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Analysis of distributed transportation with autonomous mobile agents inspired by foraging behavior of ants

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Abstract—In this paper, we discuss some phenomena of distributed object transportation inspired by foraging behavior of ants, in the light of space-discretization (or cellular automata) approach. We define fundamental event rules in a cellular world, and introduce two types of ant agents: one is an oriented ant, which perceives pheromones, the other is a random ant, which does not perceive pheromones. Then, we take a closer look at the number of pheromone trails formed by homogeneous and heterogeneous agents. Moreover, we propose a distributed control method for the number of formed pheromone trails, and examine the effectiveness of the proposed method by several simulations.

1. Introduction

In nature, not only human beings whose brain consists of more than a hundred billion neurons, but also insects whose brain consists of no more than one million neurons, move adaptively even if they are placed in unknown environment [1]. Social insects like ants or bees, which decide their action interacting locally with their neighbors but show us supple and adaptive global behaviors [2]. For example, in foraging behavior of ants one ant that found a food source, lays pheromones from the food source to their nest, attracting other ants to follow this pheromones [3] [4]. Thus, the analyses of these phenomena that stable pheromone trails were formed by ants' local interaction with their neighbors without any concentrated controller give us many effective ideas.

Meanwhile, cellular automata approach, which was first proposed by Stephen Wolfram has been considered to be an excellent way to analyze a great many natural phenomena [5]. It is now very much an established scientific discipline with applications found in a great many areas of science [6].

In this research, we suppose a tessellation of the 2-dimensional Euclidean space with *unit regular hexagons*, as shown in Figure 1 [7] [8]. We define fundamental event rules in this cellular world, and construct a discrete version of object transportation model inspired by foraging behavior of ants. We then examine the object transportation by distributed agents using pheromone trails. From the analyses of object transportation by heterogeneous agents, we propose a distributed control for the number of pheromone trails from their nest to food sources.

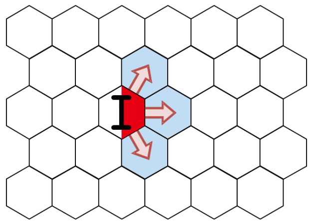


Figure 1: Ant model in the Hexagonal Grid Space: Decision of its direction to follow pheromones

2. Discrete model of object transportation inspired by foraging behavior of ants

In this section, we construct a discrete version of object transportation inspired by foraging behavior of ants.

2.1. Search mode and Transport mode

Every ant has two modes: *Search mode* and *Transport mode*. Search mode is a state from leaving their nest to catching up a food in the food source, and transport mode is a state from picking up a food to dropping it at their nest (see Figure 2).

Mode 1 (*Search mode*)

- *Ants lay homing pheromones in every step.*
- *Ants perceive recruitment pheromones.*
- *Ants change to transport mode after picking up one food in the food source.*

Mode 2 (*Transport mode*)

- *Ants lay recruitment pheromones in every step.*
- *Ants perceive homing pheromones.*
- *Ants change to search mode after transporting the food to their nest.*

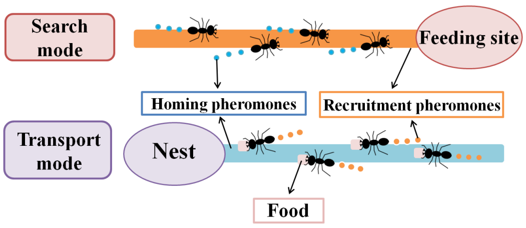


Figure 2: Search mode and Transport mode : Foraging behavior of ants.

Every food is transported by one ant, and foods in the food source is never exhausted. Ants transport a food from a food source to their nest through laying different pheromones in search or transport mode.

2.2. Discrete version of pheromones

As mentioned in the last subsection, ants lay two types of pheromones. Both pheromones are volatile. So they evaporate from the field, and diffuse into the space. Then, we call trails of pheromones laid on the field as *pheromones on the ground* and pheromones diffused into the space as *pheromones in the air*. We define the concentration of pheromones on the ground $T_j(x, y, t)$ and the concentration of pheromones in the air $P_j(x, y, t)$, where $(x, y) \in \mathbb{Z}^2$ denotes the position of pheromones in the cellular world and $t \in \mathbb{Z}^+$ denotes time step. And, $j = \{1, 2\}$ are indices of two types of pheromones, $j = 1$ denotes homing pheromones and $j = 2$ denotes recruitment pheromones, respectively. Evaporation and diffusion phenomena of pheromones are determined by the following equations:

$$T_j(x, y, t+1) = (1 - \gamma_{eva_j})T_j(x, y, t) + \gamma_{add_j}N_j(x, y, t) \quad (1)$$

$$P_j(x, y, t+1) = (1 - 7\gamma_{dif_j})P_j(x, y, t) + P_{IN_j}(x, y, t) + \gamma_{eva_j}T_j(x, y, t) \quad (2)$$

where γ_{eva_j} denotes an evaporation coefficient of pheromones j, γ_{dif_j} denotes a diffusion coefficient of pheromones j, and γ_{add_j} denotes the amount of pheromones j laid by one ant in every step. $N_j(x, y, t)$ denotes the total number of ants in mode j on cell (x, y) at t, and $P_{IN_j}(x, y, t)$ denotes the concentration of pheromones j flowed in the cell (x, y) from six neighbor cells.

2.3. Ant model in discrete world

In this paper, an *ant* occupies a cell (Figure 1), and has its own state in $\mathbb{SE}(2) = \mathbb{Z}^2 \times \mathbb{Z}_6$. Every ant perceives both pheromones on the ground and pheromones in the air in the front three cells (blue cells in Figure 1). Moreover, ants perceive that their nest exists in the moving direction.

Action type 1 (Random walk)
When ants do not perceive both pheromones on the ground and pheromones in the air in the front three cells, ants moves randomly to the front three cells.

Action type 2 (Follow pheromones in the air)
When ants do not perceive pheromones on the ground in the front three cells, but ants perceive pheromones in the air, ants move stochastically to the cell whose concentration of pheromones in the air is strong.

Action type 3 (Follow pheromones on the ground)
When ants perceive pheromones on the ground in the front cell, ants move to the front cell. When ants perceive pheromones on the ground in the right or left front cell, move stochastically to the cell whose concentration of pheromones on the ground is strong.

Action type 4 (U-turn)
In transport mode, when ants perceive that their nest does not exist in the front direction, ants change its posture to an inverse direction.

2.4. Definition of action rule

In this paper, we propose two types of ant agents (*random ant*, and *oriented ant*) as follows.

Rule 1 (Random Ant)
Ants follow only action type 1; i.e.; move randomly to a cell without perceiving pheromones.

- *Search mode: Action type* 1
- *Transport mode: Action type* 1

Rule 2 (Oriented Ant)
Ants follow all of the action rules defined in the last subsection, and decide their action as follows:

- *Search mode: Action type* $3 \to 2 \to 1$
- *Transport mode: Action type* $4 \to 3 \to 2 \to 1$

3. Analysis of object transportation

In this section, we analyze the object transportation by proposed agents. Suppose the field of 107×107 cells; nest is set to center of the field (orange area in Figure 3); six food sources also set to the field (blue areas in Figure 3). We then analyze the object transportation focusing on some evaluation indices: *the number of formed pheromone trails*, and *the ratio of object transportation* (the number of transported objects per step).

3.1. Object transportation by homogeneous agents

Let us begin to discuss the object transportation by homogeneous agents (only oriented ants). Figure 3 shows the snapshots of the object transportation by 600 oriented ants. Pheromone trails are gradually formed by oriented ants, and most of ants follow two stable pheromone trails by about 20000 steps. Figure 4(a) shows the histogram of the number of formed pheromone trails repeating simulations 50 times. It seems that there has a strong tendency to form two pheromone trails from their nest to food sources.

Figure 4(b), (c), and (d) show the histograms of formed pheromone trails when we changed the number of oriented ants 1500, 3000, 9000. We verify that the number of formed pheromone trails increases as the density of oriented ants increases. Especially, there has a strong tendency to form all pheromone trails from their nest to six food sources, in case of 9000 oriented ants.

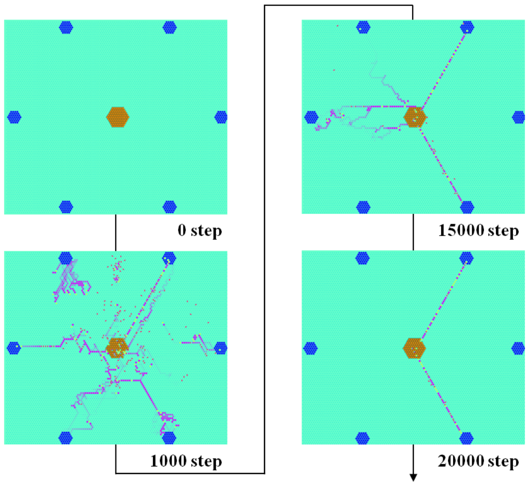
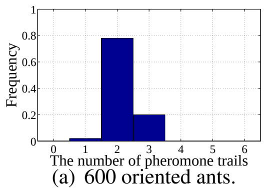
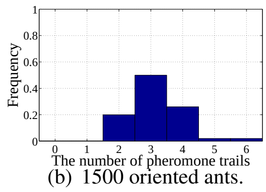


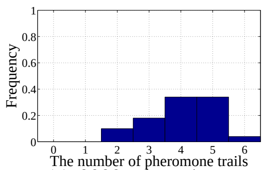
Figure 3: Formation of stable pheromone trails (purple lines) by 600 oriented ants.



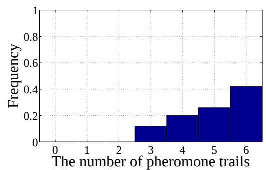
(a) 600 oriented ants.



(b) 1500 oriented ants.



(c) 3000 oriented ants.

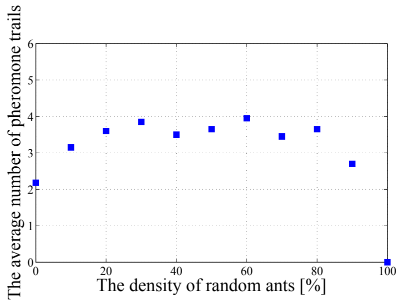


(d) 9000 oriented ants.

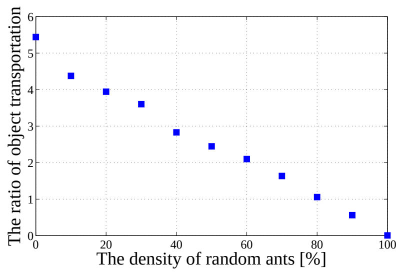
Figure 4: The relation between the number of pheromone trails and the density of oriented ants.

3.2. Object transportation by heterogeneous agents

Let us turn to discuss the object transportation by heterogeneous agents (oriented ants and random ants). The sum of ants is fixed to 600. Then, several simulations were carried out by changing the density of the oriented ants and random ants. Figure 5(a) shows the average number of formed pheromone trails at the different density of random ants. Fig. 5(a) indicates that the stable pheromone trails are not formed by only random ants, and also indicates a small number of random ants help to form larger number of pheromone trails than by only oriented ants. Figure. 5(b) shows the average ratio of object transportation at the different density of random ants. It seems that the ratio of object transportation monotonously decreases as the number of random ants increases.



(a) The relation between the average number of pheromone trails and the density of random ants.



(b) The relation between the ratio of object transportation and the density of random ants.

Figure 5: Different density of heterogeneous agents.

4. Distributed control for the number of pheromone trails

Pheromones are thickened as the number of ants following the pheromone trail increases. This leads the concentration of pheromones perceived by each ant becomes stronger as the pheromones get richer. Thus, the number of ants following the pheromone trail; of course it's a global information; will be estimated from each ant's local information ; i.e.; the concentration of perceived pheromones. From the above considerations, we propose a distributed control for the number of pheromone trails by estimating the number of ants following the pheromone trails. Every ant changes its action rule from oriented rule to random rule, or changes to the contrary based on concentration of perceived pheromones [1].

Every ant stores a memory of L steps, that records the concentration of perceived pheromones in the air. Based on this memory, every ant changes its action rule from the oriented rule to the random rule when the concentration of pheromones becomes over pre-determined thresh-

[1] The rule of the oriented ant is defined as oriented rule, and the rule of the random ant is defined as random rule.

old, and changes to the contrary when the concentration of pheromones becomes under another pre-determined threshold.

Then, we determine the threshold from the oriented rule to the random rule, and vice versa.

- C_1: threshold of the concentration of pheromones in the air from oriented rule to random rule.
- C_2: threshold of the concentration of pheromones in the air from random rule to oriented rule.

Now, we set threshold parameters to $C_1 = 500$, and $C_2 = 350$. The memory length is set to $L = 500$ step. The maximum amount of pheromones that every ant lays in one step is set to 100. Figure. 6 shows one of the simulation results. We verify that ants gradually form several pheromone trails, and six pheromone trails are finally formed. Figure 7 shows the histogram of the number of formed pheromone trails for 50 times of simulations. It seems that there has a strong tendency to form six pheromone trails, and to form five pheromone trails at least. Moreover, the average of the ratio of object transportation is calculated as 5.67 that is nearly equivalent to that of only oriented ants (see Figure 5(b)).

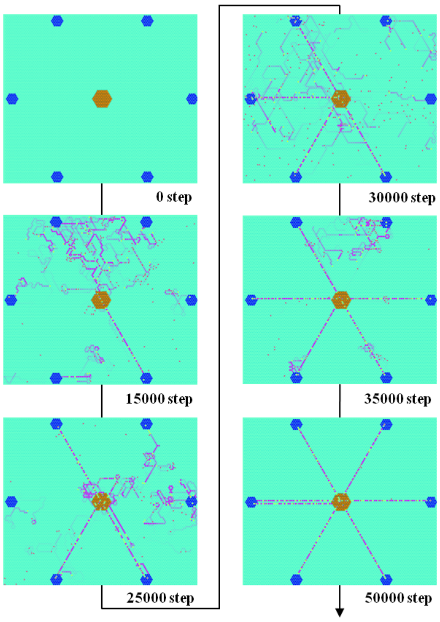


Figure 6: Formation of six pheromone trails (purple lines) by 600 distributed autonomous agents.

5. Conclusions

In this paper, we propose a discrete version of object transportation by distributed autonomous agents inspired by ant's foraging behavior using pheromones. Then, we proposed a distributed control method for the number of formed pheromone trails based on local information (concentration of perceived pheromones). We examined effectiveness of the proposed method by several simulations.

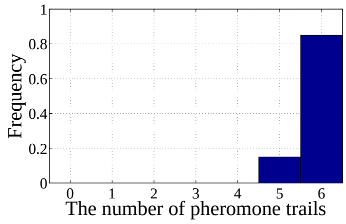


Figure 7: The histogram of the number of pheromone trails formed by 600 distributed autonomous agents.

Acknowledgments

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