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Towards exploration of pheromone effect in object pattern formation

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Abstract—This paper discusses an exploration of a role of pheromone in object pattern formation by autonomous transporting agents, such as termites in nature. This paper is motivated by the performance of termites; they build a large size of 3-dimensional nest by putting pheromones to a carrying object. Our previous study has indicated that on the cellular space, a wide variety of structures are eventually formed by distributed autonomous agents with *simple* transporting ability. The cellular automata approach proposed by Stephen Wolfram is intended as an investigation of pattern formation. After introducing a transporting agent using pheromones with evaporation and diffusion, we conducted some simulations. The simulation results indicate that the duration of clustering phase decreases as agent's pheromone sensitivity gets higher; the forming cost gets to efficient by the effect of pheromones that help to collect other agents to a construction place. Moreover, it should be said that we can control the transition process by tuning the degree of an agent's pheromone sensitivity.

1. Introduction

Tiny agents sometimes show us amazing behaviors with a group even if they have physically tiny brains with limited memory or deduction capacity. For example, social insects such as termites build complicated nest towers [1]. In this study, we aim at understanding the principle behind these apparently intellectual behavior of swarms. In particular, we will focus our attention on distributed pattern formation generated by autonomous transporting agents. In order to spot a new light on distributed pattern formation, we propose to analyze it based on a spatial discretization approach. The cellular automata approach was proposed to investigate complex systems (e.g. self-organization) [2] [3].

Our previous study has proposed a model of transporting agents which execute simple action rules like "move/load/unload" assigned for local terrain patterns. Via numerical simulation, it can be verified that a wide variety of structures are finally formed (e.g. clusters, line shapes, labyrinth, etc...) [4].

Here, let us return to the performance of termites again. Termites build huge nests by impregnating pheromones with carrying objects [5]. Pheromones pasted on the block naturally evaporate/diffuse into the air. The natural performance led to our consideration of a fundamental question: why do they use pheromones? This paper tries to provide a flavor of why they utilize pheromone effect in object pattern formation. Simply thinking, it will give a role of attracting other termites, which may connect to build construction of huge nest effectively. Our pervious study [6] has already proposed a pheromone model inspired by the foraging behavior of ants, in which they search a food source and go back to the nest by creating pheromone trails.

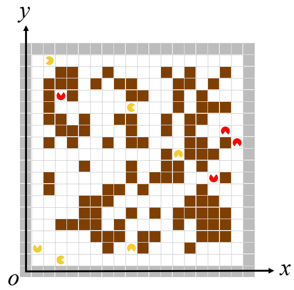


Figure 1: Overview of the horizontal cellular plane

Therefore, in this paper, we build a transporting agent using pheromones which has the ability of evaporation and diffusion. Then, we examine how pheromone effects on object pattern formation; we evaluate the simulation step (*i.e.* energy consumption).

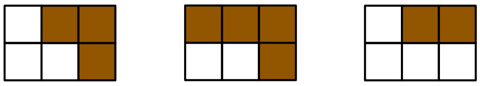
This paper is organized as follows. Section 2 introduces one pattern formation picked up from our previous study. Section 3 builds an agent model using pheromones inspired by foraging behavior of ants, and evaluates the pattern formation with special emphasis on the speed to create a pattern. Conclusions and future works is described in Section 4.

2. Our previous study: Pattern formation in the cellular space

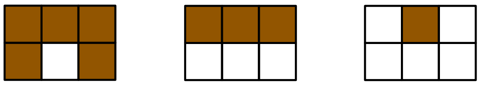
In this section, we briefly introduce our previous result; we pick up a typical pattern formation, such as forming cluster by distributed transporting agents.

(a) Block (b) Robot (empty) (c) Robot (full)

Figure 2: Three objects on the field



(a) Step (b) Half-step1 (c) Half-step2



(d) Concave (e) Flat (f) Convex

Figure 3: Possible patterns of neighboring blocks

2.1. Discretization of the field

In 2-dimensional cellular horizontal plane (Fig. 1), there are 3 types of object: a block (Fig. 2(a)), a robot carrying nothing (Fig. 2(b)) and a robot carrying a block (Fig. 2(c)). In the study, a robot is supposed to carry *only* one block, that is a robot cannot carry more than two objects at the same time.

More than two objects cannot be occupied in single cell. A robot moves autonomously by executing action rules described in the next subsection, but a block is immobile in itself.

2.2. Primitive action rules of a robot

A robot chooses one of four actions in each step as follows:

0:Unload Put down the carrying block and step backward.

1:Load Pick up the block in front of it and step forward.

2:Move Step forward.

3:Turn Rotate 90 degree to right or left randomly.

Unload, load or move action cannot be executed on the particular situations. For example, a robot without a block cannot choose unload, a robot with a block cannot choose load, or a robot cannot move into a non-empty cell. If a robot selects unexecuting action, it selects turn.

2.3. Assignment of action rules for local terrain pattern

A robot is supposed to perceive 5 cells in front of it. Then, the robot decides its action based on the arrangement of blocks, the local terrain patterns. The state of each cell in the area is occupied by a block or an empty, thus the number of combinations of local configurations is counted

(f)	(e)	(d)	(c)	(b)	(a)
Load 1	Unload 0	Unload 0	Load 1	Unload 0	Unload 0

Table 1: Code252: indicates the action rules based on local configurations respectively

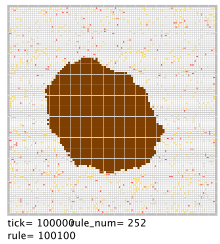


Figure 4: Typical pattern formation based on Code 252

at $2^5 = 32$. By eliminating symmetrical configurations, we can reduce these patterns to 6 patterns (Fig. 3).

Here, let us begin with explanation about how a robot selects its action. A robot selects one from three action rules, 0:unload, 1:load, 2:move, for 6 local terrain patterns (Fig. 3) in each step. All combinations are calculated as $3^6 = 729$ patterns by assigning of 3 action rules for 6 local terrain patterns. We call the combination as the term "Code" by the conversion from ternary to decimal. For example, let us suppose to select the combination of action rules as shown in Table 1. (a)-(f) in Table 1 shows the action rules that a robot selects for each local configuration (Fig. 3). Through carrying out simulations, robots with Code 252 form a cluster pattern (Fig. 4).

3. Analysis of a role of pheromones in object pattern formation

Our previous study mentioned that the simple agents can create a wide variety of patterns [4]. Here, let us return our attention to the performance of termites; they construct enormous nests by pasting pheromones to carrying objects. Such a performance raises an underlying question: what is the role of pheromone in object pattern formation?

Then, in this section, we try to introduce pheromone model referred by previous work [6]; when a robot doing unload, it puts down a block impregnated pheromone. Furthermore, we investigate the influence of pheromones to the speed for cluster formation.

3.1. Introduction of discretized pheromone model

Here, we will illustrate pheromone model and discretize it. The pheromone model has following 2 characteristics (Fig. 5).

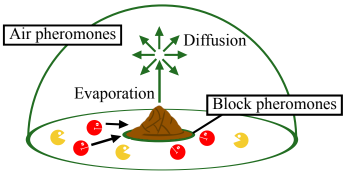


Figure 5: Evaporation and diffusion of pheromones

	Parameter of pheromones	Values
γ_{eva}	Pheromone evaporation coefficient	6.68×10^{-2}
γ_{dif}	Pheromone diffusion coefficient	7.00×10^{-2}
γ_{add}	Amount of pheromones emitted by a robot	4.95×10
B_{thr}	Threshold concentration of block pheromones	1.00×10^{-1}
A_{thr}	Threshold concentration of air pheromones	$0.00 - 3.00 \times 10^{2}$

Table 2: Parameter of pheromones

- Pheromones on a block, hereinafter referred to as "block pheromones", evaporate as time goes on.
- Evaporated pheromones, hereinafter referred to as "air pheromones", diffuse as time goes on.

We use the following Eqs. as the pheromone model with these 2 characteristics [6]:

$$\frac{\partial}{\partial t}B(x,y,t) = -\gamma_{eva}B(x,y,t) + \gamma_{add} \quad (1)$$

$$\frac{\partial}{\partial t}A(x,y,t) = \gamma_{dif}\nabla^2 A(x,y,t) + \gamma_{eva}B(x,y,t) \quad (2)$$

where $B(x,y,t)$, $A(x,y,y)$ is block pheromones, air pheromones at $(x,y) \in \mathbb{R}$ at time $t \in \mathbb{R}^+$. Additionally, γ_{eva} is the evaporation coefficient of block pheromones, γ_{dif} is the diffusion coefficient of air pheromones and γ_{add} is the amount of block pheromones emitted by a robot in doing unload.

We derive the following 2 equations from discretization of pheromone model Eq. 1, 2.

$$B(n_x,n_y,\tau+1) = (1-\gamma_{eva})B(n_x,n_y,\tau) + \gamma_{add} \quad (3)$$

$$A(n_x,n_y,\tau+1) = (1-4\gamma_{dif})A(n_x,n_y,\tau) + A_{in}(n_x,n_y,\tau) + \gamma_{eva}B(x,y,\tau) \quad (4)$$

where, $(n_x,n_y) \in \mathbb{Z}$ are coordinates in the cellular world. In addition, $A_{in}(n_x,n_y,\tau)$ denotes the amount of pheromones flowing into (n_x,n_y) from 4 neighbor cells at time step $\tau \in \mathbb{Z}^+$. $A_{in}(n_x,n_y,\tau)$ is defined by

$$A_{in}(n_x,n_y,\tau) = \gamma_{dif}\{A(n_x-1,n_y,\tau) + A(n_x+1,n_y,\tau) + A(n_x,n_y-1,\tau) + A(n_x,n_y+1,\tau)\} \quad (5)$$

Also, we define the minimum amount of block pheromones and air pheromones which robots can perceive as B_{thr} and A_{thr}, respectively. The parameters mentioned above is shown in Table 2.

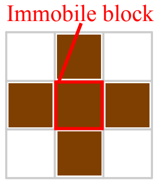


Figure 6: Immobile block

A robot carrying a block tracks air pheromones and moves to the cell determined by the following equation.

$$\begin{cases} \text{left cell} & (0 \le \theta \le \frac{\pi}{3}) \\ \text{front cell} & (\frac{\pi}{3} \le \theta \le \frac{2\pi}{3}) \\ \text{right cell} & (\frac{2\pi}{3} \le \theta \le \pi) \end{cases} \quad (6)$$

where, θ is defined by the following equation.

$$\theta = \tan^{-1}\frac{\mathbf{a}\cdot\mathbf{c}}{\mathbf{a}\cdot\mathbf{d}} \quad (7)$$

In addition, **a**, **c**, **d** are as follows.

$$\mathbf{a} = \begin{bmatrix} A_l(n_x,n_y,\tau) \\ A_f(n_x,n_y,\tau) \\ A_r(n_x,n_y,\tau) \end{bmatrix}, \mathbf{c} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \mathbf{d} = \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} \quad (8)$$

$A_l(n_x,n_y,\tau)$, $A_f(n_x,n_y,\tau)$, $A_r(n_x,n_y,\tau)$ denotes the amount of air pheromones on the left, front, right cell of a robot at (n_x,n_y) at time step τ.

3.2. Evaluation of pheromone effects on object pattern formation

Let us begin with discussing the effect of pheromones by evaluating the speed of cluster pattern formation. First, we describe the initial configuration of the field. The size of the field is $100 \times 100 = 10,000$ cells; 1000 to 3500 blocks are randomly distributed within the area surrounded by $(10,10),(90,10),(90,90),(10,90)$. In addition, 1200 robots are placed in empty cells.

Robots execute their actions based on Code 252; the action rule is identified as forming a cluster. By changing the threshold of pheromone perception A_{thr}, that is air pheromone sensitivity, from $A_{thr} = 0$ to $A_{thr} = 300$, we repeat simulations 10 times for each value of A_{thr}.

In order to evaluate the speed to form a cluster, we define "the number of immobile blocks" as a performance index. If a block is surrounded by 4 blocks as shown in Fig. 6, we call it as "immobile block". Thus, the number of immobile blocks increases as the cluster grows.

Fig. 7 shows time series of the number of immobile blocks in the case of 2,000 blocks. As the threshold of air pheromone perception A_{thr} gets lower values; pheromone sensitivity gets higher, the inclination is much steeper, that is, the speed of clustering gets faster by introduction of pheromones. Here, we paid scant attention on the difference among the convergence values. The difference would

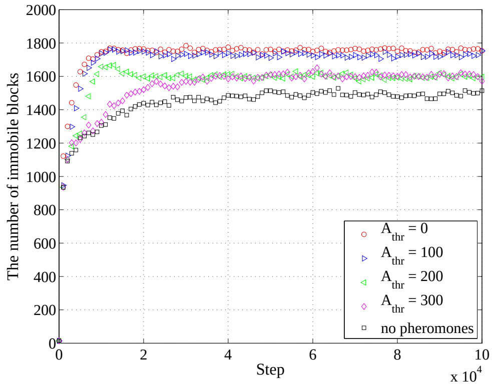


Figure 7: Changes of the number of immobile blocks in the case of $2,000$ blocks

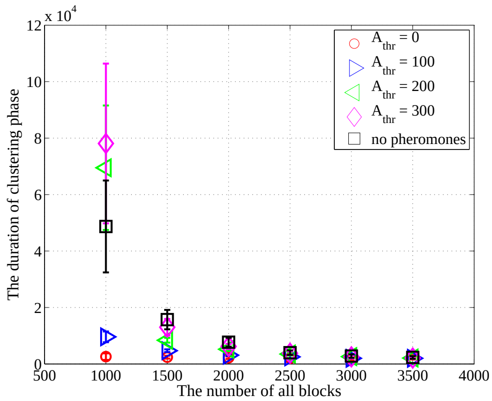


Figure 8: The relationship between the number of all blocks and the duration of clustering phase for different pheromone sensitivity

be explained by the sum of robots carrying an object in the convergence state.

Fig. 8 shows the relationship between the number of all blocks and the duration of clustering phase. Then, we introduce a sort of performance index "clustering phase" which denote the duration from the simulation start until the density of immobile blocks becomes 0.632 times as large as the sum of blocks. This evaluation idea is referred from the time constant in control theory. The whole tendency in Fig. 8 indicates that the lower the pheromone sensitivity becomes, the duration of clustering phase increases. On the other hand, we found out different tendency only in the case of 1,000 blocks. Though the analytical results was very interesting, we omit the detailed discussion for lack of space. It seems that average and variance of the duration of clustering phase greatly decreases as the threshold of pheromone perception becomes lower values. In other word, we can say that the pheromone would enhance the stability of cluster formation in terms of reducing the variance.

Moreover, as the density of blocks increases, it seems that the duration of clustering phase becomes not so different comparing with that in the case of 1,000 or 1,500 blocks. It would be for the reason that the event of encountering a block is easily occurred due to high density of blocks even if a robot moves in random direction. Thus, the effect of pheromones would be remarkably seen in a *sparse* space.

In summery, our analytical results indicate that we can control not only the equilibrium state, *i.e.* final pattern shape, but also the transition process by adjusting the pheromone sensitivity of a robot.

4. Conclusions with future works

In this paper, we discussed a role of pheromones for object pattern formation by distributed transporting agents. After designing an agent model using pheromones, we conducted numerical simulations and evaluated the duration of clustering phase by changing some parameters (the number of blocks and the sensitivity of pheromones). The simulation results indicate that introduction of pheromone enhances the stability of cluster formation in terms of reducing the variance of the duration of cluster phase. Moreover, it can be said that the transition process of clustering is controlled by adjusting pheromone sensitivity. In future, we aim at analyzing the influence of pheromones for another pattern formation (pattern generation by another Code).

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