



Herd guidance by multiple sheepdog agents with repulsive force

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Abstract

This paper proposes a scalable method of guiding sheep herding with efficiency and robustness by single or multiple sheepdogs. Recently, much attention has been paid to control methods modeled on a sheep herd by a very small number of sheepdog agents. Usually, these control systems are connected to the Internet in some way, and the system must be capable of dealing with requirements such as robot failure or hacking by malicious entities. However, except for a few studies, multiple sheepdog agents to work together efficiently have been rarely discussed. The main problem is the way to produce an efficient geographical role assignment to multiple sheepdogs. Experimental results show that the introducing repulsion gain K_{f4} between a couple of two sheepdogs can emerge circle formation, while the group of sheepdogs guides a flock of sheep to goal. Therefore, it can achieve the task more quickly and reliably than the conventional method of a single sheepdog by increasing the number of units. This paper is based on the paper presented at the proceedings of the 4th International Symposium on Swarm Behavior and Bio-Inspired Robotics (Tashiro et al., The 4th International Symposium on 528 Swarm Behavior and Bio-Inspired Robotics: 397–408, 2021).

Keywords Multi-agent system · Sheepdog-type navigation · Swarm intelligence · Complex system

1 Introduction

This study proposes a multiple sheepdog algorithm that autonomously divides roles by repulsive interaction, and shows that it can efficiently guide a flock of sheep. In recent years, a control method modeled on driving a flock of sheep with a small number of sheepdogs has been attracting attention [2–4]. Usually, sheep are larger and more numerous than sheepdogs, so they cannot be guided in a head-to-head

game. Perhaps, because of this, sheepdogs appear to guide the flock of sheep without taking undue risk by taking advantage of the characteristics of the sheep that behave in the flock (Fig. 1).

This behavior of sheepdogs can be regarded as a solution to the problem that the control input greatly exceeds the control target. Therefore, if this can be applied, it has been attracting attention as it can be the basis for the absorption of spilled oil, the prevention of inflammation of forest fires, and the control of mob crowds, which are currently problems in the world [5–7]. In the control theory community, this is known as the implicit approach [8], which has received a lot of attention in recent years.

In this paper, we consider that the robot system used for such applications must be robust by multiple control robots to increase resistance to breakdowns and hacking, and we would like to consider guidance by multiple sheepdogs. As the first step, this paper examined an efficient guidance method using multiple sheepdogs. We will try to realize a system that greatly exceeds the induction in a single sheepdog and the induction improves as the number of dogs increases. However, many conventional studies have focused on the fact that there is only one sheepdog, and there are few studies on the guidance by multiple sheepdogs. In addition,

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Fig. 1 A sheepdog and a flock of sheep (<https://www.tomamin.co.jp/news/area1/11946/>)

the division of roles among sheepdogs, which is indispensable for achieving this goal, was often heuristic.

Therefore, in this paper, we proposed to autonomously generate a circle formation by setting a repulsive interaction between sheepdogs and tried to realize an appropriate division of roles among sheepdogs, which was a subject of conventional research. The next chapter introduces related research, and Sect. 3 describes the proposed method. Next, a fixed point analysis is performed to clarify that in a small case, there is a guidance completion state in the sense of Lyapunov even if there is a repulsive interaction between the sheepdogs.

This study is based on the presentation at the international symposium Swarm2021 [1]. In particular, we newly have conducted a basic analysis of the proposed method and also clarified that the proposed method can guide a flock of sheep with even an arrangement that is disadvantageous to sheepdogs that fail to guide in conventional studies.

2 Related studies

Since ancient times, humans have used sheepdogs to efficiently guide a flock of sheep to their destinations. The sheepdog system is an engineering application of this. Most of the control objectives are to put the sheep in the goal area, like the actual ones. In the following, to simplify the problem, it is assumed that guidance is achieved at that point if all sheep are in the goal area at the same time.

Previous studies on the sheepdog system [2, 3] can be divided into those that focus on guidance by a single sheepdog and those that deal with guidance by multiple sheepdogs.

The following three types are well known for dealing with guidance by a single sheepdog. First, there is the center tracking control method [9] (CTC) proposed by Vaughan

et al., which targets the center of the flock. The second is the v-shaped pursuit method [10–12] (hereinafter, VSP) that moves left and right concern with the center of gravity of the flock. The third is the farthest individual tracking control method [2, 13] (FIT), which targets the agent farthest from the goal.

A few studies have dealt with induction by multiple sheepdogs [3]. Lien et al. [5] and Jyh-Ming and Emlyn [14] proposed a top-down method of creating and assigning shared positions for sheepdogs, and showed that multiple sheepdogs can guide sheep more efficiently than one. Pierson and Schwager [15] proposed a method of arranging sheepdogs at regular intervals around the herd, and conducts computer simulations in 2D and 3D, and verification on actual 2D machines. Ozdemir et al. [7] uses evolutionary computation to acquire a memoryless sheepdog robot suitable for a given flock and goal placement. Lee and Kim [16] proposes a method of guiding using patrol behavior and collection behavior in addition to guiding behavior. At the time of guidance, the repulsive interaction between the sheepdogs is proposed in this paper. Since it is a model that pushes the nearest sheep to each sheepdog to the goal, it is difficult for the sheepdogs to emerge an adequate geographical division of roles. Also, an overshoot always occurs after arriving at the goal. Thus, generally speaking, while studies using multiple sheepdogs have reported that efficient guidance can be achieved if the number of sheepdogs used is large, how to arrange multiple sheepdogs has not been researched sufficiently.

On the other hand, it is difficult to formulate the form of following a flock in a flock, and theoretical analysis has hardly been performed [15]. One of the few is [17]. This research proposed a method that simplifies sheep and sheepdogs as a single individual, respectively, to analyze sheepdog systems theoretically. In this study, the authors show that one sheepdog can keep the sheep in a circular orbit near the goal while moves on a circular orbit around the goal. In addition, it reports that if the sheepdog can move quicker, it can guide more accurately, and if a triad of the goal, the sheep, and the sheepdog lines up in a row, it becomes difficult to guide the sheep to the goal. The former result is consistent with previous research results [16]. In this paper, we use this method to analyze small-scale cases and examine the effectiveness of the proposed method.

3 The proposed method

3.1 Sheep agent (A-sheep)

As discussed in Sect. 2, in the conventional studies, only one sheepdog is adopted and the sheep agent is defined as accepting only one sheepdog agent. Therefore, a new sheep agent is

required for correct assessments that can behave plausibly in a multiple sheepdog environment. Therefore, first of all, the Sheep agent to be controlled here is defined. Following the sheep model of the conventional method [13], the two behavior of flocking sheep and escaping from the sheepdog are defined concerning the Boid model [18]. The Boid model can represent a flock with three rules: separation, alignment, and cohesion. This set of rules gives sheep the ability to flee from sheepdogs. In particular, the influence of the sheepdog agent is defined here as the ratio of the total number of sheepdog agents to sheepdog agents in the vicinity of a sheep. In the following, this is called A-Sheep. Equation 2 defines the acceleration $u_i(k)$ acting on the Sheep agent i at time k

$$\dot{p}_i(k) = u_i(k) \quad (1)$$

$$u_i(k) = K_{s1}a_i(k) + K_{s2}b_i(k) + K_{s3}c_i(k) + K_{s4}d_i(k), \quad (2)$$

where $a_i(k)$ is the repulsive acceleration acting on the sheep agents, $b_i(k)$ is the alignment term, $c_i(k)$ is the attraction between the sheep agents, $d_i(k)$ is the repulsion to escape from the sheepdog, and K_{s1} , K_{s2} , K_{s3} , and K_{s4} are the parameters. S_i is the set of sheep in the field of view of sheep i , and D_i is the set of sheep dogs in the field of view of sheep i . N_{S_i} and N_{D_i} are the number of Sheep agents and Sheepdog agents in Sheep agent i ' field of vision r_s , respectively. Figure 2 illustrates the relationship between these terms of Eq. 1

$$a_i(k) = \frac{1}{N_{S_i}} \sum_{j \in S_i} \frac{x_i(k) - x_j(k)}{||x_i(k) - x_j(k)||^2} \quad (3)$$

$$b_i(k) = \frac{1}{N_{S_i}} \sum_{j \in S_i} \frac{v_j(k-1)}{||v_j(k-1)||} \quad (4)$$

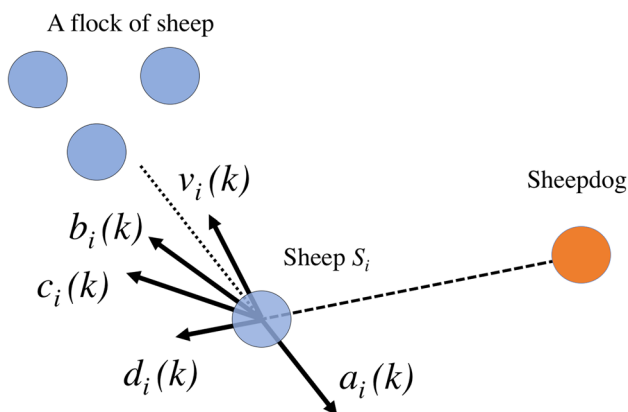


Fig. 2 Sheep agent

$$c_i(k) = \frac{-1}{N_{S_i}} \sum_{j \in S_i} \frac{x_i(k) - x_j(k)}{||x_i(k) - x_j(k)||} \quad (5)$$

$$d_i(k) = \frac{1}{N_{D_i}} \sum_{j \in D_i} \frac{x_i(k) - X_j(k)}{||x_i(k) - X_j(k)||^3}. \quad (6)$$

3.2 The proposed sheepdog agents

Here, based on the research by Sueoka et al. [4], we propose another farthest individual tracking method (FIT) using multiple sheepdog agents that have mutually repulsive interactions. Based on FIT, a sheepdog pushes a sheep whose target is the farthest from the goal, while a sheepdog based on CTC pushes the center of gravity of a flock. The farthest sheep is called Target in the following.

Our preliminary experiments have shown that a group of sheepdog agents with CTC does sheep flock tends to dissipate, because the sum of sheepdog agents' power becomes too much. On the other hand, FIT sheepdog agents that independently behave tend to lose spatial diversity, as the sheepdog agents tend to come to in one place naturally. Therefore, we propose here that repulsion occurs between sheepdog agents using FIT. In the following, this sheepdog is called S-dog:

$$\dot{p}_i(k) = v_i(k) \quad (7)$$

$$v_i(k) = K_{f1}A_i(k) + K_{f2}B_i(k) + K_{f3}C_i(k) + K_{f4}D_i(k). \quad (8)$$

Equation 8 shows the acceleration $u_i(k)$ acting at time k for the Sheepdog agent i proposed here. Sheepdog Agent i moves by the following four actions. $A_i(k)$ is the action to chase the target Sheep $T(k)$, $B_i(k)$ is the interaction to keep away from the target, $C_i(k)$ is the interaction to keep away from goal G , and $D_i(k)$ is the repulsive interaction between sheepdogs proposed here. $T(k)$ is the target sheep, and as in the conventional method [4], the sheepdog operates on a single sheep chosen each step based on a specific criterion. We call the sheep as target sheep. Figure 3 shows these interactions acting on Sheepdog Agent i . N_{P_i} is the number of Sheepdog Agent P_i in the field of view of Sheepdog Agent i

$$A_i(k) = -\frac{X_i(k) - T(k)}{||X_i(k) - T(k)||} \quad (9)$$

$$B_i(k) = \frac{X_i(k) - T(k)}{||X_i(k) - T(k)||^3} \quad (10)$$

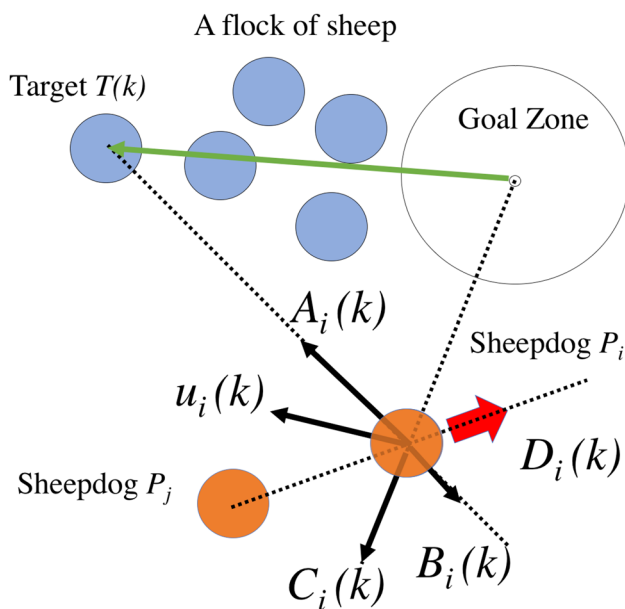


Fig. 3 Sheepdog agent

$$C_i(k) = -\frac{X_i(k) - G}{||X_i(k) - G||} \quad (11)$$

$$D_i(k) = \frac{1}{N_{P_i}} \sum_{j \in P_i} \frac{X_i(k) - X_j(k)}{||x_i(k) - X_j(k)||^3}. \quad (12)$$

The equations used in this paper are based on the equations proposed in a previous study of sheepdogs [17]. As you pointed out, Eq. 3 expresses the relationship between sheep, and Eq. 10 expresses the relationship between dogs and sheep in a concise manner with different orders, which is a simple and smart way. We also follow this model, because the relationship between sheep and dogs is different from the relationship between sheep and dogs, and we expect that by adjusting the order in the future, a wide range of analyses will be possible.

3.3 Circle formation by the proposed sheepdog agents

It is just an extension that adds repulsive interaction to FIT model, but it is very effective, because it creates the dynamics that surround the flock of sheep, namely circle formation. The upper row of Fig. 4 depicts guidance by a conventional system of a single sheepdog agent (d). Now, the flock is at the left of the goal. There, the sheepdog guides the flock from left to right by moving closer to the sheep farthest from the goal (see a1). The sheepdog in turn shifts the flock to the right, so the sheepdog moves to the right side of the flock (see a3) and pushes the flock from right to left (see

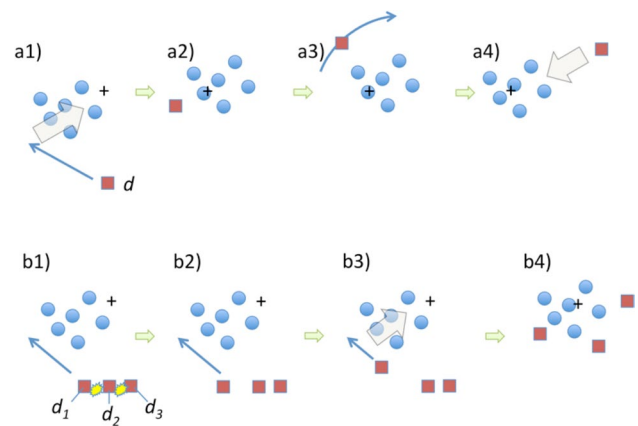


Fig. 4 Circle formation by the proposed sheepdog agents

a4). By alternating pushing direction to a flock from left and right, the flock is guided to the goal. The lower part of Fig. 4 shows the expected behavior when the proposed sheepdog agents repel each other guide. Suppose that we have a pack of three sheepdog agents d_1 , d_2 , and d_3 now. All sheepdog agents should move to the leftmost sheep (see b1). However, due to mutual repulsion (the yellow marks), d_2 and d_3 cannot move, and only d_1 can move in the direction of the sheep (see b2). Similarly, if the flock shifts to the right, only the d_3 on the right can head toward the sheep (see b3). As a result, the three sheepdogs disperse around the flock of sheep (see b4). It suggests that the proposed sheepdog group with the mutual repulsive interaction has the guidance by the circular formation, which has less overshoot.

3.4 Fixed point analysis of the number of sheepdogs $D = 2, 3$

Next, the basic analysis results for the convergence of the proposed method are shown. As far as we know, there is no theoretically established method for the stability of the sheepdog algorithm, even with two sheep except for [15]. Therefore, the simplification of [17] applies to the proposed sheepdog system with multiple dogs. Based on this simplification, we perform equilibrium point analysis for a small number of sheepdogs and show that there is a stable equilibrium point in the sense of Lyapunov even when there is a repulsive interaction between the sheepdogs. However, this simplification approximates a flock of sheep as one sheep, and it expects that the error with this analysis method will increase as the number of sheep and the number of sheepdogs increase. Therefore, in the case of a larger scale, we will conduct computer experiments in the next chapter to clarify the effectiveness of the proposed method.

Now, suppose two sheepdogs guide a flock of sheep to the goal. As shown in Fig. 5, the position of the target

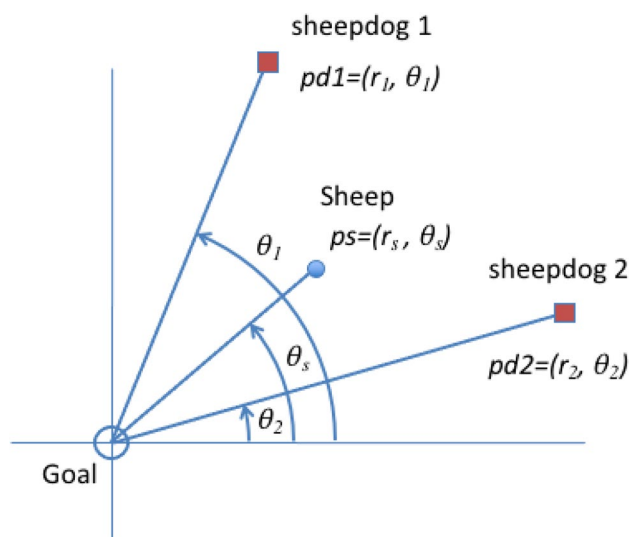


Fig. 5 Single sheep approximation in 2 sheepdogs

sheep, the position of the sheepdog 1, and the position of the sheepdog 2 with Goal as the origin are expressed as ps , pd_1 , and pd_2 , respectively

$$d(ps)/dt = k_1 \frac{ps - pd_1}{||ps - pd_1||^3} + k_1 \frac{ps - pd_2}{||ps - pd_2||^3} \quad (13)$$

$$d(pd_1)/dt = k_2 \left(-\frac{pd_1 - ps}{||ps - pd_1||} \right) + k_3 \left(\frac{pd_1 - ps}{||ps - pd_1||^3} \right) + k_4 \left(\frac{pd_1 - G}{||pd_1 - G||} \right) + k_5 \left(\frac{pd_1 - pd_2}{||pd_1 - pd_2||^3} \right) \quad (14)$$

$$d(pd_2)/dt = k_2 \left(-\frac{pd_2 - ps}{||pd_2 - ps||} \right) + k_3 \left(\frac{pd_2 - ps}{||pd_2 - ps||^3} \right) + k_4 \left(\frac{pd_2 - G}{||pd_2 - G||} \right) + k_5 \left(\frac{pd_2 - pd_1}{||pd_2 - pd_1||^3} \right), \quad (15)$$

where

$$\begin{aligned} ps &= (r_s \cos(\theta_s), r_s \sin(\theta_s)) \\ pd_1 &= (r_1 \cos(\theta_1), r_1 \sin(\theta_1)) \\ pd_2 &= (r_2 \cos(\theta_2), r_2 \sin(\theta_2)). \end{aligned} \quad (16)$$

Next, consider the situation where the guidance is successful. That is, when $G = ps$, the sheepdogs repel each other, and from the symmetry of the dogs, it is expected that $r_1 = r_2 = r$ and $|\theta_1 - \theta_2| = \pi$. At this time, from Eqs. 13, 14, 15, 16

$$r = R_{D=2} = \sqrt{\frac{k_3 - \frac{k_5}{4}}{k_2 - k_4}} \quad (17)$$

is satisfied when $d(ps)/dt = d(pd_1)/dt = d(pd_2)/dt = (0, 0)$.

From this, we think that this state where two sheepdogs are on a certain radius on the orbit with a radius of $R_{D=2}$ centered on the goal is a fixed point. In the following, this fixed point will refer to as $fp2$. Similarly, in the case with a group of three sheepdogs, the state in which the sheepdogs are placed in the orbit with

$$r = R_{D=3} = \sqrt{\frac{k_3 - \frac{k_5}{\sqrt{3}}}{k_2 - k_4}} \quad (18)$$

and their intervals are $2\pi/3$ is a fixed point. This fixed point refers to $fp3$ below.

Next, the stability of the fixed point $fp2$ was investigated. We linearize and find the eigenvalues as follows:

$$\begin{pmatrix} 0 \\ \frac{16(2k_1 + k_3)(k_2 - k_4)^2 \sqrt{\frac{4k_3 - k_5}{k_2 - k_4}}}{(k_5 - 4k_3)^2 \sqrt{\frac{4k_3 - k_5}{k_2 - k_4}}} \\ 0 \\ \frac{(8k_1 + k_5)(k_2 - k_4)(4k_3 - k_5)^5 - X1(k_2 - k_4)^6}{(k_5 - 4k_3)^6 \sqrt{\frac{4k_3 - k_5}{k_2 - k_4}}} \\ \frac{(8k_1 + k_5)(k_2 - k_4)(4k_3 - k_5)^5 + X1(k_2 - k_4)^6}{(k_5 - 4k_3)^6 \sqrt{\frac{4k_3 - k_5}{k_2 - k_4}}} \end{pmatrix}, \quad (19)$$

where

$$X1 = \sqrt{\frac{X2(k_5 - 4k_3)^{10}}{(k_2 - k_4)^{11}}} \quad (20)$$

$$X2 = 64k_1^2(k_2 - k_4) + 16k_1k_5(k_2 + k_4) - 128k_1k_3k_4 + k_5^2(k_2 - k_4). \quad (21)$$

Now, assuming that $k_1 > 0$, $k_2 > 0$, $k_3 > 0$, $k_4 > 0$, $k_5 > 0$ and the fixed point is in real space; the condition for Lyapunov stability is that the real part of this eigenvalue is less than or equal to 0. Then, we obtain the following conditions for Lyapunov stability:

$$k_2 > k_4 > 0 \wedge k_5 \geq 8k_1. \quad (22)$$

We also investigated the stability of the fixed point $fp3$. The eigenvalues of the parameters ($k_1 = 5000$, $k_2 = 10$, $k_3 = 200$, $k_4 = 8$, $k_5 = 1000$) used in the experiments in the next chapter are

$$\begin{pmatrix} -0.202893 \\ -0.0261064 \\ -0.0261064 \\ 0 \\ -0.558942 - 0.441791i \\ -0.558942 - 0.441791i \\ -0.558942 + 0.441791i \\ -0.558942 + 0.441791i \end{pmatrix}, \quad (23)$$

and because the real terms of these eigenvalues are non-positive, it turns out that this point is also Lyapunov stable. Next, we show numerical solutions around $fp3$. We introduce 2 set, $set1$ and $set2$. The $set1$ is a slightly deviated from this fixed point $fp3$, namely $ps = (-10, 10)$, $pd_1 = (100, 10)$, $pd_2 = (-100/\sqrt{3}, 100/\sqrt{3})$, $pd_3 = (-100/2, -100/\sqrt{3})$. The $set2$ is a large deviation from $fp3$, namely $ps = (-50, 50)$, $pd_1 = (90, 10)$, $pd_2 = (-100/2 + 10, \sqrt{3}100/2)$, and $pd_3 = (-100/2, -\sqrt{3}100/2)$. The numerical solutions around the 2 sets are shown in Figs. 6, 7, respectively. In both figures, the trajectories of one sheep and three sheepdogs are illustrated. In the case of $set1$, we think that it converges to $fp3$.

On the other hand, in the case of $set2$, the sheep repeatedly vibrates near the origin while being surrounded by three sheepdogs. The sheep can be guided again to the goal, although it sometimes deviates significantly.

From the above discussion, it is found that even if there is a repulsive interaction between sheepdogs based on FIT, there is a stable equilibrium point of Lyapunov when the number of sheepdogs $D = 2, 3$. In addition, the solutions

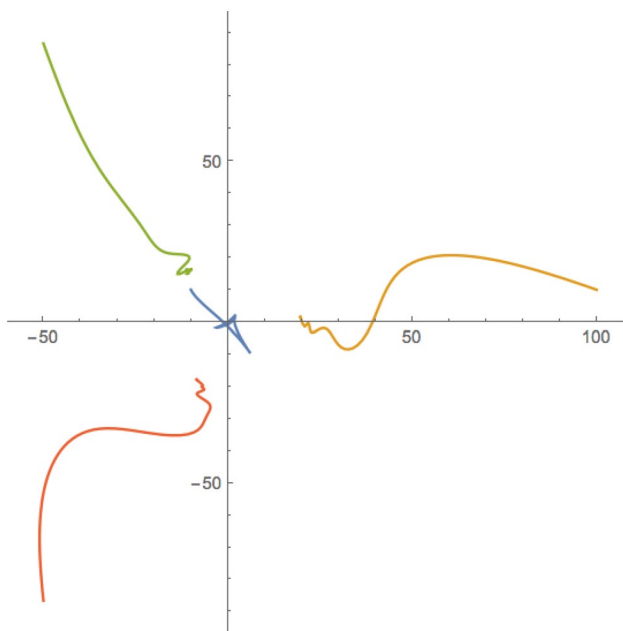


Fig. 6 Set 1: $D = 3, k_{f5} = 1000$

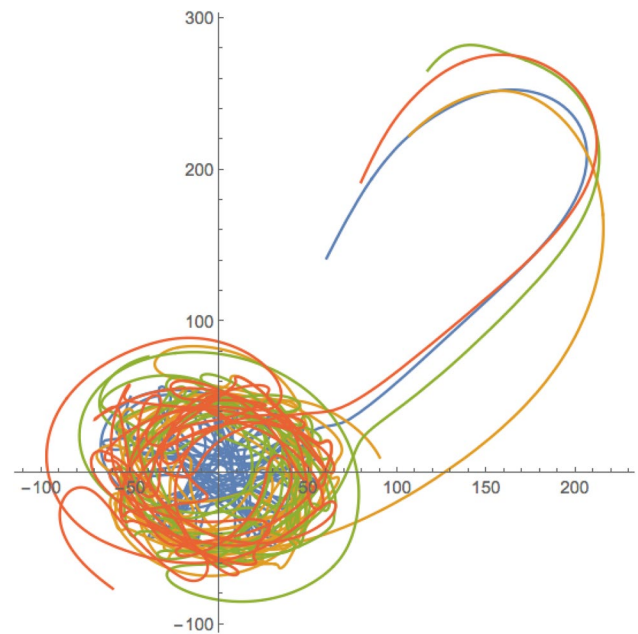


Fig. 7 Set 2: $D = 3, k_{f5} = 1000$

near the equilibrium point $fp3$ are obtained numerically. By finding it, the trajectories tend toward the goal, so it was expected that the dogs could guide a flock to the goal near this equilibrium point.

4 Experiments

Characteristics of the proposed method in larger cases are examined by computer simulations. In particular, the following points will be discussed in this chapter.

1. Confirmation that the circle formation formed as expected in Fig. 4 is performed.
2. Effect of the proposed parameter, coefficient of restitution K_{f4} , on guidance performance
3. Flock guidance performance in conventional difficult arrangements

First, the behavior of the proposed method is illustrated. Figure 8 shows the behavior when the number of sheepdogs ($D = 5$) and the argument of sheep ($N = 1000$) using the conventional method (Fig. 8A) and the proposed method (Fig. 8B). Sheepdogs of the conventional model do not have mutual repulsive interaction. Set the target area G as an area with a center point $[0, 0]$ and a radius of 10.0. The target area G (hereinafter referred to as “goal”) and its range are indicated by a circle in the center of the figure. The square is a sheepdog, and a small circle represents a

sheep. Both parameters are shown in Table 1. The initial position of the sheepdog agents (S-dog) is randomly distributed within a rectangle 30 vertical and 100 horizontal with respect to the point $[-50, 100]$. The sheep are randomly distributed within a square with a point $[-15, 40]$ on each side of 30.

In Fig. 8A, the squares of the sheepdogs tend to overlap as time T elapses. A flock of sheep can be guided near the

goal, but at $T = 500$ (s), it is difficult for the sheepdogs to guide the entire flock of sheep within the circle. In Fig. 8B, the sheepdogs guide the flock to the goal after the sheepdog moves around the flock. In addition, the time to guide is significantly reduced to $T = 140$ (s). Also, the radius of their circle is getting smaller and smaller, eventually leading the entire flock of sheep into the circular region of the goal. This reduction will be difficult with a single

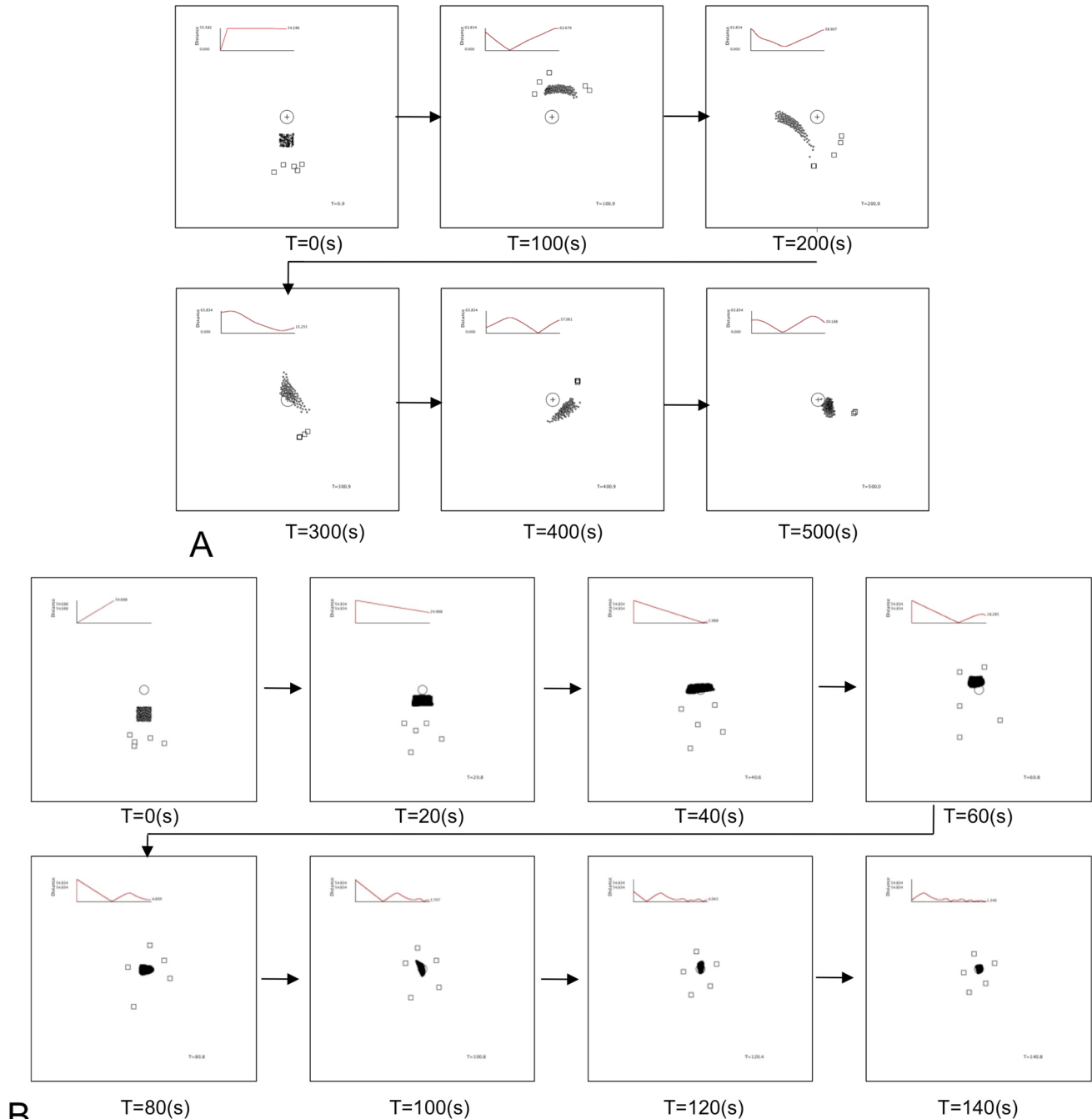


Fig. 8 Guidance with circle formation by repulsive interaction, **A** ($K_{f4}=0$), **B** ($K_{f4}=1000$): $N=1000$, $D=5$

Table 1 Parameters of sheep agent(A-sheep) and Sheepdog agent(S-dog)

r_s	Radius of interaction between Sheep	20
K_{s1}	Gain of repulsive interaction between Sheep	10
K_{s2}	Gain of alignment interaction between Sheep	0.5
K_{s3}	Gain of attraction between Sheep	2.0
K_{s4}	Gain of repulsion from Sheepdog by Sheep	5000
K_{f1}	Gain of interaction approaching the target	10
K_{f2}	Gain of interaction away from target	200
K_{f3}	Gain of interaction away from goal	8
K_{f4}	Gain of repulsive interaction between Sheepdogs	1000,3000

sheepdog system. In addition, since the proposed sheepdogs guide the entire herd, while maintaining its surroundings, it expects that efficient guidance can be achieved, because the occurrence of large overshoots is reduced.

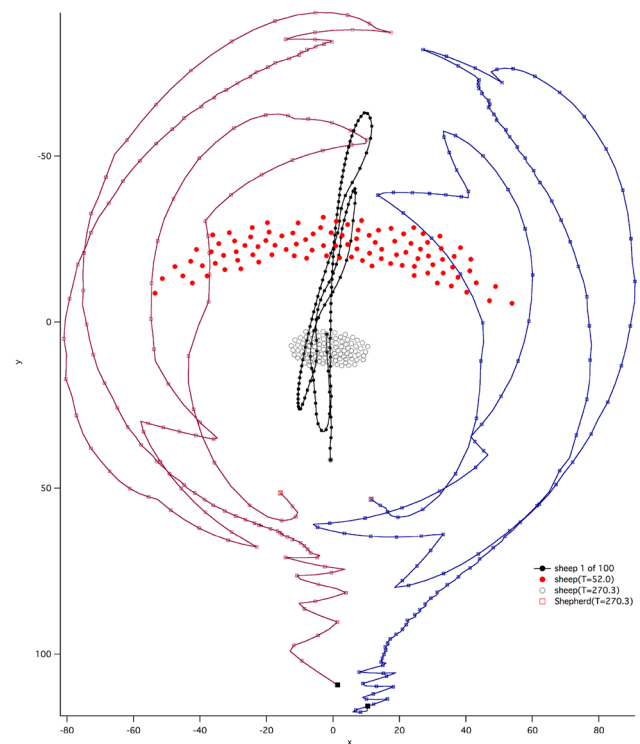
Next, the characteristics will be clarified by examining the trajectory in more detail. Figure 9 shows the trajectory of movement when $D=2$ and $N=100$. The sheepdog is “■” and the “o” shows the trajectory of one of the 100 sheep. From the bottom center, the two sheepdogs move the sheep toward the goal, but on the way, they split into left and right toward the farthest individual in the flock of sheep. In this case, since the target sheep is on the opposite side of the goal, both sheepdogs head in the direction of the figure but repel by their mutual repulsion interaction, so they are divided into left and right. This is in agreement with the behavior expected in Fig. 4. The next time, this sheep moves toward the goal; another sheep becomes the furthest individual. As a result, the sheepdog is moving again on the left and right. During their migration, by sandwiching from the left and right sides of the flock at the same time, overshoots do not occur, and a flock of sheep ($T=52.0$ (s)) that has spread to the left and right can be quickly converged ($T=270.3$ (s)).

From the above, it was confirmed that the proposed method surrounded the flock of sheep in the process predicted in Fig. 4.

4.1 Relationship between repulsion interaction and efficiency (the success rate and the guidance time)

Next, the performance of the proposed method will be clarified by quantitative comparison. First, the evaluation method used here defines the success rate Es and the guidance time Et . The following measures are introduced to quantify, which are based on previous studies.

- Number of successful inductions Es (times): Within 500 seconds of starting the simulation, the center of the

**Fig. 9** The example of trajectories of $N=100$, $D=2$

Sheep agent resides in the target region and the Sheep agent fits on a circle of radius 10.

- Induction time Et (sec): The number of seconds from the start of the simulation to the completion of guidance.

Next, we conducted an experiment on the effect of the repulsive interaction between sheepdog agents on guidance performance. While measuring these evaluation criteria, the repulsive interaction gain K_{f4} between sheepdogs was changed from 0 to 7000 every 1000. The number of sheep was $N = 1000$, and the number of sheepdog agents was $D = 1$ to $D = 20$. The results are shown in Fig. 10 for Es and Fig. 11 for Et .

The x -axis is the magnitude of the repulsive interaction among sheepdogs. These lines represent the differences in the number of sheepdogs. Looking at the x -axis of Fig. 10, when $K_{f4}=0$, the guidance almost failed no matter how many sheepdogs were increased. From this, we can say that the guidance was not successful without the repulsive interaction between the sheepdog agents. On the other hand, if K_{f4} is 1000 or more, the success rate Es improves sharply if there are multiple sheepdogs, and the success rate becomes almost 100%. However, as K_{f4} became larger than 5000, the guidance failed gradually in the system with 2 sheepdogs ($D = 2$). The reason for this degradation is because it is difficult to get close to the sheep by the too much repulsive interaction between the sheepdogs. In addition, from Fig. 11,

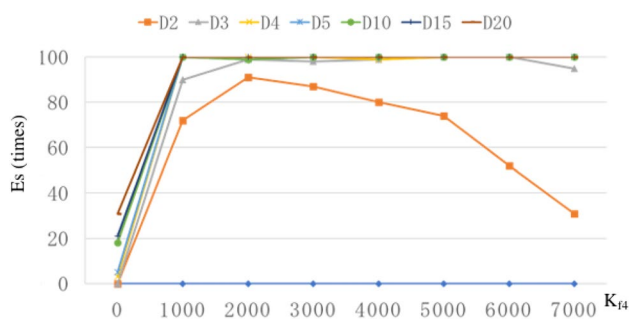


Fig. 10 Repulsion interaction and the success rate

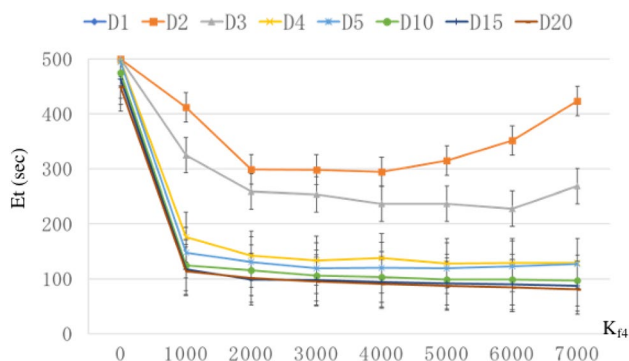


Fig. 11 Repulsion interaction and the guidance time

we found that the time to guide the sheep becomes shorter as the repulsive interaction between the sheepdog agents increases, and the time becomes quicker as the number of sheepdog agents increases.

From the above, it is found that by the coefficient of restitution between sheepdogs, it is possible to efficiently guide a herd that cannot be induced by a single sheepdog system. In addition, since the guidance time improves as the number of sheepdogs increases, we can say that the geographical division of roles can be realized by the coefficient of restitution K_{f4} within the range of the number of sheepdogs. That is, the increase in resources related to guide a flock is reflected in the guidance time.

4.2 More difficult tasks to guide

Here, we will examine the guidance of the herd in more difficult situations. When guiding sheep with an actual sheepdog, it seems that humans set up an advantageous situation before guiding the sheep. Also, in the conventional research [16], in the situation where the sheep are scattered, first, the sheepdog gathers the sheep into a flock, and then, the guidance to the goal is performed. On the other hand, the proposed method, which has the property of being able to

effectively utilize multiple sheepdogs, can guide the herd in difficult situations that have been studied in the past.

In the following, three new patterns are used. Figure 12 shows the layout used here. C0 is the arrangement used in the experiment so far, and C1, C2, C3 are the arrangements used below. In each case, the number of sheep is $N=400$. Unlike the C0 setting, the C1 places the flock of sheep on the opposite side of the goal from the sheepdog's perspective. Therefore, as shown in the lower part of Fig. 12, the flock of sheep is divided immediately after the start. Compared to C0, C2 guides larger herds from longer distances. C3 assumes a situation where sheep are scattered over a wide area at the start of guidance.

Figure 13 shows the success rate of guidance of C1, C2, and C3 when the number of sheepdogs was changed. All data are average values obtained by performing at least 100 trials for each parameter. The horizontal axis is the number of sheepdogs D , and the vertical axis is the guidance success rate Es . From the experiment, it is found that guidance was difficult in the order of C1, C2, and C3. It also is found that in a single sheepdog system, the guidances failed 100% in all cases. On the other hand, it is found that a significant improvement can be achieved by increasing the number of sheepdogs. In C1, it was difficult to guide with two sheepdogs, but it is about 76% successful with three sheepdogs. In C2, about 80% of 5 sheepdogs were successfully guided. In C3, it is difficult to guide with 4 sheepdogs, but the success rate improved as the number increased, it successes about 84% with 80 dogs. In this way, it is found that the “resources” could be utilized within this range for the increase in sheepdogs using the proposed method.

Figure 14 shows the success rate of induction of C1, C2, and C3 when the repulsive interaction was changed, while the number of sheepdogs remained constant. Experiments were conducted on the number of sheepdogs $D = 2, 3$ for C1, the number of sheepdogs $D = 3$ for C2, and the number of sheepdogs $D = 20$ for C3. As can be seen from the results of C1 and $D = 2$, if the number of sheepdogs was too small, the success rate did not improve even if K_{f4} was increased. On the other hand, in the case of $D = 3$ at C1 and $D = 20$ at C3, increasing K_{f4} improved the guidance success rate. Increasing K_{f4} makes the sheepdogs move more quickly, because they behave to keep the distance between the sheepdogs constant. Previous studies have also reported that increasing the speed of movement of sheepdogs improves guidance performance, and it is thought that this tendency is similar.

On the other hand, in the case of C1 and $D = 3$, the induction performance deteriorated when K_{f4} became too large. This deterioration is because the sheepdogs rapidly separate from each other immediately after the start of guidance, and the flock of sheep is divided into smaller multiple flocks. As Fig. 15, in the initial state, there are sheepdogs between the sheep and the goal, and in the process of reaching the siege

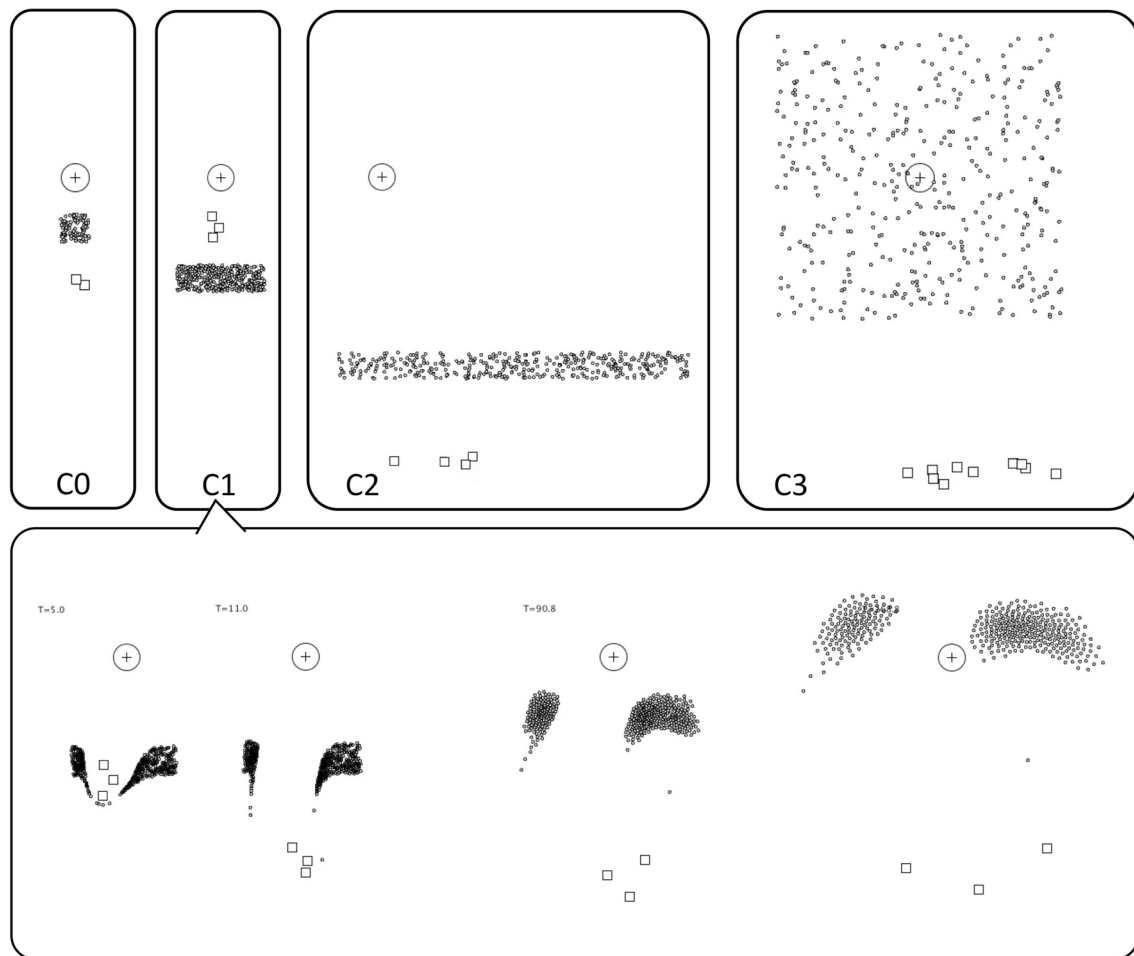


Fig. 12 More difficult tasks to guide (arrangements: C1,C2,C3)

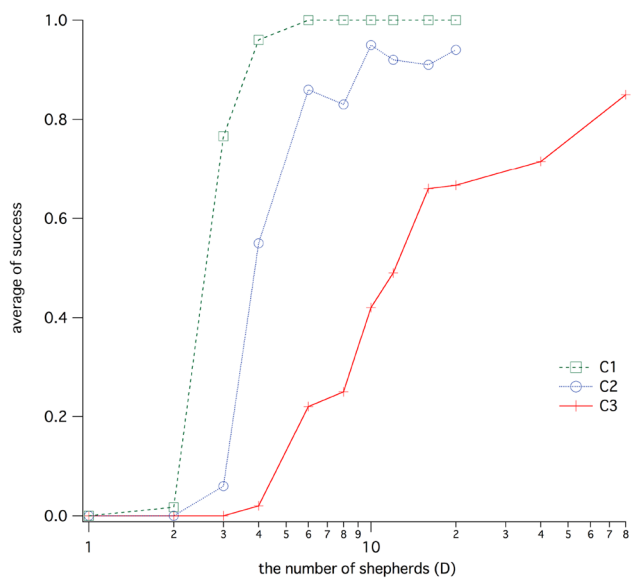


Fig. 13 The number of sheepdogs and the success rate in arrangements, C1,C2,C3

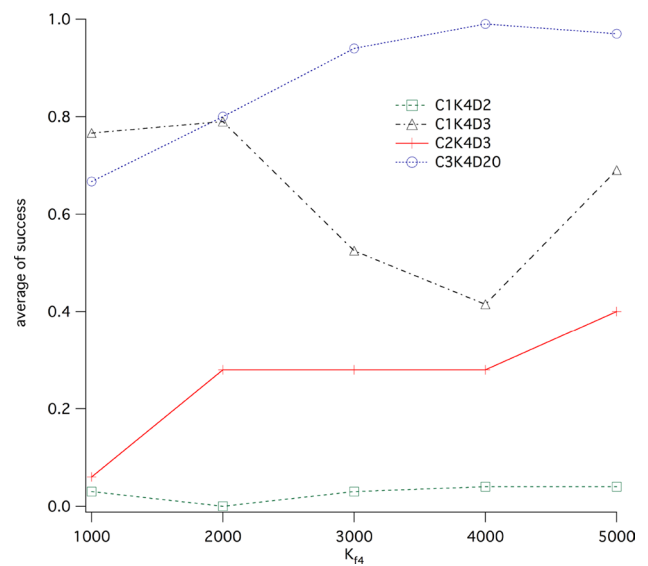


Fig. 14 Repulsive interaction and the success rate in arrangements, C1,C2,C3

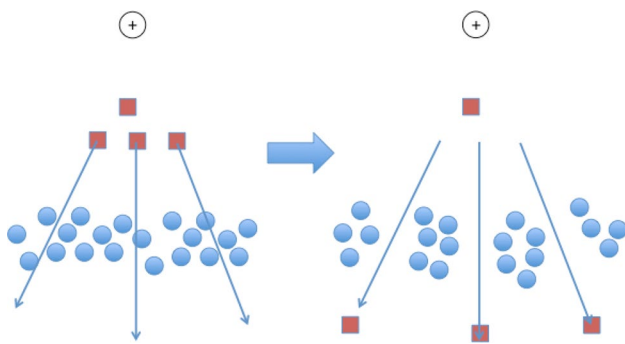


Fig. 15 Sheepdog agents with a larger K_{f4} change a flock of sheep into smaller pieces in C1

state, the sheepdogs pass among the flocks of sheep. This action breaks up the flock into smaller flocks.

To summarize these experimental results, if the sheep are surrounded by the sheepdogs, the more sheepdogs there are, the more stable the guidance will be. Also, the higher the value of K_{f4} , the more agile the sheepdog is and the faster it can be guided. However, if the K_{f4} value is too high, the dogs tend to keep their distance from each other, which leads them not to guide their sheep. As a result, it may cause the sheep to be separated from the flock, which may lead to slow guidance. However, since the tendency is mild, it is easy to set the parameters.

From the above, if the repulsive interaction between the sheepdogs is not so strong that it becomes difficult for the sheepdogs to approach the sheep, as shown in Fig. 10, this will contribute to the improvement of the guidance performance.

5 Conclusion

In this paper, we proposed a method in which multiple sheepdog agents autonomously cooperate to efficiently guide a large number of sheep agents by introducing a repulsive interaction between sheepdogs. In addition, its characteristics were verified in basic theoretical analysis and computer experiments.

We investigated the stability of the guidance completion state of the proposed system consisting of a small number of sheepdogs and it is found that there was a stable state for Lyapunov stability. In addition, from the results of computer experiments, it is possible to guide quickly and reliably by increasing the number of the proposed sheepdogs.

This study can be considered as investigating the effect of inter-dog repulsion of the conventional sheepdog algorithm. The results show that (1) The proposed model with repulsion interaction can promote a better geographic role assignment to the sheepdogs. Consequently, they form a circle

formation, and it improves their guidance performance better. (2) The proposed model can represent “sheepdog behavior” by a single sheepdog and circle formation of multiple sheepdogs. Therefore, this work gives an alternative insight that “sheepdog behavior” is a kind of circle formation. We think that these two points are our contributions to the fields of Swarm Intelligence and Swarm Robotics community.

Induction with multiple sheepdogs is expected to create new challenges that did not arise with a single dog. What we found in this study is that as the number of sheepdogs increases, the destruction of the sheep flock unwillingly occurs. One of the future challenges is to deal with such an event by devising a detailed guidance method based on the distribution of sheep.

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