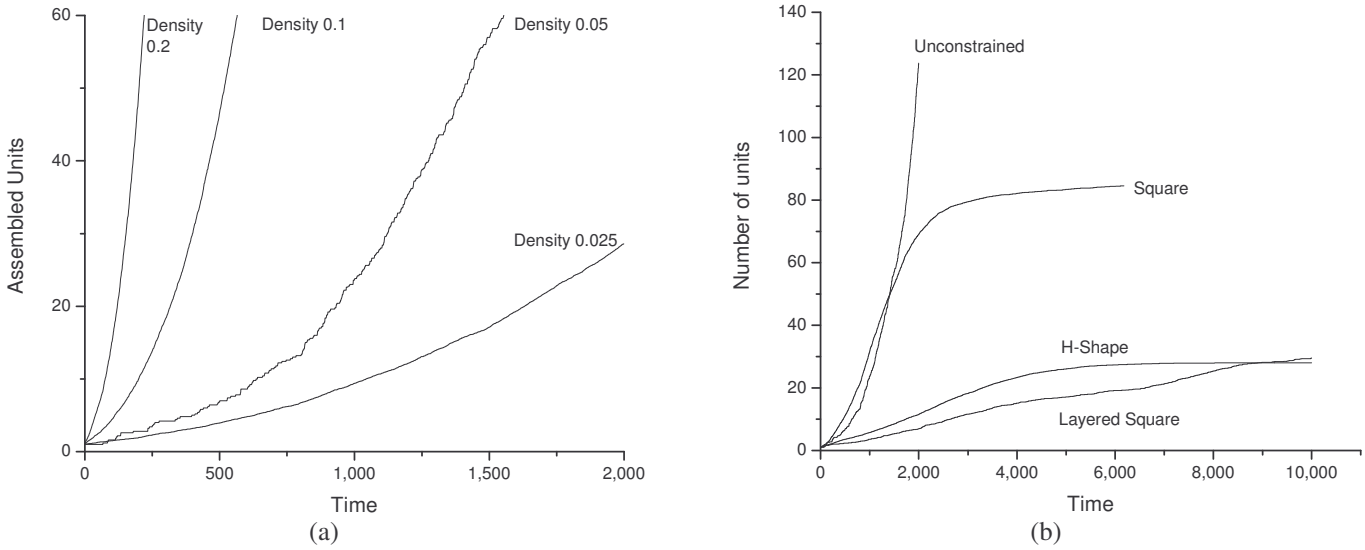


Figure 6. **Self-configuration rates**. (a) unconstrained geometries under four densities; (b) Comparing different control scemes for reconfiguration width density 0.05: Uncontrolled, 10x10 square, 10x10 square with growth rate control, and H-structure with diameter equivalent to a 10x10 square. Time units are arbitrary.

The four parameters of the problem, namely the average density and energy of the units, and the attraction and retention of the bonds can be adjusted in the simulator at any time. For example, figures 5a, 5b, and 5c show densities of 0.025, 0.05, and 0.1, respectively. The density is the ratio between the area of free robots and the free area of the arena. Because of the collision computations, the performance of this simulator currently scales with $O(n^2/\delta)$ where n is the number of units and δ is the simulation time step.

The first set of experiments carried out was to confirm the model of Eq. (2) predicting second-degree growth. Four densities were tested (0.025 0.05, 0.1, 0.2), and each run was repeated 100 times, each for 2,000 time steps. The geometry was unconstrained, yielding arbitrary configurations such as that shown in Figure 5a. The averaged curves showing number of units as function of time are plotted in Figure 6a. All curves fit a 2nd-degree polynomial very well ($R^2>0.995$, $p<0.0001$). According to the model, the coefficient of the 2nd-degree term should quadruple when the density is doubled. Working out the actual coefficients showed they increased 25% faster than predicted; we postulate this may be because of the irregularity of the perimeter, which tends to increase bonding rate. Further investigation is required.

Reconfiguring into specified morphologies

The primary goal of reconfigurable robotics is to reach specific, predetermined morphologies, and so control schemes must be developed to allow deterministic formation of geometry despite the stochastic nature of the substrate.

A straightforward approach for configuration control is to allow each unit to locally determine which of its free bonding sites to activate, according to a configuration map distributed to each unit as it attaches. However, depending on the actual geometry, this approach may lead to deadlocks in the development, as cavities are sealed off irreversibly.

Consider, for example, the formation of the structure into a 10×10 unit square. Starting with a seed unit at the center, each joining unit learns of its relative position to the center and determines which of its own surfaces to activate. However, as the structure develops, cavities form leading to porous assemblies such as the one shown in Figure 5b. For some applications this may be acceptable, but for precision assembly more than geometry-based control is required.

An alternative scheme investigated is to temporally moderate the formation such that cavities do not form. One approach is a *layered* construction, where the target configuration is reached layer-by-layer, starting from the seed

or from the largest substructure common to both the current configuration and the target configuration. For example, by locating the seed unit at the center of the 10×10 square, one can form a perfect square as shown in Figure 5c. However, a layered formation has two disadvantages: First, it is significantly slower than formation constrained by geometry alone. The average progress of the layered square is plotted in Figure 6b. Second, it requires global knowledge at each unit: Units must know the current state of other units to determine if construction of the next layer can begin. More sophisticated control schemes can be devised to accelerate layered construction and reduce local communication, by requiring only *local* near-convexity. The amount of local concavity tolerable is implementation specific.

Reconfiguration time

A number of factors govern the time to reach a configuration. The bonding rate coefficient (α) discussed earlier governs the local physical properties. The control scheme, such as the layered assembly process described above is a second factor. The third factor is the number of steps required to transition from the source configuration to the target configuration. Since assembly process is parallel in nature, it is not merely the number of units, but rather the number of steps that need to be carried out *in serial*. If a structure is constructed from scratch, this would imply that the criteria for the number of steps would be the *diameter* of the structure, where diameter has the graph-theoretic meaning of the longest shortest-path between any two nodes in the connectivity graph of the target structure. The seed unit would then be optimally placed at the center of the longest path. Figure 5d shows a structure reconfiguring from a line into an H-shape, and Figure 6b plots its configuration progress. The H-shape has the same diameter (20) as the 10×10 cube, but the H-shape assembles much faster as is evident in Figure 6b. It appears that the actual reconfiguration time depends heavily on the geometric concavities of the shape; for example fitting the last unit into an otherwise complete row may take significantly longer time. It is thus still necessary to model the effect of various local geometries on the statistics of assembly.

VII. Conclusions

Deterministic and planned behavior has been a fundamental cornerstone in the design of robotic systems – in many cases, elaborate control schemes and mechanisms have been designed specifically to remove or compensate for uncertainties. However, as we are challenged with designing robotics systems of increasing numbers of components and progressively smaller scales, we may consider exploiting stochastic effects rather than avoiding them. Biological systems and physical patterns at the micro- and nano-scales are composed of small building blocks that are not fully self-contained – they have little internal energy and locomotion ability, and make extensive use of Brownian motion and other sources of ambient energy.

Inspired from such biological systems, we have examined some issues in stochastic self-reconfigurable cellular robotics. The field of self-reconfigurable robotics seems the most appropriate starting point, since such systems already address questions regarding formation and reconfiguration of complex structures composed of multiple simple units. As in molecular biology, it seems that docking geometry plays a key role in determining reconfiguration capabilities, and we have only examined very few of the questions.

Further research is needed in (a) development of more accurate computational models, (b) construction of more realistic, three-dimensional physical prototypes to test these models, and (c) exploration of microfabrication-compatible switchable bonding mechanisms [1] that will allow implementation of these concept at the microscale.

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