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Friction based social force model for social foraging of sheep flock

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ABSTRACT

Social foraging of large herbivores shows collective behaviors of movement and grazing. Conspecific effects and interactions between individual and food distribution are known as important factors to influence foraging behaviors of sheep. Many rules of movement have been designed largely depending on conspecific effects. However, few simulation methods consider individual interactions with food distribution. In this paper, we first introduce instinct of feeding to represent individual interaction with currently located patch and then propose a novel friction based social force model to simulate different behaviors in social foraging. Friction force quantifies individual instinct of feeding on currently located patch since conspecific effects and attractions of food in other patches are external forces causing positional adjustment. In our model, agent decides to move if external forces are larger than current friction force and the destination patch can provide enough friction force to resist external forces. This result shows variable effects of instinct of feeding on social foraging and exhibits typical tortuous migration paths and departure-following collective movement of sheep flock. Our model emphasizes the importance of individual interactions with food distribution and may provide new insights into the mechanism governing internal decision process.

1. Introduction

During social foraging, large mammalian herbivores show collective movements, dynamic spatial patterns and grazing behaviors. Conspecific effects represent the actions and interactions of individuals which are essential factors inducing collective behaviors (Couzin and Krause, 2003). Many real field data have reported complex behaviors during social foraging caused by the interactions between animals and food distribution (Adler et al., 2001; de Knegt et al., 2007; Dumont and Hill, 2004). For example, movement of bighorn sheep always involves feeding behaviors which cause low migration speeds, winding trails and short movement distances (Woolf et al., 1970). Furthermore, de Knegt et al. (2007) found that goats (*Capra hircus*) could modulate speeds and tortuosity of movement paths according to different patch densities. Different from these wild herbivores, sheep (*Ovis aries*) keeps most of time stationary to feed in grazing case (Pillot et al., 2010). Meanwhile, a motivational conflict between conspecific effects and attraction of food appears: sheep may feed on less-preferred patches (Dumont and Boissy, 2000; Sibbald and Hooper, 2004) in order to stay close to other flock members when food is distributed unequally in discrete patches, but some "bold" sheep may move to new patches ignoring other flock members (Michelena et al., 2009). The motivational conflict indicates the largely unknown mechanism governing individual decision process which is a central issue to the study of collective behaviors (Conradt and List, 2009). Simulation model is a powerful method of visualizing the dynamic real world phenomena and helps to reveal the internal mechanisms if simulation results accord with real field data (Baumont et al., 2004; Parsons et al., 1994; Vicsek and Zafeiris, 2012). However, many related works such as consensus decision model and self-propelled model nearly overlook individual interactions with food distribution.

In consensus decision model, individual decision is made collectively with other flock members to reach a consensus about certain behavior (Conradt and Roper, 2005). Conspecific effects are the main factors in decision processes (Dyer et al., 2009b; Kendal et al., 2004). Many works have suggested that animals process stimulus-response functions and perform certain behaviors based on a voting procedure (Sueur et al., 2009) or a quorum of group members (Pratt et al., 2002; Ward et al., 2008). Pillot et al. (2010, 2011) observed and analyzed the departure-following behaviors of sheep: collective movement of certain direction was elicited by an incidental motion of individual. It has been suggested that individual decision to move depends on the already-departed members and non-departed members, as sheep moves one by one instead of simultaneously running if the departure of one sheep successfully triggers the collective movement (Pillot et al., 2011).

Self-propelled model is a widely adopted simulation method to quantitatively interpret the macroscopic states of collective movements (Vicsek et al., 1995). Vortex, finger-like structure and parallel marching are well-known orientational patterns of fish

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school, bird flock and migrating locust (Sumpter, 2006; Vicsek and Zafeiris, 2012). In these groups, individual moves continuously or adjusts position frequently. Therefore, self-propelled models always assume individual has an inherent velocity and propose functions for speed or direction adjustment depending on conspecific effects (Albano, 1996; Aldana et al., 2007; Ginelli and Chaté, 2010; Levine et al., 2000). Social force model is an extension of self-propelled model and proposes a mixture equation of physical and psychological forces influencing pedestrian behavior in a crowd inspired by Newtonian mechanics (Helbing et al., 2000; Helbing and Molnar, 1995). However, social foraging behaviors of sheep share different features and simplex velocity adjustment function may not describe the internal decision process.

In this paper, we therefore propose a friction based social force model to simulate social foraging of sheep and emphasize the importance of individual interactions with food distribution in internal decision process. According to the concept of "social force" (Helbing et al., 2000; Helbing and Molnar, 1995), sheep's motivations to perform certain actions are quantified by different "forces". The instinct of feeding is suggested to represent the individual interaction with currently located patch and quantified by friction force. Individual interactions with other patches are named as attractions of food and quantified by pulling forces. Conspecific effects are usually represented by repulsion–attraction forces between individuals (D'Orsogna et al., 2006; Romanczuk and Schimansky-Geier, 2012). In friction based social force model, agent moves if pulling force and repulsion–attraction force are both larger than friction force and the destination patch can provide enough friction force to resist external forces. The main objectives of this paper include (1) proposing plausible decision process of sheep foraging based on instinct of feeding, (2) simulating social foraging behaviors and testing the effects of instinct of feeding on behaviors of sheep, and (3) mimicking the observed departure-following behaviors. Instinct of feeding is a decision threshold to move or graze. We anticipate that the novel introduction of individual interactions with food distribution in internal decision process helps to understand the formation of collective behaviors in social foraging.

2. Preliminary and modeling methods

2.1. Patches and sheep agent

Computer simulation requires abstracted models of meadow and sheep, as shown in Fig. 1. The meadow is supposed to be a discrete two-dimensional flat and consist of orderly matrix of M patches ($i = 1, 2, \ldots, M$). The quantity and quality of grass in patch i are jointly named as the value of grass in patch i and represented by positive number R_i. The sheep (agent and sheep are interchangeable concepts in the following) has a facing direction and visual acuity range. Visual acuity range is a fan-shaped area with radius r and angular resolution $[-\theta/2, \theta/2]$, which is similar to the representation of visual information in behavioral heuristics research (Moussaïd et al., 2011). The facing direction bisects the visual acuity angle. A similar concept is mentioned as "desired direction" in the research of spatial dynamics of animal groups (Couzin et al., 2002). We use c_i and p_a to represent the positional coordinates of patch i and agent a.

The agent moves between patches within the visual acuity range and consumes a part of the "forage grass". Time is partitioned into discrete time steps with unit interval spacing. If agent a is in patch i in time t, $p_a(t)$ equals c_i; and if agent a moves to patch j in time t', $p_a(t')$ equals c_j. Then, agent a changes facing direction as follows:

$$f_a(t') = \frac{p_{a(t')} - p_{a(t)}}{\left|p_{a(t')} - p_{a(t)}\right|} = \frac{c_j - c_i}{\left|c_j - c_i\right|} \quad (1)$$

When agent moves, the facing direction is changed and patches within visual acuity range are updated. In this way, agent may explore new patches. Meanwhile, the agent is abstracted as a particle, with no volume (Couzin et al., 2002; Sumpter, 2006; Vicsek et al., 1995).

2.2. Three forces in social foraging

In the following, three forces that influence the decision of agent a will be introduced. Friction force is the product of friction coefficient and the value of grass. With reference to related works (Ginelli and Chaté, 2010; Levine et al., 2000; Romanczuk and Schimansky-Geier, 2012), pulling force of patch and repulsion–attraction force of conspecifics are calculated as forms of natural exponential functions.

2.2.1. Friction force

The instinct of feeding represents individual direct interaction with currently located patch and is the main reason for grazing behavior. The "friction coefficient" represents the magnitude of instinct and is denoted by μ. When agent a is currently located in patch i, patch i provides the friction force for agent a:

$$F_f(a, i) = R_i \times \mu_a \quad (2)$$

2.2.2. Pulling force

Generally, agent tends to move to a patch which can provide abundant food. Patch i within the visual acuity range shows an attractive effect, which is represented by pulling force:

$$F_p(a, i) = \left[\exp\left(\frac{R_i}{\tau_1}\right) - 1\right] \times \frac{c_i - p_a}{\left|c_i - p_a\right|} \quad (3)$$

τ_1 is constant and determines the steepness of the pulling force.

2.2.3. Repulsion–attraction force

Consecifics effects are usually represented by repulsion–attraction force and a "comfortable" distance is always assumed to be the dividing line between repulsive force and attractive force (D'Orsogna et al., 2006; Romanczuk and Schimansky-Geier, 2012). If distance between two members is less than the comfortable distance, repulsive force drives agents away from each other. Attractive force prevents sheep from being separated from the flock. Therefore, the repulsion–attraction force F_e (a, b) is a piecewise function with value d which denotes the distance between agent a and b.

$$\begin{aligned} F_e(a, b) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times \frac{p_b - p_a}{\left|p_b - p_a\right|}, \quad d > d_c \\ F_e(a, b) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times \frac{p_a - p_b}{\left|p_b - p_a\right|}, \quad 0 < d < d_c \\ F_e(a, b) &= 0, \quad d = d_c \end{aligned} \quad (4)$$

where d_c is constant and denotes the comfortable distance, and τ_2 is also constant and determines the steepness of repulsion–attraction force. Meanwhile, we have:

$$F_e(a, b) = -F_e(b, a), \quad d > 0 \quad (5)$$

If agent a and b are in the same patch ($d = 0$), we assume that the directions of repulsion–attraction forces depend on the facing directions of agents:

$$\begin{aligned} F_e(a, b) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times f_a \\ F_e(b, a) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times f_b \end{aligned} \quad (6)$$