化学走性によるトレイルの形成とその機能

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Abstract

Inspired by the foraging behavior of ants, a simple model for the adaptive
trail formation is proposed[1]. In the simulation, several types of trails are seen
to be made up depending on the spatial and temporal schedule of feeding to
realize the the efficient foraging according to each regime.

1 Introduction

So far, various studies have been made on the collective behavior of social insects
[2, 3, 4, 5, 6, 7, 8, 9, 10]. Specially, the trail formation of ants [2, 3, 4, 5, 6, 7, 8, 9, 10]
have called a wide interest as one of the remarkably synergetic behavior fulfilled by
presumably innocent individuals [11, 12]. Still, many points are left unconfirmed
on the trail formation process, like the detailed ingredient of almost all types of
chemicals(pheromone) [2, 3] secreted by individual ants and their roles in each socio-
biological regime [2, 3, 4, 5, 6, 7].

In spite of such inadequate understanding of the real counterpart, various mod-
els on ants [7, 8, 9] have been proposed to imitate their behaviors using heuristic
approaches. Thence, possible scenarios for the formation process of trails and the
branching process of them have been introduced [7, 8, 9]. However, such approaches
have serious disadvantage that each of them is not exclusively reliable as reflecting
the reality. Yet, if we focus our attention on investigating the general feature of the
trail formation beyond that of individual species, such approaches partially based on
unconfirmed assumptions have a certain meaning. From such a point of view, setting
a simple set of rules several parts of which are following previous studies [7, 8, 9],
we investigate the flexible foraging by ants. Particularly, we focus on the relation
between the geometry of trails and foraging efficiency under temporally and spatially
unsteady feeding.

2 Model

The Model consists of i)a triangular 2D lattice with periodic boundary condition
on which all the dynamics proceeds. ii)movable agents (we call them 'ants')each of

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possible sites in the next step
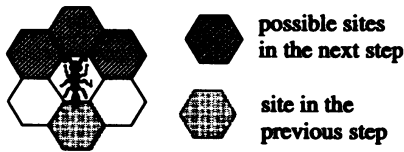
site in the previous step

Fig.1

Figure 1: Each ant is, at each time step, facing one of the six nearest sites. This facing direction corresponds to the moving direction in the previous time step. The possible moving directions in each time step are: the forward (=facing) direction and its neighboring (right and left) directions. To choose one of them, a stochastic rule with the weight, $P_\alpha = exp(-\Delta^\alpha/T)/Z$ is adopted where Z is the normalization factor. Here α indicates forward, right, or left direction relative to the facing direction, and $\Delta^\alpha \equiv \rho_\beta^\alpha - \rho_\beta(\mathbf{x}, t)$ is the gradients of pheromone density to the candidate directions where β is the index to indicate the recruit phermone(for mode-II ants) or the foot pheromone(for mode-III ants). Note the above weight is not applicable for ants in mode-I which is making random walk independnt of pheromone field.

which is, at each time step, located at one site and facing in the direction of one of six nearest sites(Fig1). iii)the nest situated at one site in the lattice(Fig2), and iv)foods located at two corners of an equilateral triangular the 3rd corner of which is the nest site(Fig2). The amount of foods varies with time, i.e., decreases as taken away by ants or increases by the additional supply at every constant time. On each site $\mathbf{x}$ at time time step n, two kinds of field variables, $\rho_{rec}(\mathbf{x}, n)$:the amount of recruit pheromone and $\rho_{foot}(\mathbf{x}, n)$:that of foot pheromone [2, 3], are allocated. Both of these pheromones are chemicals emitted by individual ants according to their temporal modes which consist of: i)the inactivated mode(mode-I), ii)the activated mode without food (mode-II) and iii) the activated mode with food (mode-III).

More concrete descriptions are the followings:

[mode-I]After leaving the nest until an ant reaches on a site with $\rho_{rec}(\mathbf{x}, n) > \rho_{rec-c}$, he keep within the mode-I and walk randomly while emitting a certain amount of foot pheromone at corresponding sites.

[mode-II]An ant is excited into the mode-II on reaching the site with $\rho_{rec}(\mathbf{x}, n) > \rho_{rec-c}$, thereafter he walks perceiving the local gradient of recruit pheromone density(in fig.1) while keeping to emit the foot pheromone at the corresponding site. In this mode, if he fails to keep himself along the sites$\rho_{rec}(\mathbf{x}, n) > \rho_{rec-c}$ his mode turns back to the previous mode-I.

[mode-III]On arriving at the food, regardless of his previous mode, he changes into the mode III in which mode, perceiving the local gradient of foot pheromone he walks back to the nest. In this mode the recruit pheromone are kept to be emitted at each site of the walk.

In addition, pheromone evaporates in the air with time, also diffuses to the nearest sites. Namely,if without additional emission by ants, the pheromone density at site $\mathbf{x}$ decays as

$$\rho_\beta(\mathbf{x}, n + 1) - \rho_\beta(\mathbf{x}, n) = -A\rho_\beta(\mathbf{x}, n) + D(<< \rho_\beta(\mathbf{x}, n) >> -\rho_\beta(\mathbf{x}, n)) \quad (1)$$

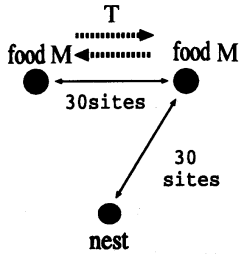where $<<>>$ means the average over the nearest sites of $\mathbf{x}$. A and D are, respectively,

Fig.2

Figure 2: The method of feeding. Feeding sites are located at two corners of an equilateral triangular the 3rd corner of which is the nest site. The amount M of foods are supplied, by turn, from one of these sites to the other at every feeding interval T. After each feeding event, they decreases as taken away by ants.

the evaporation rate and diffusion constant, and β is the index to indicate the recruit pheromone(for mode-II ants) or the foot pheromone(for mode-III ants). Further details of the rules are explained in fig.1.

3   Simulations

Under these rules, we investigate the, seemingly, synergetic foraging behavior of ants under temporally and spatially varying feeding. All the simulations are performed on a 150×150 triangular lattice with periodic boundary condition. At the initial time step 500 ants are located at the nest, and no pheromone are distributed in the field, thence, all ants are simultaneously released from the nest. Note the unit time in our simulation corresponds to one Monte Calro step within which totally 500 randomly chosen ants will sequentially take one step. A certain amount M of foods are supplied, by turn, from one site to the other site of food at regular intervals T. (hereafter we call T 'the interval of food supply'). The amount of supplied foods at these sites of foods decrease as ants bring them away before the next supply.

4   Results

Under a proper combination of fixed variables *on ants* (i.e.,total number of ants, evaporation rates and diffusion constants of pheromones, the location of the nest, and, energy supply at the sites of foods and nest, the critical energy to continue the foraging behavior), with a finite variation range of control parameters $\{M, T\}$ *on feeding*, formation processes of trails are seen along which ants make the much more efficient foraging than the case without them. In such regime we see:i)the geometries of trails and ii)the accompanying foraging efficiency.

Now, before showing the several characteristic geometries of trails and the conditions for the appearance of each of them, we introduce (or reconfirm) three time scales which are relevant for the trail formation: i)T:interval of food supply, ii)T':remaining time of food at each site of food after each event of supply. This is, in term of a control parameter, roughly proportional to M, that is, $T' \simeq aM$ where a is constant depending on ants. Note T' itself is not a controllable variable in the simulation because
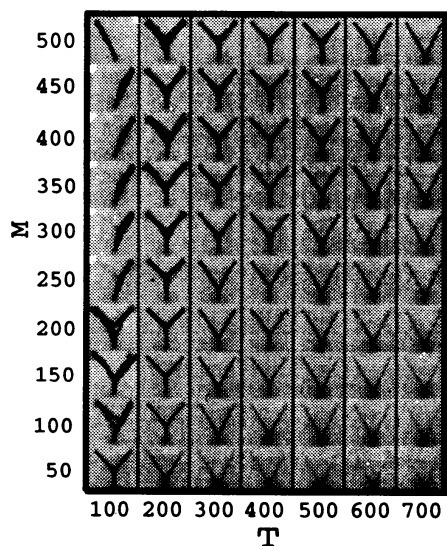
Figure 3: The relation between emergent trail patterns and the combinations of feeding schedule parameters, $\{M,T\}$. Here darkness in each figure means ants density averaged over sufficient longer time than T, the interval between successive feedings. The trail geometries are, while fluctuating (or switching) with time, roughly categorized into three types after averaged over sufficiently longer period than T: i)V-shaped trail, ii)Y-shaped trail, and iii)Straight trail.

Fig.3

of the Y-shaped trail gradually approaches to the nest and finally V-shaped (in time average) trail is realized.

To investigate the relation between the efficiency of the foraging and the trail geometry, the total amount F_{eff} of foods carried by ants into the nest per unit time is measured under various M with T fixed. Fig.4 is the case for $T = 100$. Here, monotonically increasing relation between M and F_{eff} is seen until F_{eff} reaches the saturation value at which most ants is involving in the foraging along the straight trail to one site of food. In the $M - F_{eff}$ relation there seems four characteristic zones indicated by symbols A, B, C and D in fig.4. Zone D is the saturation phase mentioned above. In zones A and C are seen the almost linear $M - F_{eff}$ relations whereas the inclination within A is approximately twice as that within C. These inclinations correspond, respectively, to the foraging tactics with the Y-shaped trail and that with the straight trail, while a crossover tactics appears at the zone B where the trail shape is varying from the Y-shaped trail tactics to the straight trail tactics depending on time. In such a way the change of trail geometry is accompanied with that of foraging efficiency. Especially, across the zone B ants are forced to switch their tactics from one to the other. At the zone A, the 'total transport capacity' of ants exceeds the total supply of foods, thus trails will extend to both sites of foods to take all of them. On the contrary, at the zone D the 'total transport capacity' of ants can not afford to cover both sites of foods, in other words, foods at each site are more than enough for all ants. Also in the zone C, ants are insisting to only one site of food as long as the food does not run out from one site, and, in the zone B where the food of each site becomes insufficient to be maintained steadily, ants come to explore the other sites and Y-shaped tactics appears though irregularly varying into and back from the straight tactics. In the present stage it is not simply concluded that the crossover zone C in our simulation falls on the most efficiently range for the switching from Y-shaped trail to the straight trail. However it is remarkable that through the above switching of trail geometry ants will flexibly change tactics from effective one for inadequate environment(with Y-shaped trails) to that for abundant environment(with straight trails).
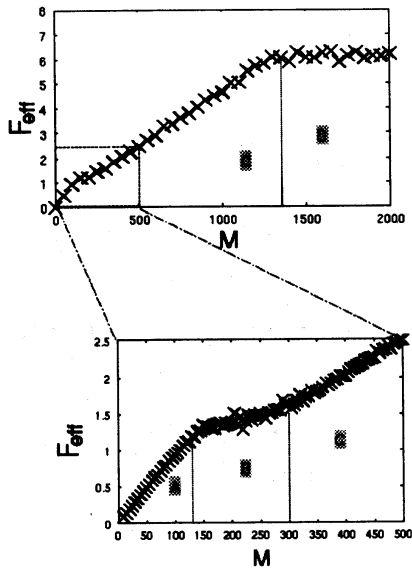
Figure 4: The simbols × show the the relation between the amount of food supply M at each feeding and F_{eff} total amount of foods carried by ants into the nest per unit time. The figure at the bottom is the inset of the above. There are four charctersitic zones A,B,C and D along the $F_{eff} - M$ relation. Each zone is accompanied by each foraging tactics: at the zone A is realized the Y-shaped trail, zones C and D corresponding to the straight trail, and within the zone B the Y-shaped trail and straight trail to each characterstic geometry of trail Y-shaped trail, shown in fig.3. It means ants flexibly make trail patterns according to the regime of feeding to realize efficient foraging.

The similar is the transition from the V-shaped trail to the Y-shaped trail under the variation of T with fixed value of M/T. This transition also is accompanied by the switching of the foraging efficiency, and connects two extreme cases, i)the case for $T >> \tau$ where V-shaped trails is formed as the superposition of the temporally optimized two straight trails. ii)the case for $T < \tau$ where Y-shaped trail is recognized. The details of these cases are left to be reported.

5 Discussion

Still many problems remain to be solved; Firstly, the more precise relation between trail geometries and their foraging efficiency should be investigated which includes the detailed discussion on the location of crossover zone B. Also a wider class of studies varying other parameters than the present case. Secondly the comparison of 'our' ants to real ants is required though several tough problems should be overcome, like the specification of pheromones relevant to the trail formation. However, in this stage, it would have a certain meaning to discuss possible mechanism how the adaptive tactics emerges among the innocent agents according to dynamically changing environment.

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