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Self-Organizing Collective Robots with Morphogenesis in a Vertical Plane*

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This paper presents a novel concept of self-organizing collective robots with morphogenesis in a vertical plane. For physical reconfiguration of a swarm of robots against gravity, new types of mechanisms and control strategies are proposed and demonstrated. Basic feasibility of the mechanisms was confirmed through an experiment adopting four prototype robots. Each robot is composed of a body and a pair of arms. The body is equipped with permanent magnets for bonding with another robot. The arms change the bonding configuration by rotating and sliding motions. As for the control strategies, we proposed algorithms which can generate specific global formations of robots from local and minimum interactions between neighboring robots. It is shown that the proposed algorithms can successfully conduct the swarm of robots to the predetermined configurations.

Key Words: Self-Organization, Self-Reconfiguration, Self-Assembly, Collective Robots, Mobile Robot, Cellular Automata

1. Introduction

In Distributed Autonomous Robotic Systems (DARS), a group of simple individual robots achieves complicated tasks by cooperation(1)(2). Such systems have robustness, adaptability, and other advantages. One central concept of DARS is self-organization. Although a strict definition of self-organization is difficult, an essential aspect of that is creation of a global pattern caused by local interaction between many individual elements. From this point of view, complex phenomena in various fields—physics, chemistry, biology, and economics—have been elucidated(3).

As for artificial self-organizing systems, most researchers have focused only on its informational aspect(4). On the other hand, there have been several experiments for mechanical self-organization in the real world. Penrose(5) developed some primitive (but sophisticated) mechanisms for self-assembly by using hooks and levers. Fukuda and Nakagawa(6) proposed the "Dynamically Reconfigurable Robotic System". In their experiment, two mobile robots were autonomously connected to each other. Murata et al.(7) constructed "fracta" robots which were linked together by electromagnets. They could change their linking formation by switching the electromagnets. Chirikjian et al.(8) formalized kinematics of such reconfigurable robotic systems in order to evaluate the motion planning of each module. Hosokawa et al. studied random self-assembly by using plastic elements with permanent magnets(9), and microfabricated thin films(10).

One goal of this research is to apply mechanical self-organization to autonomous mobile robots. Especially, we have been interested in the motion in a vertical plane. In a usual environment, mobile robots can move in a horizontal plane by their locomotion systems. If they can move to the third dimension (vertical direction) by mechanical self-organization, their ability would be dramatically expanded. Figure 1 shows two examples of possible applications. In Fig 1(a), when the robots encounter a large cliff, they could climb it by constructing a stairs-like structure. Consider another case in which the robots encounter a

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wide gap as shown in Fig. 1(b). To pass over the gap, the robots could construct a bridge-like structure. In such a system, gravity becomes the most essential problem among all physical constraints. However, gravity has never been explicitly discussed in the previous work on self-organizing mechanisms. The gravitational problem can be divided into two subproblems. First, mechanisms of each robot should be powerful enough to overcome gravity, or in other words, the weight of the robot should be sufficiently light. Second, the system requires a control strategy to avoid collapsing or tumbling in the final configuration as well as in the intermediate states.

Section 2 discusses the first problem. Mechanical design issues of the prototype robots are detailed. The basic feasibility of the mechanisms has been proved by an experiment using open-loop, centralized control. In Section 3, we propose distributed control algorithms for global morphogenesis based on local communications. The proposed algorithms have been tested by computer simulations. In Section 4, we discuss the difference between our control algorithms and those in the related literature.

2. Mechanisms

In our current stage, locomotion and navigation systems are out of scope, since these technologies have been widely studied so far. We have been concentrating on: (1) bonding between individual robots, and (2) mechanisms for changing the bonding configuration. For these two purposes, we developed two kinds of bonding: static and transient. Figure 2 shows the schematic view of our robots. Each robot is composed of a cubic body and a pair of arms. The body has four bonding faces (x- and z-directions) which can make the static bonding with another robot's body. For the transient bonding, the tip of each arm is equipped with a connecting mechanism. The arms of a robot can synchronously move with two degrees of freedom: they rotate around y-axis, and slide (extension/contraction). The robots can change their bonding configuration within xz-plane using their arms.

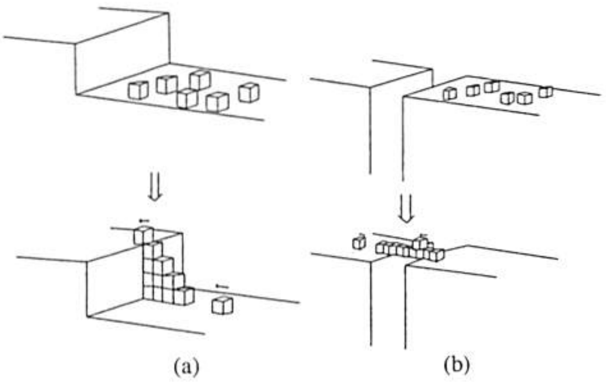
(a) (b)

Fig. 1 Examples of possible applications of the proposed system

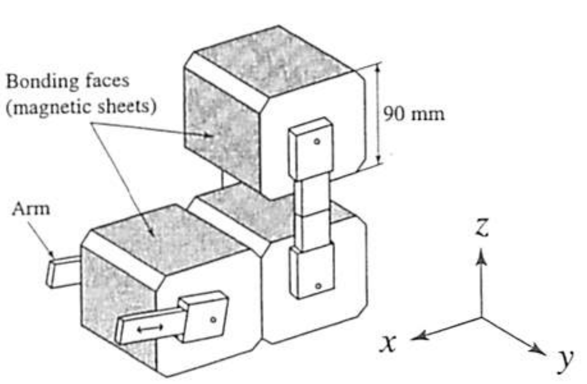

Fig. 2 Schematic view of the robots

Figure 3 shows an example of constructing a stairs-like structure using these mechanisms from three robots bonded in a row at the beginning. When two robots change the bonding configuration, they connect their arms and extend them to disconnect their bodies. After rotating their arms by specific angles, the robots contract their arms and make bonding between another pair of bonding faces. In the implementation of the robotic system described above, it is obvious that the weight of each robot is critical. Therefore, we gave top priority to lightness and simplicity. The weight of the prototype robot is about 600 gf including batteries. In the rest of this section, the design consideration of the prototype is detailed.

2.1 Body

The body can be regarded as a cube with edge length of 90 mm, and is composed of six plastic plates

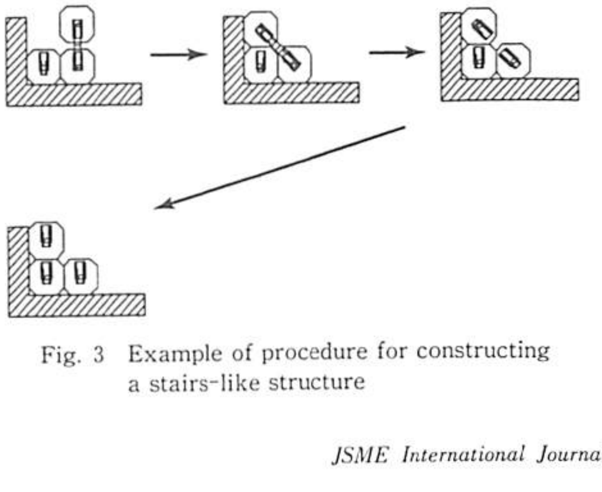

Fig. 3 Example of procedure for constructing a stairs-like structure

which are joined by bolts. On the four surfaces of the body, permanent magnetic sheets were pasted. The magnetic sheet is a commercial product. We measured the bonding strength between two magnetic sheets. We obtained the tensile strength as 3.3 kPa, and shearing strength as 4.8 kPa. It was experimentally confirmed that the magnetic bonding was strong enough to support the structure in the situation shown in Fig. 4. When a robot was bonded by its one side face (Fig. 4(a)) or its bottom face (Fig. 4(b)), the robot could lift another robot up without tumbling. Only one robot could overhang without collapsing (Fig. 4(c)).

2. 2 Arm bonding

For the arm bonding, we adopted the simplest "lock-and-key" structure which is passively combined with each other. One important consideration for this structure is lack of "polarity" (male/female discrimination). If there are two classes of arms, and the bonding is limited between different ones, then the reconfiguration process would be very complicated, or practically impossible. To avoid this, we made the arms homogeneous: each arm is equipped with both a lock part and a key part as shown in Fig. 5. Two arms are linked together by inserting one's pin into the other's notch. The connection is stable against compressing force and bending moment.

2. 3 Arm driving

As described above, the arms have two degrees of freedom: rotation and sliding. Both motions are driven by servomotors, which are commercial products for radio-controlled toys. They are cheap and sophisticated—a DC motor, a control circuit, and a gear unit with a potentiometer are packaged in a small space. And of course, it is easy to control them in wireless mode. This is a great advantage for making a prototype, because electric wiring to external apparatus (e.g. computers or power supplies) is unacceptable in such a system. Such cables would be immediately tangled by the rotating arms. Although the most desirable way may be loading a computer on each robot, the wireless control is convenient in our current stage. Figure 6 shows the diagram of the arm driving system. A radio transmitter is controlled by a computer through a D/A converter. For arm sliding, we developed the linkage mechanism shown in Fig. 7, since we could not find any linear actuator fitting this toy system.

2. 4 Self-alignment

Practically, alignment is one of the most important problems when the robots move through many step. If errors in bonding position are accumulated, then it would cause deadlock or other catastrophic situation. In a typical case, the arms could not be connected. The alignment should be automatically corrected for each reconfiguration steps. Our strategy against this problem can be summarized as "tight body, loose arm". As shown in Fig. 8, four prism-shaped guides were attached onto the top plate of each robot, which is slightly broader than the main body. When a robot is placed on another robot, the position and the orientation of the upper robot is corrected. Whereas the body connection was made

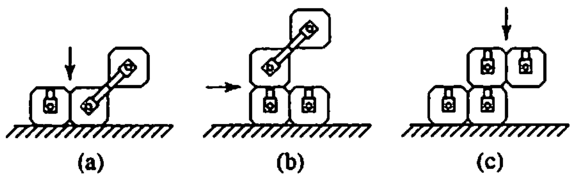

Fig. 4 Some barely stable states. The arrows indicate the critical connections: (a) (b) lifting up, (c) overhanging

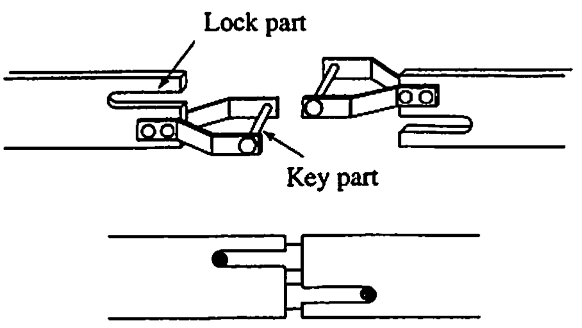

Fig. 5 Bonding structure for the arms

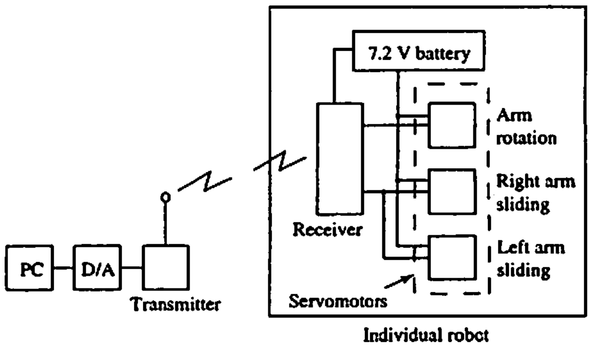

Fig. 6 Diagram of the arm driving system

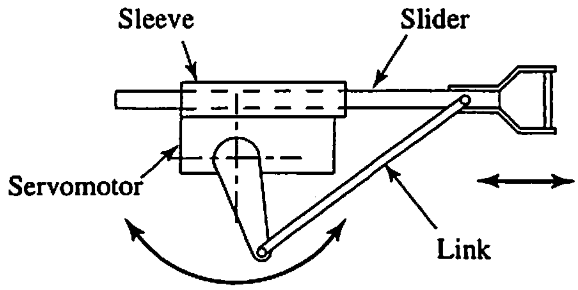

Fig. 7 Top view of the linkage mechanism for arm sliding

relatively strict as described above, we made the arm connection loose to avoid unnecessary mechanical stress.

2.5 Experiment

We built the four prototype robots described above and experimented for the proof of practicality of the concept. Figure 9 shows a photograph of the experiment. The assumed task was to lift a robot up to the top of a cliff which is twice as high as one robot. This task can be divided into two processes: (1) making stairs-like structure with three robots, (2) lifting the fourth robot up to the goal. They were successfully accomplished without tumbling or collapsing.

3. Control Strategies

In this section, we demonstrate our control strategies using three examples—formation of stairs-like structures, the reverse motion of it, and locomotion by reconfiguration — which indicate that global configuration can be controlled by only local communication between individual robots. The overall scheme is similar to cellular automata (CA)[11]. The behavior of each robot is determined by its own state and by those of the adjacent robots, according to a specific rule. Morphogenesis of the global formation depends on the initial condition and the rule. It might be possible to prepare several rules for different kinds of morphogenesis and to adopt an appropriate one depending on a particular purpose. However, this decision must be extremely difficult for robots. In this paper, we assume that the switching of the rule is carried out by some upper level intelligence including human beings.

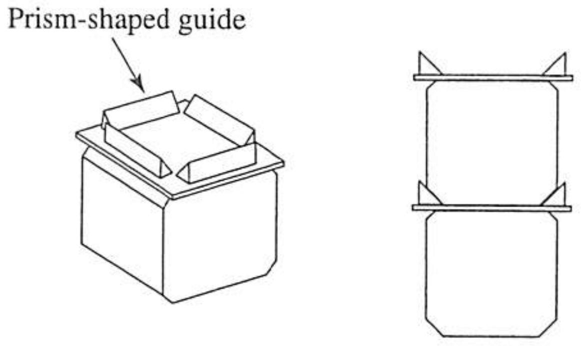

Fig. 8 Structure for self-alignment between robot bodies

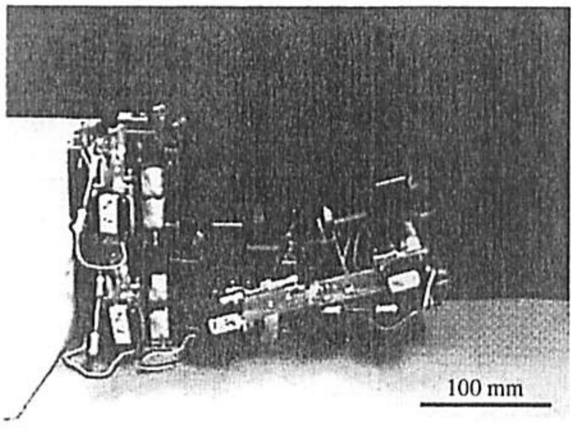

Fig. 9 A photograph of the experiment

The most distinct point of this system from conventional CA is that two neighboring robots—the moving robot and the pivotal robot—should cooperate for the physical morphogenesis. To do this, it is necessary to introduce some explicit message exchange between the two robots*1. In this system, two adjacent robots are assumed to be capable of communicating with each other through their common bonding face. Such communication could be easily realized using infrared, for example. In this case, an arbitrary robot A knows its own state *Self* (A) and the states of adjacent robots in four directions—upper, lower, left, and right. They are denoted as *Upper* (A), *Lower* (A), *Left* (A), and *Right* (A), respectively.

3.1 Formation of stairs-like structures

This example of algorithm demonstrates construction of a stairs-like structure ascending to the left. The initial configuration is a horizontal row of indefinite number of robots (see Fig. 11). To construct the stairs-like structure, the robots should move into two directions—upper-left and left. These elementary motions are illustrated in Fig. 10, and are separately detailed below.

Moving upper-left

Each robot has only one state denoted as "1". For convenience, we introduce a dummy state "0" to symbolize an empty space. If an arbitrary robot A satisfies the following condition:

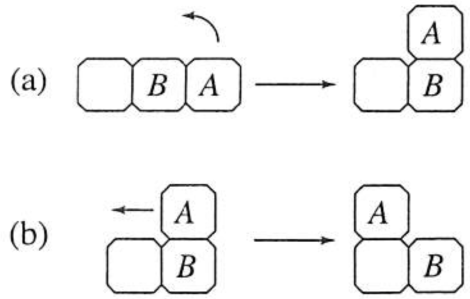

Fig. 10 Two elementary motions to form a stairs-like structure: (a) moving upper-left, (b) moving left

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*1 Probably an equivalent system can be constructed using conventional CA scheme with more complicated description.

$\mathit{Left}(A)=1$, and $\mathit{Upper}(A)=0$, and $\mathit{Right}(A)=0$, (1)

then robot A sends *Lift-Me-Up* request to robot B, which is bonded to the left side of robot A (see Fig. 10 (a)). Receiving the request, robot B begins to investigate the states of its neighbors. If the following condition is met:

$\mathit{Upper}(B)=0$, and ($\mathit{Left}(B)=1$ or $\mathit{Lower}(B)=1$), (2)

then robot B replies as *Yes* to robot A, otherwise it replies as *No*. If the answer is *Yes*, robot A moves to upper-left (i.e. onto robot B) by cooperating with robot B. In the case of *No*, they do nothing. Note that the condition in the parentheses in Eq. (2) is required for mechanical stability against gravity.

Moving left

An arbitrary robot A sends *Move-Me-Left* request to its lower adjacent robot B (see Fig. 10(b)) if the following condition is met:

$\mathit{Lower}(A)=1$, and $\mathit{Upper}(A)=0$,
and $\mathit{Left}(A)=0$. (3)

Then, robot B begins to inspect the circumstance. In the case of:

$\mathit{Left}(B)=1$, (4)

it replies as *Yes*, otherwise *No*. After this negotiation, the two robots behave in a similar way to the previous case.

Obviously, Eq. (1) and (3) cannot be satisfied concurrently, so any priority of these movements is unnecessary to be considered. We tested the algorithm described above by a simulation for the case of 15 robots. The results are shown in Fig. 11. The robots successfully formed the goal structure. In this simulation, one cycle (corresponding to one tick of time parameter t) can be divided into two steps—decision step followed by moving step. At first, the robots inspect their circumstances and negotiate each other to decide their next movements. Next, they move simultaneously according to their decisions. Such a parallel and distributed reconfiguration can be achieved by real robots if the clocks of all robots are synchronized at the beginning.

3.2 Reverse formation of stairs-like structures

The second example described below is just the reverse of the previous case—formation of a horizontal row from a stairs-like structure. The elementary motions are illustrated in Fig. 12. They are also just the reverse of those in Fig. 10. A major difference from the previous example is that the sequence of morphogenesis should be controlled to some degree. Otherwise the system may fall into a deadlock situation such as shown in Fig. 13. In this case, the black robot cannot move anywhere, since going down more than two steps is mechanically impossible (the arms would be disconnected). Generally, a tall tower-like structure means a deadlock state, which may occur when we allow downward motions. It is caused by the robots at lower level moving too early before all robots at upper level have gone down. To avoid this, we have introduced new robot states—*Active* and *Inactive*. A robot in *Inactive* state cannot be a moving robot, in other words, it does not send any request. It is activated by working as a pivotal robot. Once it becomes *Active*, it does not return to *Inactive* state again. The transition is irreversible.

As the initial condition, all robots are *Inactive*.

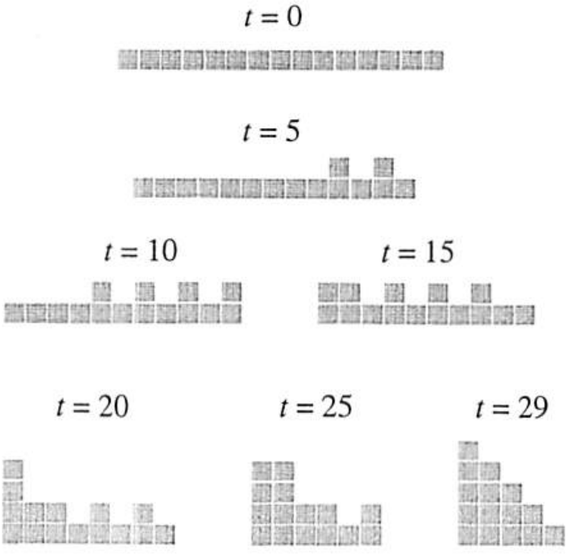

Fig. 11 Results of the simulation for 15 robots forming a stairs-like structure. It was completed at $t=29$, and did not change any more

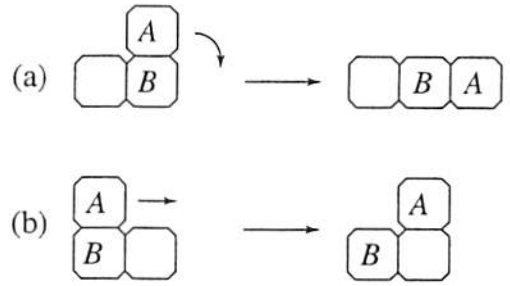

Fig. 12 Two elementary motions to flatten a stairs-like structure: (a) moving lower-right, (b) moving right

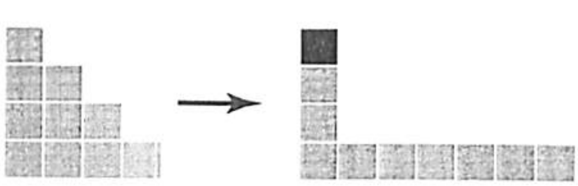

Fig. 13 A typical deadlock situation. The black robot cannot move anywhere

The top robot T turns into *Active* first by recognizing its position which is represented by the following condition:

$$Upper(T)=0, \text{ and } Left(T)=0. \qquad (5)$$

The situation at this moment is shown in Fig. 14 as $t=0$.

An arbitrary robot A sends *Move-Me-Anywhere* request to its lower adjacent robot B (see Fig. 12) if the following condition is met:

$$Self(A)=Active, \text{ and } Lower(A)\neq 0, \text{ and } Upper(A)=0, \text{ and } Right(A)=0. \qquad (6)$$

Receiving the request, robot B begins inspection of its circumstance. There are three cases.

(Case 1) The condition is described as follows:

$$Right(B)=0, \text{ and } (Left(B)\neq 0 \text{ or } Lower(B)\neq 0). \qquad (7)$$

In this case, robot B replies to robot A as *Go-Lower-Right* (see Fig. 12(a)).

(Case 2) The condition is described as follows:

$$Right(B)\neq 0. \qquad (8)$$

In this case, robot B replies to robot A as *Go-Right* (see Fig. 12(b)).

(Case 3) If neither Eq.(7) nor (8) is satisfied, robot B replies to robot A as *No*.

In Cases 1 and 2, the two robots cooperate according to the agreement, and robot A goes to proper direction. After the movement, robot B turns into *Active* state if it has been *Inactive*. In Case 3, they do nothing.

The above algorithm was also tested by a computer simulation in a similar way to that described in Section 3.1. Figure 14 shows the results of the simulation. The stairs-like structure was flattened into a horizontal row without falling into deadlock structure. The *Inactive* state worked effectively.

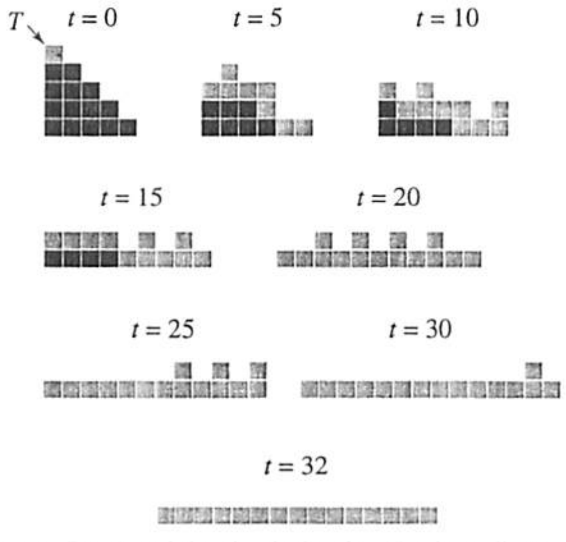

Fig. 14 Results of the simulation for 15 robots disassembling a stairs-like structure. It was completed at $t=32$, and did not change any more. *Active* and *Inactive* robots are represented as gray and black squares, respectively

3.3 Locomotion by reconfiguration

The third example described below is locomotion by reconfiguration. A group of robots connected to each other can travel to a specific direction only by reconfiguration, without locomotion mechanisms for individual robots. This example of algorithm is for a group of robots, horizontally connected in a row at the beginning, traveling to the left. The algorithm can be obtained by a minor modification of that described in Section 3.1. There are three elementary motions as shown in Fig. 15: moving upper-left, moving left, and moving lower-left. State definitions are the same as in Section 3.1: state "1" for a robot, and state "0" for an empty space.

Moving upper-left

This part is completely identical to the corresponding part in Section 3.1.

Moving left or lower-left

An arbitrary robot A sends *Move-Me-Anywhere* request to its lower adjacent robot B (see Fig. 15(b) and (c)) if the following condition is met:

$$Lower(A)=1, \text{ and } Upper(A)=0, \text{ and } Left(A)=0. \qquad (9)$$

Then robot B begins to inspect the circumstance. There are three cases. In the first case expressed by:

$$Left(B)=1, \qquad (10)$$

robot B replies to robot A as *Go-Left*. In the second case expressed by:

$$Left(B)=0, \text{ and } (Right(B)=1 \text{ or } Lower(B)=1), \qquad (11)$$

robot B replies to robot A as *Go-Lower-Left*. In the third case that neither Eq.(10) nor (11) is satisfied, robot B replies as *No*.

The results of the computer simulation are shown in Fig. 16. The group of six robots went to the left in

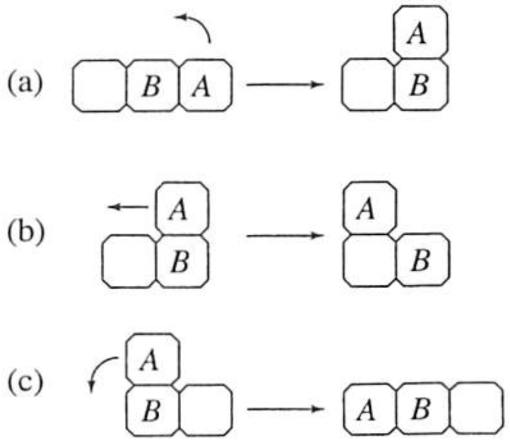

Fig. 15 Three elementary motions for locomotion: (a) moving upper-left, (b) moving left, (c) moving lower-left

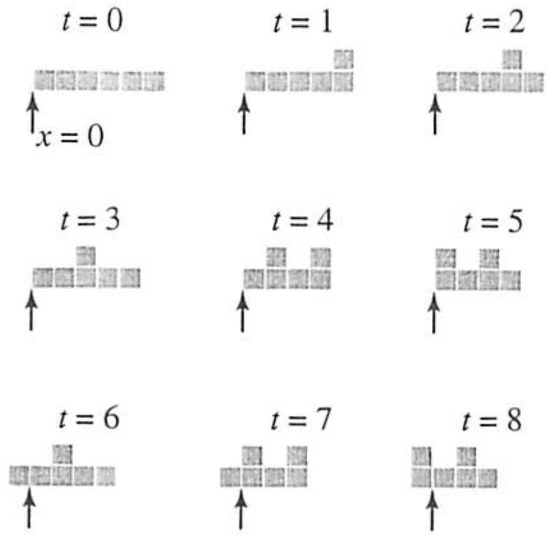

Fig. 16 Results of the simulation for 6 robots traveling to the left by reconfiguration. One cycle consisting of three steps (e.g. $t=3$ through $t=5$) is infinitely repeated. The arrows indicate the initial position of the forward end of the group of robots

a crawler-like manner by reconfiguration.

4. Discussion

In this section, our control algorithms described above are compared to those in the related literature. There have been two classes of control strategies to conduct a multi-module robotic system to a predetermined final configuration. One class is to move the modules according to a strict sequence which is planned in advance. For example, the framework presented by Chirikjian et al.(8) belongs to this class. Using such schemes, any physically possible configuration can be formed via an optimal sequence (minimum time or minimum energy). However, the computational complexity of the planning increases with the number of modules. In general, it cannot be computed within a polynomial time.

The other class of control strategies is to embed a uniform rule into all the modules. The rule determines the behavior of each module depending on the local situation around the module. The modules move autonomously, and form the final configuration as a result. This class includes our system and the "fracta" system(7). Using such schemes, computational complexity is independent of the number of modules. However, optimal sequence cannot be expected, and it is not clear to what degree of complex configuration can be constructed.

There are two major differences between our system and the fracta system. First, our algorithm, consisting only CA-based discrete computation, is much simpler than the algorithm of the fracta system, which requires real numbers to estimate the local average value of the fitness functions of modules. Our method will save the limited hardware resources in the modules for computation and communication. Second, our algorithm is deterministic, whereas the algorithm of the fracta system includes random processes. Therefore, our system will reach the final configuration faster than the fracta system, especially in the case of a large number of modules. The advantage of the fracta system may be its versatility and robustness. It can start from any initial configurations, whereas our system is sensitive to the initial configuration. This also means that the fracta system should be more robust against disturbance than our system.

5. Conclusions

We have proposed a new concept of self-organizing collective robots with morphogenesis in a vertical plane. In order to develop such systems, mechanism design issues and control strategies were discussed. For the mechanisms, lightness and simplicity are critical to reconfigure against gravity. Basic feasibility of the proposed mechanisms was confirmed by an experiment using four prototype robots. For the control strategies, three examples demonstrated that some global structures can be controlled by local, minimum interactions between individual robots. In fact, we have tested rather simple cases. For example, overhanging structures were implicitly prohibited by their initial conditions and the rules. However, more complicated behavior would be possible by introducing more states.

Based on the knowledge acquired from this investigation, the second generation of robot system is under development. In the new system, each robot will be equipped with a microprocessor inside the body, and infrared transceivers on the four bonding faces. These devices will enable each robot to communicate with four adjacent robots, and to control its own motion. The new system will prove the compatibility of the mechanism design with the control algorithms, which have been separately discussed in this paper.

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