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우두머리가 있는 두 생물무리의 가로지르기 동역학

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Crossing Dynamics of Leader-guided Two Flocks

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ABSTRACT

In field, one can observe without difficulties that two flocks are intersected or combined with each other. For example, a fish flock in a stream separates into two part by obstacles (e.g. stone) and rejoins behind the obstacles. The dynamics of two flocks guided by their leader were studied in the situation where the flocks cross each other with a crossing angle, θ, between their moving directions. Each leader is unaffected by its flock members whereas each member is influenced by its leader and other members. To understand the dynamics, I investigated the order parameter, ϕ, defined by the absolute value of the average unit velocity of the flocks' members. When the two flocks were encountered, the first peak in ϕ was appeared due to the breaking of the flocks' momentum balance. When the flocks began to separate, the second peak in ϕ was observed. Subsequently, erratic peaks were emerged by some individuals that were delayed to rejoin their flock. The amplitude of the two peaks, d_1 (first) and d_2 (second), were measured. Interestingly, they exhibited a synchronized behavior for different θ. This simulation model can be a useful tool to explore animal behavior and to develop multi-agent robot systems.

Key words : Flocking behavior, Virtual leader, Flocks' collision, Order parameter.

요 약

우리는 두 생물무리가 서로 가로지르거나 결합하는 현상을 주변에서 흔히 볼 수 있다. 예로, 하천의 물고기 무리가 운동하다 바위나 돌같은 장애물을 만나 두 무리로 나누어졌다가 장애물 뒤에서 다시 하나로 합쳐지는 현상이 있다. 우두머리를 가지는 두 생물 무리가 각도θ를 가지고 서로 충돌하면서 가로질러 지나갈 때의 동역학을 연구하였다. 두 무리의 각 우두머리 개체는 다른 개체에 의해 영향을 받지 않는다. 이에 비해 무리의 개체들은 우두머리의 운동방향을 좇아 가도록 시뮬레이션 되었다. 이 두 무리의 가로지르기 동역학을 이해하기 위해서, 무리개체의 평균 단위속도의 합으로 정의되는 질서매개변수ϕ를 조사하였다. 두 무리가 서로 만나는 순간, 두 무리의 운동량 균형이 무너지면서 ϕ값이 급격히 올라갔다. 그리고 두 무리가 서로 분리되어질 때, 두 번째로 ϕ값이 피크를 보였다. 무리개체들은 서로 충돌하면서 그들의 우두머리 개체를 좇아가는데 방해를 받게 되는데 이로 인해 두 번째 피크이후에 불규칙적인 작은 피크들이 관측되었다. 두 피크값, d_1 (첫번째) 그리고 d_2 (두번째), 은 서로 다른 충돌각도 θ에 대해서 동기화 현상을 보였다. 이 시뮬레이션 모델은 생물행동을 연구하거나 다개체 로봇 시스템 개발에 유용하게 사용되어 질수 있다.

주요어 : 생물무리행동, 가상의 우두머리, 무리의 충돌, 질서 매개변수

1. INTRODUCTION

The motion of a flock of animals is one of nature's delights. Flocks and related synchronized group behaviors such as schools of fish or herds of land animals are both beautiful to watch and intriguing to contemplate. Such flocking behavior has certain advantages such as reducing the risk of capture by predators, higher mating

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efficiency, and easier search for food and efficient learning of external stimuli[1,2].

Because of these biological importance, the flocking behavior has been much studied by physicists or theoretical biologist in several types of quantitative methods such as equations of motion for description of particle systems[3-6], partial differential equations on advection-diffusion-reaction[7], and simulation through multi-agent systems[8]. Among the models, equation-based particle models have been intensively used to explore the animal flocking behavior. Lee et al[4-6] explored the dynamics of prey-flock's escaping behavior in response to the predator's attack behavior. They revealed interesting physics residing the complicated behaviors, such as phase transition in prey-flock's behavior in response to different attack angel. However, these studies only dealt with a flock without a leader because most animals in flocks maintain the flock without a supervisor leading or external stimuli[9,10].

However, recently, the concept of a leader-guided flock has attracted much attention in many fields such as robotics and control engineering. For instance, in Ref.[11], moving reference points were viewed as virtual leaders used to manipulate the geometry of autonomous vehicle group and direct the motion of group. The cohesion of the members of swarms following an edge-leader was analyzed in Ref.[12]. Jadbabaie et al.[13] investigated leaderless/ leader coordination of mobile autonomous agents using nearest neighbor rules. Leader-follower networks were also considered in Ref[14].

These studies developed formation control, distributed cooperative control and coordination of multiple mobile autonomous agents, but many problems still remain unexplored because they have short duration.

One of them is the crossing behavior of two flocks, which can be faced by the situation where separated flocks, sometimes splitting apart to go around an obstacle, are rejoined together[15]. In practical aspect, this behavior is more likely to be linked with a traffic problem of multi-robots or autonomous vehicles.

In the present study, I constructed a two-dimensional model for simulating two flocks guided by their leader. I investigated the crossing dynamics of the flocks by using the order parameter defined by the absolute value of the average unit velocity of the flocks' members.

2. MODEL DESCRIPTION

The particles in my model were used to represent two flock members and their virtual leaders. Each leader is external individual that guides the movement of its flock and is unaffected by the flocks' members. Each flock was composed of N(=200) individuals with mass m_i at position, x_i, with velocity, v_i, for each individual i($i = 1, 2, 3, \cdots, 200$), and its leader. Initially, two flocks were generated by same governing equations at different regions in which they do not interact with each other. The governing equations for controlling the movement of each individual i of a flock are

$$\begin{aligned} m_i d_t \vec{v}_i &= \vec{f}_i^{align} + \vec{f}_i^{att} - \vec{f}_i^{rep} - \vec{f}_i^{fric} - \vec{f}_i^{avoid} + \vec{f}_i^{leade} \\ d_t \vec{x}_i &= \vec{v}_i \end{aligned} \quad ,$$

where $\vec{x}_i$ is the position vector of i-th individual. f_i^q (q=*align, att, rep, fric, avoid* and *leader*) represents various forces to address interactive behaviors among individuals(*align*: alignment, *att*: attraction, *rep*: repulsion, *fric*: friction, *avoid*: avoidance from the opposite flock's members, and *leader*: attraction to their leader).

The force of alignment was given as[16]

$$\vec{f}_i^{align} = \sum_{j(i \neq j)} \frac{g}{\left|\vec{x}_i - \vec{x}_j\right|^2} \hat{v}_j \quad ,$$

where x_i and x_j indicate the i-th and the j-th individual position. v_j is the velocity of the j-th individual and g is the strength of the aligning force. The aligning force, g, contributed to making each member of the flock move in the same direction. In the present study, the value of g was appropriately set as 0.5.

In presenting the attracting force between the individuals, a decreasing exponential function was used. When the i-th individual was located in the attractive field of the j-th individual, the i-th individual was as sumed to move towards the j-th individual, more rapidly if they are closer.

The attractive force was described as below:

$$\vec{f}_i^{att} = c_{att}\sum_{i\neq j}\exp\left(-\left|\vec{x}_i-\vec{x}_j\right|/l_{att}\right)\hat{f}_{i,j}^{att} ,$$

where $\hat{f}_{j,i}^{att} = (\vec{x}_j-\vec{x}_i)/\left|\vec{x}_j-\vec{x}_i\right|$, and c_{att} is a constant.

The strength of the attractive force was characterized by a length scale l_{att} in the decreasing exponential function. This force is global on all the time and is responsible for the aggregation of the individuals. The repulsive force between the individuals was expressed additionally by the decreasing exponential function. When the *i*-th individual was in the repulsive field of the *j*-th individual, the *i*-th in dividual moved away from the *j*-th individual to avoid a collision depending upon distances between the two individuals. The repulsive force was described as follows

$$\vec{f}_i^{rep} = c_{rep}\sum_{i\neq j}\exp\left(-\left|\vec{x}_i-\vec{x}_j\right|/l_{rep}\right)\hat{f}_{i,j}^{rep} ,$$

where $\hat{f}_{i,j}^{rep} = \vec{x}_i-\vec{x}_j/\left|\vec{x}_i-\vec{x}_j\right|$ and C_{rep} is a constant. Similar to the case of attraction, l_{rep} was used for characterizing repulsive forces.

To prevent individuals from moving too quickly, the friction force with coefficient γ was set to be proportional to the current speed of an individual:

$$\vec{f}_i^{fric} = \gamma\vec{v}_i \ .$$

To manipulate flock's moving direction, I introduced a virtual leader and described the leader-following behavior of individuals as Hook's law:

$$\vec{f}_i^{leader} = c_{leader}\left(\vec{x}_{leader}-\vec{x}_i\right),$$

where $\vec{x}_{leader}$ is the positional vector of the leader, and c_{leader} was a constant.

In this model, the two flocks, guided by their leader with moving speed k=1.5, crossed with a crossing angle, θ, between their movement directions.

When the two flocks collide, if the *i*-th individual of one flock recognizes the presence of the *p*-th individual of the other flock in a given distance, *R*, the *i*-th individual runs to the opposite direction of the *p*-th individual This rule was described as

Table 1. Parameters used for simulation on the flocks guided by their leader

Parameter values	
C_{att}=7	N=200
C_{rep}=5	m=1.0
C_{avoid}=0.3	Δt=0.1
g=0.5	ω=0.5
γ=0.05	κ=2.0
l_{att}=100	l_{rep}=120
c_{leader}=0.001	R=10

$$\vec{f}_i^{avoid} = \sum_{p=1}^{N} c_{avoid}\frac{1}{1+\exp\left[\omega\left(\left|\vec{x}_p-\vec{x}_i\right|-R\right)\right]}\hat{x}_{p,i} ,$$

where $\vec{x}_p$ is the position vector of the p-th individual, and $\hat{x}_{p,i}$ was the unit vector directing from the p-th individual to the i-th individual In the model, ω controls the degree of decay in avoiding forces.

In this model, I used the parameters shown in Table 1 to generate the two flocks.

3. SIMULATION RESULTS

Initially, the individuals of the two flocks were aligned to their leader's movement direction. The flocks crossed with a crossing angle, θ, formed between their moving directions(Fig. 1).

In order to quantitatively describe the dynamics of the two flocks intersecting, I used the order parameter of the flocks, ϕ, defined by the absolute value of the average unit velocity[5-8];

$$\phi \equiv \frac{\left|\sum_j \hat{v}_j\right|}{N_{tot}} ,$$

where N_{tot}(=400) was the total number of individuals in the two flocks, and $\hat{v}_j$ was the unit velocity vector of the j-th individual(j = 1, 2, 3,⋯, 400).

Figure 2 (a) shows the plots of ϕ, against time for the different crossing angles θ(θ=100°, 120°, 140°, 160°, and 180°). The changes in ϕ, showed two main peaks and small peaks. The trend of the plots was characterized by three different regimes(Fig. 2 (b)), and each regime was explained in terms of individual movement in Fig. 3 and 4.

Figure 3 shows snapshots of the flocks' crossing. When the flocks collided, they were compressed on the contiguous region by, which led to individual f^{leader} density difference between the compressed and the less compressed region(Fig. 3 (a) and (b)).

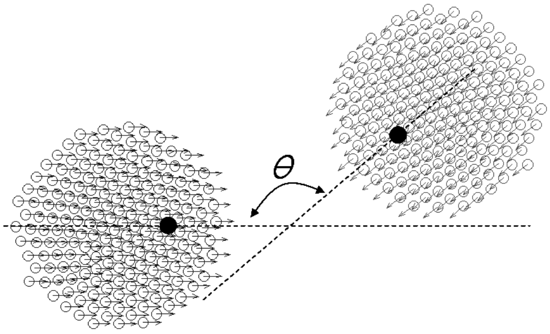


Fig. 1. Two flocks' crossing with a crossing angle, θ, between their moving directions. The empty and the filled circle indicate the flocks' members and their leader, respectively whereas the arrows are individuals' velocity. The two flocks were discerned in different color.

Individuals, located near the interface between the compressed and the less compressed region, were forced to move toward the less compressed area. This was due to the f^{avoid} caused by the individual density difference in the given distance R(Fig. 3 (c)).

In this situation, some individuals of one flock entered the inside of the other flock a very short time ahead of others, affecting their neighbors' movement. This influence transferred to all individuals of the opposite flock very quickly, which consequently led to the imbalance of momentum of the two flocks(Fig. 3 (d)).

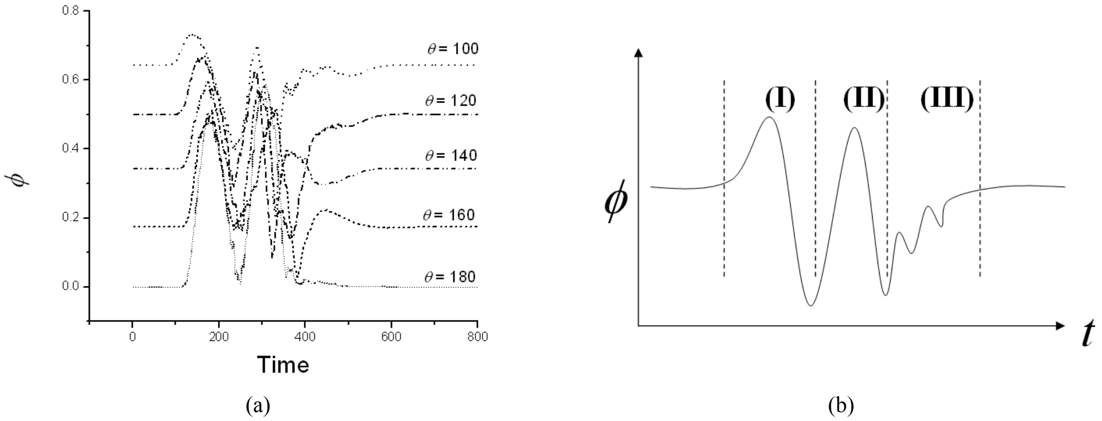
As soon as the unbalance took place, the number of individuals passing through an opposing flock increased rapidly. This gave rise to the increase of ϕ as shown in the regime I of Fig. 2 (b).

Once the flocks were more mixed, ϕ decreased due to the increase of randomness in individual movement (Fig. 4 (a) and (b)).

After that, the mixed flocks began to be separated from each other, which caused the increase of ϕ as shown in the regime II in Fig. 2 (b) (Fig. 4 (c) and (d)).

In this situation, some individuals of a flock were confined to the opposite flock, their ability to rejoin their flocks decreased. This resulted in the erratic peaks in ϕ shown in the regime III of Fig. 2 (b).

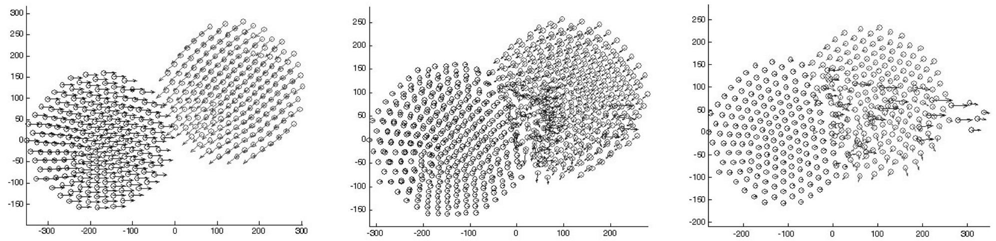
In order to quantify how individuals of one flock penetrate the inside of the other flock in an initial



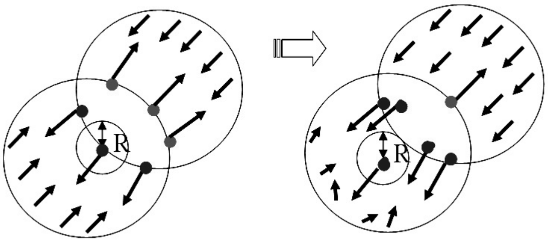
(a)

(b)

Fig. 2 (a) The plots of order parameter ϕ against time for different crossing angle θ. (b) The trend of the changes in ϕ according to time.

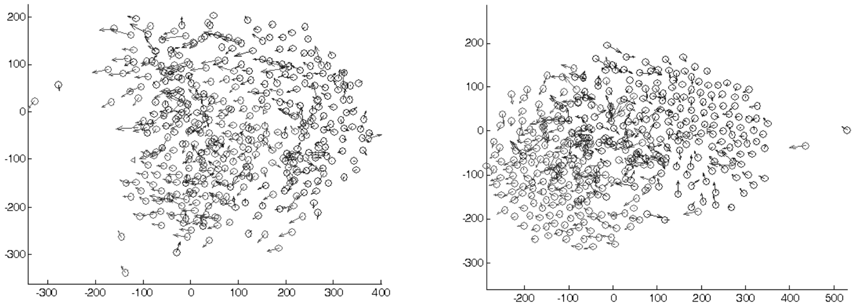


(a) t=100 (b) t=125 (c) t=150

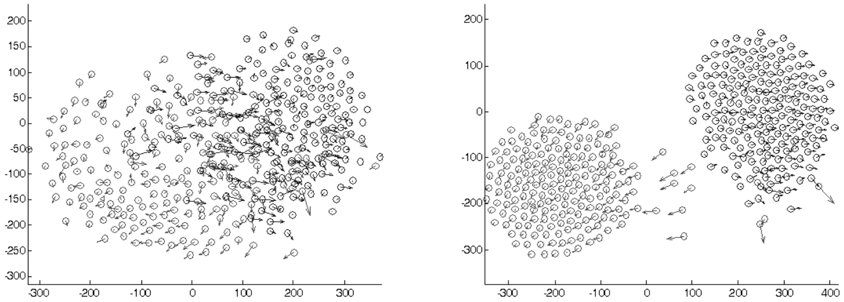


(d)

Fig. 3. (a-c) The process of the two flocks' collision to cross each other in early stage (0 < t < 150). (d) Causes of imbalance of the flocks' momentum.



(a) t=280 (b) t=320



(c) t=340 (c) t=390

Fig. 4. The process of the flocks' separation in late stage (280 < t < 390) where θ = 140°.

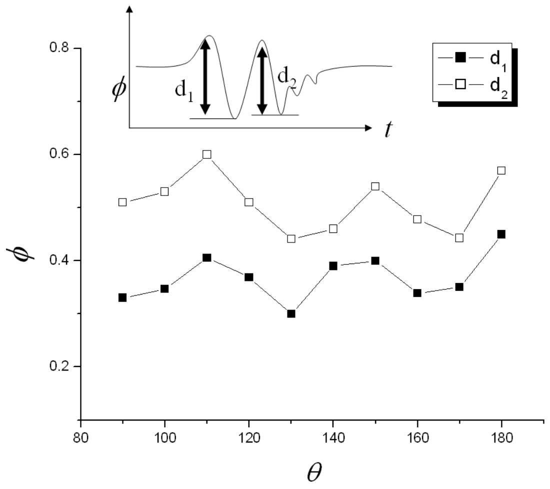


Fig. 5. The synchronized behavior between d_1 and d_2, which are the amplitudes of the first and second peak in time varying ϕ.

collision or how the flocks are separated from each other, I measured the amplitude of the first and second peak(d_1 and d_2) in the regime I and II for different θ.

d_1 and d_2 peaked at some angles: θ. = 110°, 150°, and 180°. This means that more individuals of one flock passed through the other flock at these angles, and when the two flocks are separated, the separation progressed smoothly with less individuals confined to the inside of an opposite flock. The values of the angles varied for parameter values used in this model such as flock size, leader's speed, and individual mass. However, where $1.0 \leq \kappa \leq 3.5$, I observed a uniform synchronization between d_1 and d_2. This reflects that the flocks' state at the initial collision significantly influenced their state at the separation time.

4. CONCLUSION

In order to study the crossing dynamics of two flocks, I used a two dimensional model simulating two flocks guided by their leader. The order parameter, ϕ, was investigated as a measure of flock's kinetic state. In this study, I observed two interesting phenomena; the first was that although the two flocks were generated by same governing equations, the balance of flocks' momentum was broken by individual density difference caused by the flocks' compression at an initial collision, and the second was that the amplitude of the first and second peak in time varying ϕ exhibited a synchronized behavior for $90° < \theta < 180°$ where $1.0 \leq \kappa \leq 3.5$. My findings in this simulation may provide insights for practical applications such as traffic problem of multi agents or robots. This simulation model was programed by using MATLAB ver. 6.5. The equation governing the two flocks' behavior was numerically solved by molecular dynamics simulation method.

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