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Stable and Spontaneous Self-assembly of a Multi-robotic System by Exploiting Physical Interaction between Agents

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Abstract— **One of the most amazing phenomena widely observed in nature is self-assembly; living systems spontaneously form their body structure through the developmental process. While this remarkable phenomenon are not thoroughly understood in biology, the concept of self-assembly becomes undeniably indispensable also in artificial systems as they increase in size and complexity. Based on this consideration, this paper discusses the realization of self-assembly with the use of a multi-robotic system each of which has simple motile function. The main contributions of this paper are twofold: the first concerns a fully decentralized control method derived from the mutual entrainment between coupled nonlinear oscillators; and the second is related to the exploitation of physical interaction between agents stemming from a passive deformation mechanism, which allows an efficient movement of individual agents during the course of self-assembly. Here, form generation by self-assembly is considered as the result of time evolution toward the most dynamically stable state. Owing to this, in principle, the proposed method also satisfies significant ability of self-repair without making any modification to the proposed algorithm. In this paper we validate proposed method by exploiting real physical robotic agents. Experimental results show that stable and spontaneous self-assembly is achieved irrespective of the initial positional relationship between the agents.**

I. INTRODUCTION

Self-assembly is a phenomenon where basic units gather together and form some specific configuration stably and spontaneously. In the natural world, this phenomenon is observed widely among living and non-living things. For example, hydra, a primitive coelenterate, is known to reproduce itself by recreating its original body structure even if it is artificially dissociated into cells. Amphipathic molecules organized from hydrophilic and hydrophobic groups spontaneously form a *micelle* or *vesicle* structure. As an aggregate of approximately 60 trillion cells, the human body is generated by a process where cells from a single fertilized egg continually repeat cell-division and self-assembly processes. Even in artificial constructions, this concept will become essential as the system to be designed increases in size and complexity. In addition, as in the hydra example, self-assembly is a concept strongly associated with *self-repair*. Therefore, discussion toward the realization of self-assembly can be also expected to provide useful information for artificial construction of highly fault tolerant systems.

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Based on this viewpoint, several studies are currently underway in the field of robotics to realize self-assembly using a multi-robotic system consisting of many (normally identical) mechanical agents, which was originally initiated by Fukuda and his colleagues [1]. In contrast to a conventional robotic system on a fixed-morphology basis, a multi-robotic system can reconfigure itself according to the situation encountered by actively altering the relative positional relationship between the agents. What has to be noticed is that, in many of these studies, the behavior of each agent in the self-assembly process is individually determined in a fully algorithmic manner: a control algorithm — or sometimes an external operator — precisely specifies which agents should be connected physically as well as how each agent should be moved. Under this kind of *rigorous* control method, however, the control algorithm required may end up to be extremely complicated and intractable as the system scale increases in size and complexity.

Consider the self-assembly phenomenon observed in the natural world. It should be noted that there is no entity corresponding to an algorithm that fully specifies all events in the self-assembly process behind this phenomenon; the resultant form is *emerged* by exploiting a *physiochemical interaction* between substances as well. For example, *different intercellular adhesiveness* are known to play a significantly important role in the time evolution toward the final form in an individual morphogenesis [2]. Since self-assembly is based on the presumption that the number of system components is extremely large, we strongly believe it is important to adopt an approach that explicitly considers the exploitation of *physical interactions between agents* from the initial stage of investigation.

In light of these facts, this study aims at the development of a multi-robotic system that enables stable and spontaneous self-assembly from the initial to the final configuration by exploiting *emergent phenomena* through the interplay between the control and mechanical systems. In order to achieve this goal, this study has focused on a *mutual entrainment between nonlinear oscillators* and a *passive deformation mechanism*. By using the former as a core control mechanism for the generation of *cohesive force between agents* acting as a central driving force for the self-assembly and the latter as a mechanism that enables an efficient movement of individual agents during the course of self-assembly, we attempt to realize self-assembly in a fully decentralized manner. Note that this study considers form generation by self-assembly as the result of the time evolution toward the most dynamically stable state, *i.e.*, the equilibrium state. Owing to this, in principle, self-repair can be also considered without any additional mechanisms. Here, the behavior of individual agents is not determined only by the control algorithm; exploitation of the physical interaction between agents is also well considered, which allows us to significantly reduce the computational cost required for the connectivity control.

This paper is structured as follows. The following section briefly outlines related studies and sheds light on some issues to think about. Section 3 introduces design strategies for the mechanical and control systems for a multi-robotic system that enables time evolution into a specific final form and shows typical simulation result. Section 4 validates the proposed method with real physical robotic agents. Section 5 discusses quantitative evaluate passive deformation mechanism, followed by the conclusion and further work.

II. PREVIOUS AND RELATED WORKS

This section briefly introduces several prior studies related to self-assembly. Murata *et al.* discussed a method which enables a staged formation toward a goal structure using a modular robot called Fractum [3]. Yoshida *et al.* extended the Fractum to a three-dimensional robot [4]. Using a modular robot called M-TRAN, Kamimura *et al.* realized self-assembly to a serpentine or four-legged robot [5]. In addition, Dorigo *et al.* achieved form generation using a group of mobile robots called Swarm-bots [6]. These studies, however, were based on a fully algorithmic manner: the control algorithm precisely specifies the behavior of an individual robot to realize the goal structure, particularly focusing on efficient procedures. Similar approaches are also found in [7]-[12].

On the other hand, several studies have also been reported on self-assembly achieved through fully exploiting physical interactions between units. These studies, however, discussed self-assembly on the order of micrometers or smaller, and there still remains unclear about whether they can be directly employed for centimeter-ordered or larger applications. Recently, inspired by a seminal study done by Hosokawa *et al.* [13], Bishop *et al.* have constructed a self-assembling robot [14]. In their study, however, since the physical interaction between the robots greatly depends on random collision, efficient time evolution to the final form may be difficult.

III. THE MODEL

A. The Design Strategies

The design strategies for the self-assembling multi-robotic system considered in this study can be summarized as followings:

1) Self-assembly is considered as an emergent phenomenon. More specifically, the form generation by self-assembly is regarded as the result of the time evolution toward the most dynamically stable state, *i.e.*, the equilibrium state.
2) In the self-assembly process, the behaviors of individual agents are not determined simply by a control algorithm. Exploitation of an *physical interaction between agents* should also be well considered.

(a) Mechanical structure of each agent

(b) The entire system (Top view)

Fig. 1. A schematic of the two-dimensional multi-robotic system considered in this study.

In what follows, we will explain how we have designed the control and mechanical systems of the multi-robotic system that can self-assemble, taking the above idea into account.

B. The Mechanical System

As an initial step of the investigation, a two-dimensional multi-robotic system has been considered, consisting of many identical agents, each of which has a mechanical structure like the ones shown in Fig. 1 (a). A schematic of the entire system is also illustrated in the Fig. 1 (b). Each agent has simple motile function derived from omni-directional wheels, by which each agent can move in any direction. Each agent is also equipped with a mechanism which informs the agent whether it is positioned as an *inner* agent or a *surface* agent in the entire system. The circumference of each agent can *passively* deform which allows the agent to efficiently move during the course of self-assembly (explained later). We also assume that local communication with the neighboring agents within a prespecified distance is possible, which will be used to create phase gradient inside the entire system (discussed below).

C. The Control System

Under the above mechanical structure, now we consider a control method that enables the agents to move toward a particular *equilibrium configuration*, *i.e.* a goal shape, stably and efficiently. For simplicity, in the following we first consider a disk-like shape as the equilibrium configuration.

In order to effectively drive all the agent toward the equilibrium configuration, in this study, we consider a control algorithm that generates a *cohesive force* inside the entire system acting like an effect stemming from the *surface tension*. Here, it should be noted that the control algorithm to be designed should be fully decentralized manner and should not depend on the number of the agents. Taking these requirements into account, we have focused on *nonlinear oscillators* since they exhibit an interesting phenomenon called the *mutual entrainment* when they interact each other.

We have implemented a nonlinear oscillator onto each agent of the multi-robotic system. We then create *phase gradient* inside the entire system through the mutual entrainment between the locally-interacting nonlinear oscillators. This is done by a local communication between the locally-interacting agents within a prespecified distance. By exploiting the phase gradient created as a key information for controlling the driving force of each agent, we have successfully generated a cohesive force inside the entire system in a fully decentralized manner. In what follows, we will explain this in more detail.

1) Creating phase gradient through the mutual entrainment: As a model of a nonlinear oscillator, the *van der Pol oscillator* (hereinafter VDP oscillator) has been employed, since this oscillator model has been well-analyzed and widely used for its significant entrainment property. The equation of the VDP oscillator implemented on agent i is given by

$$\alpha_i \ddot{x}_i - \beta_i (1 - x_i^2)\dot{x}_i + x_i = 0, \tag{1}$$

where the parameter α_i specifies the frequency of the oscillation. β_i corresponds to the convergence rate to the limit cycle.

The local communication between the locally-interacting agents is done by the local interaction between the VDP oscillators of these agents, which is expressed as:

$$x_i = x_i^{tmp} + \varepsilon_i \left\{ \frac{1}{N_i(t)} \sum_{j=1}^{N_i(t)} x_j^{tmp} - x_i^{tmp} \right\}, \tag{2}$$

where x_i^{tmp} represents the state right before the local interaction. $N_i(t)$ is the number of agents locally-interacting with agent i at time t, respectively. The parameter ε specifies the strength of this interaction. Note that this local interaction acts like a *diffusion*, through which all the VDP oscillators in the entire system eventually behave in phase.

When the VDP oscillators interact according to equation (2), significant phase distribution can be created effectively by varying the value of α_i in equation (1) for some of the oscillators. In order to create an equiphase surface effective for generating an appropriate cohesive force, we set the value of α_i as:

$$\alpha_i = \begin{cases} 1.3 & \text{if the agent is positioned as} \\ & \text{a } \textit{surface agent} \\ 1.0 & \text{if the agent is positioned as.} \\ & \text{an } \textit{inner agent} \end{cases} \tag{3}$$

Fig. 2. Phase distribution created through the mutual entrainment among the VDP oscillators in a circular arrangement. The color and height of cylinder denote the value of the phase at the corresponding point. Each arrow represents the direction of the gradient vector at the corresponding point. Note that all the arrows point toward the center.

Note that the value of α_i is increased when the agent is positioned as a surface agent in the entire system. As a result, the frequency of the VDP oscillators in the outer agents will be relatively decreased compared to the ones in the inner agents. This allows us to create the phase gradient inside the entire robotic system, which can be effectively exploited to endow the entire system with the cohesive force (explained later). Fig.2 shows the phase distribution created through the mutual entrainment when the agents are arranged circularly. In the figure, arrows — each of which represents the direction of the gradient vector at the corresponding point — are also depicted for clarity. It should be noticed that the direction of each gradient vector points toward the center of the entire system.

2) Generating effective cohesive force: Based on the above arrangements, here we will explain how we have generated effective cohesive force required for the self-assembly in the entire system. Exploiting the phase gradient created from the aforementioned mutual entrainment between the locally-interacting VDP oscillators, each agent is driven by the driving force, which is expressed as:

$$\boldsymbol{F}_i(t) = -k \sum_{j=1}^{N_i} \left\{ \left(\theta_j(t) - \theta_i(t)\right) \boldsymbol{r}_{ij} \right\}, \tag{4}$$

where $\boldsymbol{F}_i(t)$ denotes the driving force to be exerted by the omni-directional driving system of agent i at time t and N_i is the number of agents locally-interacting with agent i at time t. $\boldsymbol{r}_{ij}$ is the normalized direction vector from agent i to agent j, and k is an coefficient. $\theta_i(t)$ denotes the phase of oscillation of the VDP oscillator in agent i at time t, which is obtained by

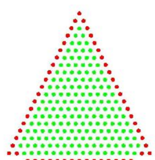
$$\theta_i(t) = \arctan \frac{\dot{x}_i(t)}{x_i(t)}. \tag{5}$$

Due to the algorithm mentioned above, the movement of each agent will become most significant along the phase gradient (see Fig. 2). As a result, all the agents are encouraged to move toward the center of the entire system, through which a cohesive force will be automatically generated.

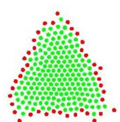
D. Passive deformation mechanism

Based on above mechanism, cohesive force is generated inside the entire system. Due to this, we expect that the shape of the entire system achieves the most stable configuration, *i.e.*, typically, disk-like shape. However, the shape ends up to be hexagonal closest packing structure before the agents achieve most stable configuration during the process of self-assembly. Because of flexibility of this structure, it is impossible that the shape realizes most stable configuration stably and spontaneously. This situation is similar to the phenomena observed in *powder-particle fluid*. To avoid this situation, we implement passive deformation mechanism into each agent. This mechanism enables the entire system break hexagonal closest packing, by which the agents can achieve most stable configuration.

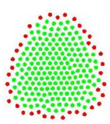
Fig.3 illustrates a typical simulation results. In this figure red dots represent surface agents and green dots represent inner agents. In this simulation the task is to self-assemble the entire system toward a disk-like shape.



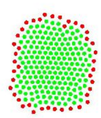
(a) Initial state



(b) Time steps = 3000



(c) Time steps = 6000



(d) Time steps =12000

Fig. 3. Typical result of the self-assembly toward a disk-like shape (see in alphabetical order). Red dots represent surface agents and green dots represent inner agents.

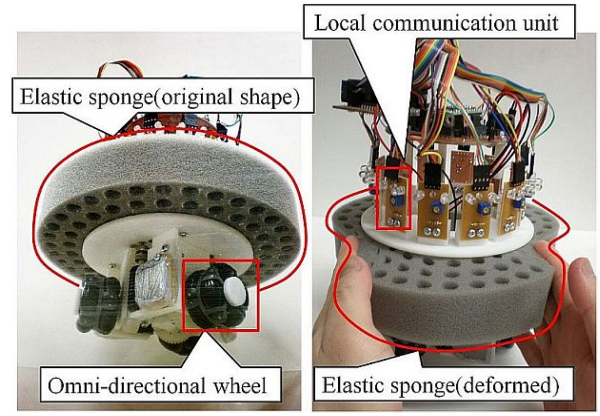


Fig. 4. A photo of the agent. The diameter and the height of the agent are 200[mm] and 250[mm], respectively.

IV. EXPERIMENTS

A. A real physical robotic agents

In order to verify the feasibility of our proposed method, an experiment with a real physical multi-robotic system is significantly important. A robot is represented in Fig. 4. Each agent has three omni-directional wheels, by which each agent can move in any direction holonomically. And the agent has cyrindrical sponge and the circumference of the agent can passively deform according to an external force. The agent is implemented 24 infrared LEDs and 12 photodiodes, by which the each agent can communicate with neighbors. For the ease of hardware realization of the local communication system, we have referred to the method proposed by Kurabayashi and his colleagues [15].

B. Verification of the passive deformation mechanism

As we have already mentioned, one of the significant features of the proposed method is that we have intended to fully exploit the physical interaction between agents occurred in the self-assembly process as well as the *implicit* control. To this end, we have implemented the passive deformation mechanism into each agent, by which we expect an efficient movement of individual agents during the course of self-assembly. In order to verify this physical interaction between agents mechanism, we have conducted experiments with real physical robotic agents.

Fig.5 and Fig.6 show representative experimental results. In these experiments, the task is to self-assemble the entire system toward a disk-like shape. Very interestingly, as the figures indicate, the passive deformation mechanism implemented into each agent enables the efficient movement of individual agents in the entire system, which leads to the stable convergence to the final configuration. The robotic system without the passive deformation mechanism ends up to stuck during the process of self-assembly, which is similar to the phenomena observed in *powder-particle fluid*. This strongly suggests the importance of the interplay between the control and mechanical systems: a certain amount of *computation* should be offloaded from the control system to its mechanical system when one wants to construct this kind of system with large degrees of freedom.

C. Verification of self-repair

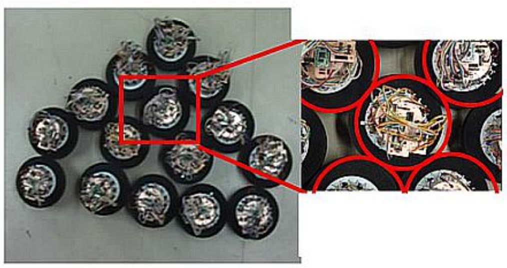
One of the crucial points proposed in this study is that self-assembly is considered as the result of time evolution toward the most dynamically stable state. This will automatically lead to the following conclusion: self-repair can also be realized, in principle, without making any modification to the proposed algorithm. In order to verify this, we have conducted experiments. A typical result is shown in Fig. 7. In this experiment, an external force was applied inward from the left side and broke the shape. As the figures explain, the shape of the cluster finally returns to the original shape, *i.e.*, a disk-like shape.

V. DISCUSSION

In order to quantitatively evaluate the result of the experiment, (*i.e.*, the verification of the passive deformation

(a) Initial state

(b) Transient state

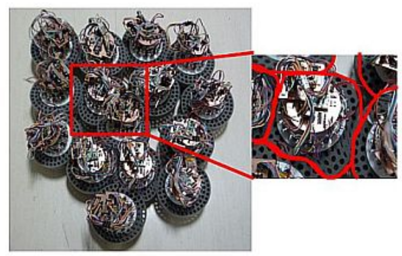


(c) Final state

Fig. 5. Time evolution of the self-assembly without the passive deformation mechanism (see in alphabetical order). Similar to the phenomena observed in powder-particle fluid, the agents end up to stuck during the process of self-assembly. As a result, the final configuration, *i.e.*, disk-like shape cannot be realized and circularity ratio C is 0.39.

(a) Initial state

(b) Transient state



(c) Final state

Fig. 6. Time evolution of the self-assembly with the passive deformation mechanism (see in alphabetical order). The physical interaction between agents stemming from the passive deformation effectively enables the stable convergence toward the final configuration and circularity ratio C is 0.6. This can be seen as a beautiful instantiation of *computational offloading* from the control system to its mechanical system.

mechanism), we measured circularity ratio C, which is expressed as:

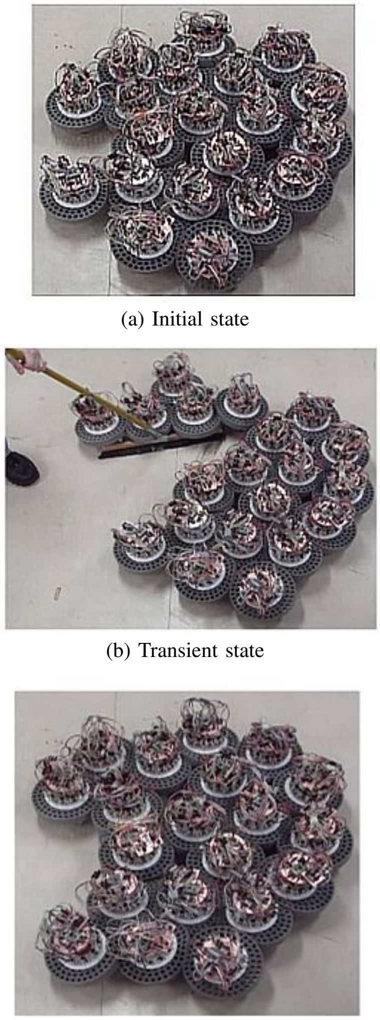
$$C = \frac{4\pi S}{L^2}, \tag{6}$$

where L denotes the perimeter (*i.e.*, the shape of the cluster) and S denotes the area of the entire system. Here, C is normalized from 0 to 1. C increase to 1 as entire system get closer to circle. In Fig.5, C is 0.39. On the other hand, in Fig.6, C is 0.6. Therefore, the entire shape of Fig.6 is more similar to circle than the entire shape of Fig.5. This evaluation result is summalized as follows, passive deformation mechanism, *i.e.*, physical interaction between agents, enables computational offloading from the control system to the mechanical system.

VI. CONCLUSIONS AND FUTURE WORKS

This paper has investigated the realization of self-assembly with the use of a real physical multi-robotic system consisting of many identical mechanical agents, each of which has simple motile function. The main contribution of this study can be summarized as: first, we considered form generation by self-assembly as the result of the time evolution toward the most dynamically stable state, *i.e.*, the equilibrium state; second, the behaviors of individual agents was not determined simply by the control algorithm. The physical interaction between agents stemming from the passive deformation mechanism was also well exploited during the course of self-assembly; third, the self-assembly was done in a fully decentralized manner by using the mutual entrainment between the locally-interacting nonlinear oscillators; fourth and finaly, we showed that self-repair can be also realized without making any modification to the proposed method.

There are many interesting topics for further investigation. One of the crucial topics is to increase the geometrical complexity of the equilibrium configuration. A promising idea would be to introduce a mechanism which enables



(a) Initial state

(b) Transient state

(c) Final state

Fig. 7. Time evolution of the experiment of self-repair (see in alphabetical order). An external force is applied from the left side and break the shape of the cluster. This shows the shape of the cluster finally returns to the original shape, *i.e.*, a disk-like shape.

spontaneous *cell differentiation*. To this end, as the seminal work done by Eggenberger [16] indicates, we envision that incorporating an artificial *gene regulation network* would be highly promising.

VII. ACKNOWLEDGMENTS

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