Robustness of Herding Algorithm with a Single Shepherd Regarding Agents’ Moving Speeds

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Abstract The shepherding problem is to control and guide a flock of multiple autonomous agents by means of one or more external controllable agents. A critical example is a sheepdog/shepherd guiding a flock of sheep/agents and herding them to a target destination. Solving this problem is expected to lead to the development of robots for herding livestock and for guiding people who need evacuation. Strömbom et al. modeled a shepherd’s behavior mathematically, in which a single shepherd can herd a flock of agents to a target. They evaluated the performance of the herding algorithm (HA) with a constant difference between the shepherd’s and agents’ moving speeds. In this study, we evaluate simulated HA proposed by Strömbom et al. for various differences between the shepherd’s and agents’ moving speeds caused by the agents’ stride length and analyze the robustness of this algorithm regarding the agents’ moving speeds. The experimental results show that the success of herding is mostly guaranteed when the moving speeds of all the agents in the flock are lower than the shepherd’s moving speed. Also, the results show that the herding succeeds even if the flock consists of agents having various moving speeds. From these results, we have clarified that HA with a single shepherd is mostly robust regarding agents’ moving speeds.

Keywords: shepherding problem, multiagent system, flock control, herding algorithm, robustness

1. Introduction

The shepherding problem is to control and guide a flock of multiple autonomous agents by means of one or more external controllable agents. A critical example can be easily found in agriculture or husbandry, where a sheepdog guides a flock of sheep and herds them to a target destination. By solving the shepherding problem, we can expect its applicability in the real world. Many attempts to develop applications have been made, including crowd control, developing robots for herding livestock and for guiding people who need evacuation [1], and developing multiple robots to prevent marine oil spills from spreading when cleaning up after a spill [2]. Many studies have proposed various approaches to solve the shepherding problem. To guide a flock of agents toward a target destination, approaches using not only a single shepherd [3], [4], [5], [6] but also multiple shepherds have been proposed [7], [8].

In the real world, a single sheepdog/shepherd gathers a flock of sheep/agents and guides them to a target destination by herding. The response of a flock of sheep to a sheepdog is a classic example of the selfish herd theory proposed by Hamilton [9], which posits that aggregation in a flock results from each individual action to reduce its own predation risk by moving towards the center of a group. King et al. investigated the behavior of sheep (46 merino sheep) under threat from a sheepdog (an Australian Kelpie) in an empirical experiment using a global positioning system (GPS) [10]. Strömbom et al. modeled a shepherd’s behavior mathematically in 2014 [6]. In their model, a single shepherd adaptively switches between two behaviors (‘collecting’ and ‘driving’) to herd a flock of...
agents toward a target. In this paper, we call this algorithm proposed by Strömöm et al. the ‘herding algorithm’ (HA). Strömöm et al. also compared and evaluated their model against the empirical data obtained in [10]. They evaluated the performance of HA with a constant difference between the shepherd’s and agents’ moving speeds by computational simulation. However, they did not investigate the performance for various differences between the shepherd’s and agents’ moving speeds caused by the agents’ stride length.

In this study, since it is unrealistic to expect a constant difference in moving speeds because of differences in the stride lengths of sheep caused by differences in the size of actual sheep, we evaluated simulated HA for various differences between the shepherd’s and agents’ moving speeds caused by the agents’ stride length. We also assumed that there are various differences in moving speeds between swarm-like behavioral agents and that an autonomously controlled vehicle robot or quadruped walking robot will be developed for application in the real world, such as for crowd control, for herding livestock, for guiding people who need evacuation and any other applications. We performed simulations under two conditions: (I) all agents in a flock have the same moving speed, and (II) each agent in a flock has a different moving speed. In experiment (I), we investigated the success rate of HA and the average number of time steps required to complete the herding task. In the other experiment (experiment (II)), we investigated whether a flock consisting of agents having various moving speeds influences the success of herding. From the results of the simulations, we clarified the robustness of HA regarding agents’ moving speeds for the case of a single shepherd with adaptive switching behaviors herding a flock of agents.

2. Overview of Herding Algorithm

HA is a procedure in which a single shepherd with adaptive switching behaviors herds a flock of agents toward a target destination. This algorithm was proposed by Strömöm et al. in 2014 [6]. The shepherd and agents determine each behavior and change each position in each time step by interacting with each other. We describe the rules of the agents’ motion and the shepherd’s motion below.

2.1 Rules of agents’ motion

If an agent is further away from the shepherd than the shepherd detection distance $r_s$, the agent grazes. That is, the agent does not interact with the shepherd and typically remains stationary except for occasional random movements. If an agent is within distance $r_s$ from the shepherd, the agent interacts with the shepherd and other agents, and two forces are generated, $\hat{R}^a$ and $\hat{C}$. Figure 1 illustrates the rules governing the agents in the case that the shepherd is within the shepherd detection distance $r_s$. $\hat{R}^a$ is the repulsion force corresponding to an agent trying to move away from the shepherd. $\hat{C}$ is the attraction force of an agent to the local center of mass (LCM) of its $n$ nearest neighbors. This attractive behavior is caused by each agent attempting to escape from the potential predator by mitigating the predation risk, which is typical for sheep and many other collective animals [9]. In addition, an agent is repelled away from other agents that are within a very short distance $r_a$, which generates a local repulsion $\hat{R}^a$ regardless of the distance from the shepherd. The new movement direction of agent $i$, $\hat{H}_i'$, is determined by a linear combination of these three (normalized) vectors weighted by the corresponding parameters $\rho_s$, $\rho_a$, $c$ and $\rho_a$ plus an inertia term $h \cdot \hat{H}_i$ and an error term $e \cdot \hat{e}_i$, which can be described as follows:

$$\hat{H}_i' = h \cdot \hat{H}_i + \rho_s \cdot \hat{R}^a_i + c \cdot \hat{C}_i + \rho_a \cdot \hat{R}^a_i + e \cdot \hat{e}_i \quad (1)$$

where $h$ is the weight for the inertia term, $\hat{H}_i$ is the
(normalized) vector moved by agent $i$ in the previous
time step, $e$ is the weight for the error and $\tilde{e}_i$ is the
random component of the (normalized) force of agent
$i$ generated by the interactions of agents.

$\vec{H}'_i$ is normalized and the displacement of the agent
$i$ in each time step is determined using the agent’s
moving speed $\delta$ as a parameter. That is, agent $i$’s
new position at time step $t + 1$, $\vec{A}_i(t + 1)$, is given by

$$\vec{A}_i(t + 1) = \vec{A}_i(t) + \delta \cdot \vec{H}'_i(t) \quad (2)$$

where $\vec{A}_i(t)$ is agent $i$’s position at time step $t$ and
$\vec{H}'_i(t)$ is the normalized $\vec{H}'_i$ at time step $t$.

2.2 Rules of shepherd’s motion

Figure 2 illustrates the rules of the shepherd’s in-
teraction. Depending on the distance $d_f$ between the
global center of mass (GCM) and the agent furthest
from the GCM at position $A_f$, the shepherd switches
between two actions, which are collecting and driving
to herd the flock of agents to a target destination. The
shepherd switches between the two behaviors during
the herding task so that the shepherd’s motion appears
as side-to-side motion behind the flock of agents
to make the flock cohesive. The side-to-side motion is
not coded/programmed especially in the shepherd’s
behavior.

Collecting is the behavior performed by the shep-
herd to bring back the agent furthest from the GCM
at position $A_f$ to make the flock cohesive in the case of
$d_f > f(N)$, where $f(N) = r_a \cdot \sqrt{N}$, $r_a$ is the agent-to-
agent interaction distance and $N$ is the total number
of agents. The shepherd moves in a straight line to-
ward point $P_c$ in collecting, where $P_c$ is the collecting
position, which is $r_a$ [m] behind the furthest agent.

Driving is the behavior performed by the shep-
herd to guide a sufficiently cohesive flock to a tar-
get destination in the case of $d_f \leq f(N)$, where
$f(N) = r_a \cdot \sqrt{N}$. The shepherd moves in a straight
line toward point $P_d$ in driving, where $P_d$ is the driving
position, which is $r_a \cdot \sqrt{N}$ behind the GCM.

The shepherd’s moving speed $\delta$ is set to zero if
there is at least one agent within $3r_a$ from the shep-
herd. This is because the shepherd rarely approaches
the flock of sheep at close range in real herding. The
shepherd is subjected to the same noise as the agent
$e \cdot \tilde{e}$.

3. Experimental Conditions

We implemented HA as the multiagent system
(MAS) and simulated HA to analyze its robustness re-
garding agents’ moving speeds. $N$ agents are placed at
random positions in the upper right quarter of an $L \times L$
square field and a single shepherd is placed in the cen-
ter of the lower left quarter, where $L = 150$ [m]. The
square is not enclosed, meaning that the agents and
the shepherd may leave the square during the herding
task. The target destination is set in the lower
left corner of the field. The shepherd and the agents
interact with each other according to their behavior
rules in each time step, and the shepherd herds a flock
of agents to the target destination. The simulation is
terminated when the GCM of the flock reaches the tar-
get destination within 8,000 time steps or 8,000 time
steps have elapsed. If the GCM of the flock reaches the
target destination within 8,000 time steps, the herd-
ing succeeds, otherwise it fails. The parameter values
are shown in Table 1.

Figure 3 shows the shepherd’s and agents’ trajecto-
ries throughout a herding simulation when all agents
of the flock have the same moving speed. The pa-
rameters are the typical values listed in Table 1 ex-
cept for $N = 32$ and $\delta = 1.0$. Green dots show the

Table 1 Parameter values used in the experiments

| Parameter | Description | Values |
|-----------|-------------|--------|
| $N$       | total number of agents | 1, 2, 3, ..., 64 [agents] |
| $n$       | number of nearest neighbors | 0.7 · $N$ [agents] |
| $r_a$     | shepherd detection distance | 65 [m] |
| $r_s$     | agent-to-agent interaction distance | 2 [m] |
| $\rho_s$  | relative strength of repulsion from shepherd | 1 |
| $\rho_a$  | relative strength of attraction to LCM of $n$ nearest neighbors | 1.05 |
| $h$       | relative strength of repulsion from other agents | 2 |
| $\epsilon$ | relative strength of motion in the previous direction | 0.5 |
| $e$       | relative strength of angular noise | 0.3 |
| $\delta$  | agent displacement per time step, i.e., agent’s moving speed | 0.1, 0.2, 0.3, ..., 3.0 [m/ts] |
| $p$       | probability of moving per time step while grazing | 0.05 |
| Shepherd parameters | | |
| $\delta_s$ | shepherd displacement per time step | $1.5$ [m/ts] |
| $P_d$     | driving position | $r_a \cdot \sqrt{N}$ [m] behind flock (GCM) |
| $P_c$     | collecting position | $r_a$ [m] behind furthest agent |
| $e$       | relative strength of angular noise | 0.3 |
agents’ starting and end positions, and their trajectories throughout the simulation are shown by thin gray lines. The blue asterisk is the shepherd’s starting position. The blue dotted line shows the shepherd’s trajectory during collecting, the red dotted line shows that during driving and the black dotted line shows that during the stationary condition because of a short distance to at least one of the agents.

To investigate the performance of HA in the cases of various differences between a single shepherd’s and agents’ moving speeds caused by the agents’ stride length, we changed the agents’ moving speeds while keeping the shepherd’s moving speed constant. In the study of Strömbo et al., they investigated the performance of HA in which agents have a time-invariant moving speed. Therefore, to investigate the performance of HA when changing the agents’ moving speed caused by the differences in the agents’ stride length, the experimental conditions in this study should be equalized by excluding the parameter regarding the agents’ moving speeds \( \delta \). For these reasons, in this study, we performed two experiments assuming that the stride length of the agent for a given moving speed is time-invariant. However, since the moving speed of actual sheep is considered to be time-variant, we plan to investigate the performance of HA for the case of agents whose behavior is closer to that of actual sheep in further research.

We performed two simulation experiments for the cases that all agents of the flock have the same moving speed, and for the cases that each agent of the flock has a different moving speed. We describe the detail of the two experiments below.

### 3.1 Experiment (I): Cases that all agents have the same moving speed

We investigated the success rate of HA and the average number of time steps for the herding task to be completed in the cases of \( N \in [1, 64] \) agents while changing the moving speed of all agents \( \delta \) gradually as \( \delta = \{0.1, 0.2, 0.3, \ldots, 3.0\} \text{[m/ts]} \), where all agents have the same moving speed and the speed of the shepherd \( \delta_s \) is constant (\( \delta_s = 1.5 \text{[m/ts]} \)). In this experiment, we attempted to clarify the limits of the agents’ moving speed for which a single shepherd can herd a flock of agents having the same moving speed, such as a swarm of vehicle robots [11]. We performed the experiment 50 times under each condition.

### 3.2 Experiment (II): Cases that each agent has a different moving speed

We investigated whether a flock consisting of agents having various moving speeds influences the success of herding. The moving speed of each agent \( i, \delta_i \), was determined by a random number generated by a truncated normal distribution with the domain \([\mu - 3\sigma, \mu + 3\sigma]\), \( \mu = 1.0 \) and \( \sigma = \{0.05, 0.10, 0.15, 0.20, 0.25, 0.3\} \). Thus, we implemented conditions where there are many agents whose

![Side-to-side motion](image)

Fig. 3  Simulation of herding trajectories with \( N = 32, n = 22, \delta = 1.0 \) when all agents of a flock have the same moving speed: Green dots are agents’ starting and end positions and thin gray lines show the agents’ trajectories throughout the herding simulation. The blue asterisk is the shepherd’s starting position. The blue dotted line shows the shepherd’s trajectory during collecting, the red dotted line shows that during driving and the black dotted line shows that during the stationary condition because of a short distance to at least one of the agents. Especially in the shepherd’s behavior. From the shepherd’s trajectory, it was found that the shepherd adaptively switches between the two behaviors to solve the shepherding problem in HA.
moving speeds are close to $\mu$ while there are a few agents whose moving speeds have a large difference from $\mu$. Determination of the moving speed of each agent according to the truncated normal distribution is based on the assumptions that the size of sheep is not uniform, with many sheep of average size, and that the stride length of agents has a fixed relation with their moving speeds. By changing the standard deviation $\sigma$ of the moving speeds of the agents, it is possible to determine the maximum and minimum values that the agents’ moving speeds can take. In this experiment, we attempted to clarify the performance of HA in the cases that the agents in a flock have various different moving speeds for application in the real world, for instance, for crowd control, herding livestock or guiding people who need evacuation. We performed the experiment 50 times under each condition.

4. Results and Consideration

First, we show the results of the simulations in the cases that all the agents in the flock have the same moving speed.

Figure 4 shows the success rate of HA in the cases that the moving speed of all agents in a flock $\delta$ was changed gradually, where 1.0 is a success and 0.0 is a failure as shown in the right color bar. In the case of $N = 1$, the driving position $P_d$ is set to a position behind the agent relative to the target destination for herding. The herding is successful when the agent’s moving speed $\delta$ does not exceed the shepherd’s moving speed $\delta_s$, even if the target, the shepherd and the agent are on the same straight line in the order of target – shepherd – agent, where $P_d$ is also on this straight line. Since $\hat{C}_i$ and $\hat{R}_i^j$ do not appear in Eq. (1) in the case of $N = 1$, the influence of the $e\hat{c}_i$ term on $\hat{R}_i^j$ is relatively large. Therefore, the shepherd can run around behind the agent relative to the target destination for herding due to random movements of the agent and the shepherd caused by the error terms of the agent and the shepherd and the random movement during the agent’s grazing.

In the case of $N = 2$, the herding does not succeed regardless of the agents’ moving speed. Since the agents try to get away linearly from the shepherd and the shepherd approaches them from the side of the target destination for herding, the following phenomenon occurs: the target, the shepherd, one of the two agents, the GCM and the other agent lie on the same straight line in the order target – shepherd – one agent – GCM – other agent. Because all these points lie on the same straight line, both $P_c$ and $P_d$ are also on this straight line. The shepherd needs to run around behind the two agents relative to the target so that the herding in HA succeeds. However, the shepherd is not able to escape from this straight line because both $P_c$ and $P_d$ lie on the straight line and the shepherd must go directly toward $P_c$ or $P_d$. Therefore, the shepherd cannot run around behind the two agents. For this reason, the herding in HA fails in the case of $N = 2$ regardless of the agents’ moving speed.

If $0.6 \leq \delta \leq 1.8$ ($N = 3$) and $0.1 \leq \delta \leq 1.7$ ($4 \leq N \leq 64$), the success rate of HA is approximately 1.0. In particular, we confirmed that the region with a high success rate even extends to above the black solid line which shows the shepherd’s moving speed $\delta_s$ in Fig. 4. This means that the shepherd can herd the flock even when $\delta$ is greater than $\delta_s$.

Figure 5 shows the average number of time steps for the herding task to be completed in the cases that the moving speed of all agents in a flock $\delta$ was changed gradually. The color in the right color bar means the number of time steps when the herding task was completed. We confirmed that the agents’ moving speed
Fig. 6 Scatter plot showing the success and failure of herding, where the horizontal axis is the number of agents, the vertical axis is the difference between the mean and minimum moving speeds in the flock and \( N \in [2, 64] \): The upper of the two black solid lines indicates a difference between the mean and minimum moving speeds in the flock of 0.4, and the lower line indicates a difference of 0.2.

\( \delta \) for which the herding task was completed in fewest time steps is approximately 1.0 since the color near to \( \delta = 1.0 \) is dark blue, that is, the average number of time steps required for success is small. If \( \delta \) exceeds \( \delta_s \), it takes at least approximately 1,500 time steps even if the herding in HA is successful. If \( \delta \) is lower than 0.3, it takes a comparatively large number of time steps (approximately 2,000 to 4,000) for success. When \( \delta \) is too small, the shepherd approaches agents immediately and then its speed \( \delta_s \) becomes zero for many time steps. Therefore, it takes more time steps until the herding task is completed.

Next, we show the results of the experiment in which each agent in the flock has a different moving speed, which are shown in Figs. 6, 7 and 8. The horizontal axis in the three figures is the number of agents \( N \). The vertical axis in the three figures are the difference between the mean and minimum agents’ moving speeds in the flock, the difference between the maximum and mean agents’ moving speeds in the flock, and the difference between the maximum and minimum agents’ moving speeds (range of values) in the flock, respectively. In the three figures, blue circles and red crosses respectively mean success and failure in herding.

In Fig. 6, if the difference between the mean and minimum moving speeds in the flock is less than around 0.4 in the cases of \( N > 20 \), the success of herding by HA is mostly guaranteed. However, the herding may not succeed in the cases of \( N \leq 10 \) even if the difference between the mean and minimum moving speeds in the flock is around 0.2.

Here we describe the reason why the existence of a much slower agent affects the success of the herding. First, the agents move toward the target destination and away from the slowest agent, and the distance between the slowest agent and the other agents increases steadily over time. Therefore, the slowest agent is frequently the agent furthest from the GCM at position \( A_f \), and \( P_c \) is located behind the slowest agent for many time steps. Figure 9 shows the proportion of time steps for which the shepherd performs driving behavior in a herding simulation, where the horizontal axis is the difference between the mean and minimum agents’ moving speeds in the flock and \( N = 32 \). From this scatter plot, the proportion of time steps the shepherd spends driving markedly decreases, and hardly any driving occurs when the difference between the mean and minimum moving speeds of the agents exceeds 0.4. Since the shepherd performs driving when \( d_f \leq f(N) \), where \( d_f \) is the distance between the GCM and the furthest agent from the GCM, and \( f(N) = r_a \sqrt{N} \), in the case that hardly any driving occurs due to the existence of a much slower agent, we
can see that the distance between the slowest agent in a flock and the GCM is larger than $f(N)$ in most time steps. In other words, the shepherd can perform hardly any driving because the slowest agent cannot catch up with the other agents within a distance of $f(N)$ when the difference between the mean and minimum moving speeds of the agents exceeds 0.4. Also, it is very difficult for the shepherd to take a flock of agents to the target destination without ‘driving’ behavior. Thus, it is impossible for the shepherd to herd a flock toward a target destination when the difference between the mean and minimum moving speeds of the agents is larger than 0.4. Figure 10 shows the moving speed of the GCM in each time step and the moving speed of the slowest agent when $N = 32$. The upper figure shows a case of successful herding and the lower one shows a case of unsuccessful herding. In both figures, the blue lines denote $v_{GCM}$ and the red lines denote $\delta_{min}$ in both figures.

with the other agents and the shepherd can herd the flock to a target destination since it can perform driving because of a shorter distance between the slowest agent and the GCM. On the other hand, in the unsuccessful herding, the slowest agent cannot catch up because there are many time steps in which $v_{GCM}$ is larger than $\delta_{min} = 0.6098$. For these reasons from Figs.9 and 10, the existence of a much slower agent affects the success of the herding.

In Fig.7 in the cases of $N > 4$, herding sometimes fails when the deviation of the mean moving speed
from the maximum moving speed is approximately 0.2; however, in other simulations, herding sometimes succeeds even when the deviation is approximately 0.7. From the results, we have considered that successful herding is not strongly influenced by the difference between the maximum and mean agents’ moving speeds in the flock.

From Fig.8, if the range of the agents’ moving speeds in the flock is less than approximately 0.6 and $N > 10$, the herding in HA with a single shepherd mostly succeeds. If the range of the agents’ moving speeds in the flock is larger than approximately 0.6, the herding may not succeed.

From these results shown by Figs.6, 7 and 8, we have confirmed that the herding in HA with a single shepherd will succeed for a flock with a small variation of agents’ moving speeds. Furthermore, we have confirmed that the success of herding in HA with a single shepherd is notably influenced by the existence of an agent with a much lower speed than the average moving speed in the flock rather than an agent with a much higher speed.

5. Conclusions

In this study, we have simulated HA proposed by Strömbo et al. [6] for various differences between a single shepherd’s and agents’ moving speeds caused by the agents’ stride length.

First, we simulated the case of a single shepherd herding a flock in which the agents have the same moving speed. In this experiment, we confirmed that the success of herding is mostly guaranteed when the moving speed $\delta$ of all the agents in the flock is lower than the shepherd’s moving speed $\delta_s$. In the case of $N = 1$, the herding is successful if $\delta$ does not exceed $\delta_s$. In the case of $N = 2$, the herding does not succeed regardless of $\delta$. If $0.6 \leq \delta \leq 1.8$ ($N = 3$) and $0.1 \leq \delta \leq 1.7$ ($4 \leq N \leq 64$), the success rate of HA is approximately 1.0. We also confirmed that the herding succeeds even if $\delta$ is slightly higher than $\delta_s$.

Furthermore, we confirmed that the herding succeeds even if the flock consists of agents having various moving speeds. For these cases, we also confirmed that the success of herding in HA with a single shepherd is markedly influenced by the existence of an agent with a much lower speed than the average moving speed rather than an agent with a much higher speed.

From these results, we clarified that HA is mostly robust regarding agents’ moving speeds. In addition, we showed one of the indicators regarding agents’ moving speeds required for herding a flock by a single shepherd in HA for application, for instance, to develop an autonomously controlled vehicle robot or a quadruped walking robot for crowd control, herding livestock and guiding people who need evacuation.

In further research, we plan to analyze HA in the cases of multiple shepherds and a huge number of agents.

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