Proceedings of the 2025 SICE Festival with Annual Conference
September 9-12, 2025, Chiang Mai, Thailand

Experimental Verification of Robot Shepherding System for Local-Sensing Based Autonomous Distributed Group Robot

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Abstract: Sheepdog system is a control system in which a small number of controller agents (shepherds) indirectly guide and control a large number of agents (flock of sheep). This system is expected to be applied to the guidance and control of biological groups such as birds and schools of fish, and to wide-area exploration and navigation by an operator-teleoperated swarm robot system at disaster sites. Previous studies on the system have used the navigation control based on positional information via wireless communication. However, as the number of robots increases, the amount of communication increases, resulting in delays in system operation. In addition, control methods that use sound or light to estimate the relative positions of robots are prone to malfunctions due to noise.Therefore, this study aims to develop the sheepdog-type group navigation method for a large group of agents. As a first step, this study develops a local sensing-based navigation system fo sheep robots. Specifically, we developed a sheep robot interacting locally by ultrasonic sensors, and conducted navigation experiments using the existing shepherd controller, farthest-agent targeting control. We successfully navigated the autonomous distributed sheep robot we developed.

Keywords: Swarm robotics, navigation, shepherding, local sensing, sheepdog system

1. INTRODUCTION

Inspired by the shepherding, many researchers have proposed a sheepdog system (shepherding) in which a small number of controller agents (shepherds) indirectly guide and control a large number of agents (flock of sheep)[1]. This system is expected to be applied to navigation and control of biological groups such as a flock of birds or a school of fish, and to wide-area exploration and navigation by an operator-teleoperated swarm robot system at disaster sites. In previous studies on sheepdog-type swarm robot navigation, the location information of all robots is captured by an external PC using a global camera, and the control inputs of all robots are calculated and controlled via wireless communication[2, 3]. However, as the number of robots increases, the amount of communication also increases and delays in system operation occur. There are also methods to control robots by estimating the relative positions of robots using sound [4] or light [5], but they are prone to malfunctions due to noise and are limited to navigation of a small number of robots. Therefore, this study aims to develop a navigation control method for large-scale robot swarms using shepherding. As a first step, this paper describes the development of a local sensing-based sheepdog-type robot swarm guidance system and navigation experiments. Specifically, we develop the sheep robots by estimating their distance using ultrasonic sensors. In addition, the shepherd robot is controlled by the farthest-agent targeting control, which has better navigation performance than the conventional method[6]. We conducted experiments by varying the number of sheep robots while keeping the shepherd controller parameters constant, and verified whether the navigation independent of the number of sheep robots is feasible.

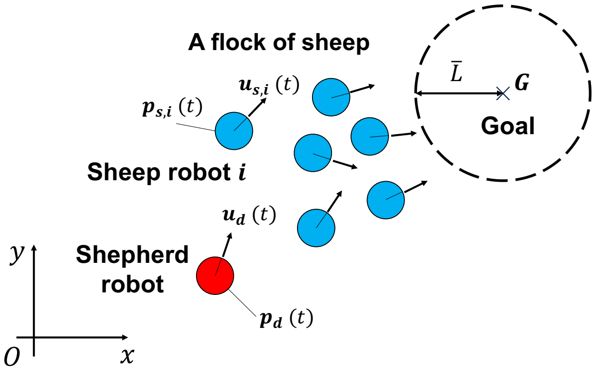

Fig. 1: Description of the navigation problem

2. PROBLEM DESCRIPTION

Fig. 1 shows the problem setup. We consider the navigation of $n \in \mathbb{N}$ sheep robots and one shepherd robot in a 2D plane. The positions of the i-th sheep robot and the shepherd robot are denoted by $\boldsymbol{p}_{s,i}(t)$ and $\boldsymbol{p}_d(t)$, respectively, and the goal center is denoted by $\boldsymbol{G}$. The dynamics of each robot follow first-order differential equations as shown in eq. (1).

$$\dot{\boldsymbol{p}}_{s,i}(t) = \boldsymbol{u}_{s,i}(t), \ \ \dot{\boldsymbol{p}}_d(t) = \boldsymbol{u}_d(t) \tag{1}$$

The control objective is to guide all sheep robots to a circular region centered at $\boldsymbol{G}$ with a radius of $\bar{L}$ as shown in eq. (2).

$$\forall i \ (i = 1, \cdots, n), \ \exists \bar{L} : \lim_{t \to \infty} \|\boldsymbol{p}_{s,i}(t) - \boldsymbol{G}\| \leqq \bar{L} \tag{2}$$

3. ROBOT DEVELOPMENT

Fig. 2 shows an overview of the sheep robot and shepherd robot developed. Furthermore, the 3DCAD models

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[†] Yusuke Tsunoda is the presenter of this paper.

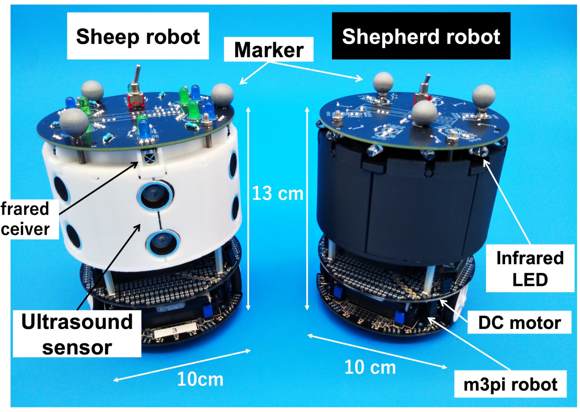


Fig. 2: Developed robots (left: sheep robot, right: shepherd robot)

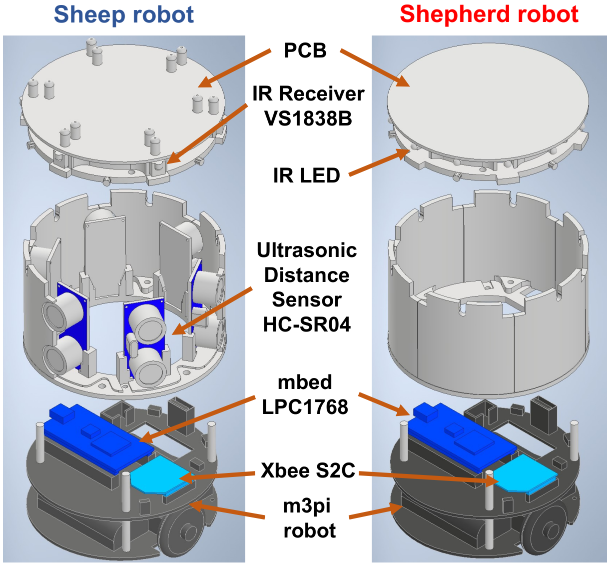


Fig. 3: Images of the 3DCAD model of each robot(left: sheep robot, right: shepherd robot)

of each robot are shown in Fig. 3. The dimensions of the sheep robot and shepherd robot are 13 [cm] in height and 10 [cm] in width. The upper body is equipped with sensors, and the lower body is a m3pi robot (Pololu). The sheep robot is equipped with six ultrasonic sensors (HC-SR04) and infrared sensors (VS1838B) on each side at 60-degree intervals. The shepherd robot is equipped with infrared LEDs on the side to distinguish it from the sheep robot.

3.1. Modeling of the sheep robots

The control of the sheep robot is based on a common swarm model, the Boid model [7]. Fig. 5a shows the interaction model between sheep robots, and Fig. 5b shows the interaction model between sheep robots and shepherd robots. The sheep robot has a circular repulsion, stop, and attraction area centered on itself, and receives attraction and repulsion depending on the distance from the sheep robot within the area. In addition, when the sheep robot receives IR, it escapes from the shepherd robot by repelling it according to the distance between them. As shown in Fig. 4, the unit vectors in the direction of the center of the robot O from the six ultrasonic sensors S_j $(j = 1, \cdots, 6)$ attached to the side of the robot are de-

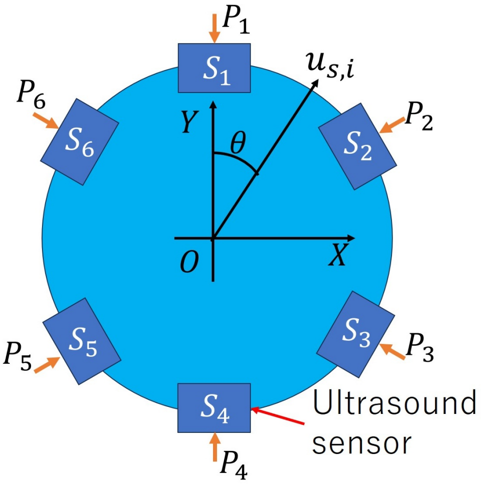
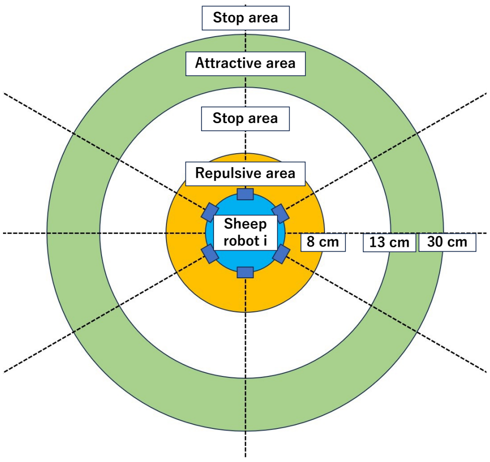
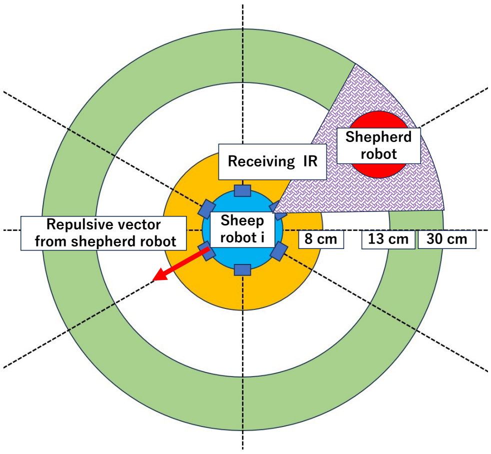


Fig. 4: Unit vectors $\boldsymbol{P}_j$ and $\boldsymbol{u}_{s,i}$ viewed from above the sheep robot



(a) Interaction between sheep robots



(b) Interaction between sheep robot and shepherd robot

Fig. 5: Modeling of the local interaction of the sheep robots based on boids model

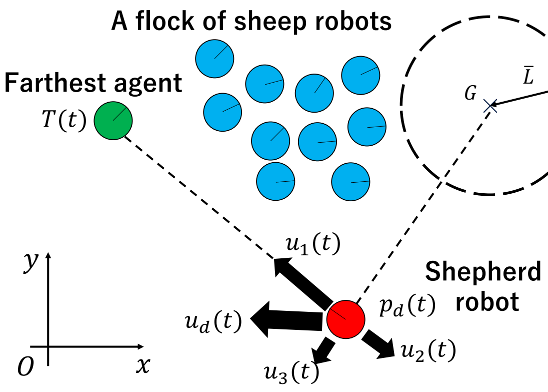


Fig. 6: Farthest-agent targeting control

noted by $\boldsymbol{P}_j$ (eq.(3)), and the magnitude of the interaction vector calculated when the distance d_j [cm] is measured by the sensor S_j is denoted by $D_j(t)$. $D_j(t)$ is calculated as shown in eqs.(4) and (5). The interaction vector is calculated based on the upper equation of eq.(4) when the sheep robot faces the ultrasonic sensor j. On the other hand, when the sheep robot faces the shepherd robot, the interaction vector is calculated based on the lower equation of eq.(5). K_1, K_2, and $K_3 \in \mathbb{R}_+$ are the repulsive and attractive forces between sheep robots, and the repulsive force gain from the shepherd robot, respectively. The robot's velocity input $\boldsymbol{u}_{s,i}(t)$ is calculated from eq.(6). The sheep robot turns and then moves straight ahead by a fixed distance based on the vector $\boldsymbol{u}_{s,i}(t)$.

$$\boldsymbol{P}_j = -[\sin\frac{(j-1)\pi}{3},\ \cos\frac{(j-1)\pi}{3}]^T \tag{3}$$

(a)The sheep robot j doesn't sense IR

$$D_j(t) = \begin{cases} K_1\frac{1}{d_j(t)^3} - K_2\frac{1}{d_j(t)} \\ \qquad (1 \le d_j < 8, 13 < d_j < 30) \\ 0 \qquad (8 \le d_j \le 13, d_j \ge 30) \end{cases} \tag{4}$$

(b)The sheep robot j senses IR

$$D_j(t) = \begin{cases} K_3\frac{1}{d_j(t)^3} & (1 < d_j \le 30) \\ 0 & (d_j > 30) \end{cases} \tag{5}$$

$$\boldsymbol{u}_{s,i}(t) = \sum_{j=1}^{6} D_j(t)\boldsymbol{P}_j \tag{6}$$

3.2. Control strategy of the shepherd robot

We use the farthest-agent targeting control that chases the sheep robot $\boldsymbol{T}(t)$ farthest from the goal $\boldsymbol{G}$ as the control of the shepherd robot [6]. Fig. 6 shows the schematic diagram of the control law of the shepherd robot. The control law for the shepherd robot is shown in eq.(7). K_4, K_5, $K_6 \in \mathbb{R}_+$ are the gain values for the attraction and repulsion to the farthest sheep robot and the repulsion from $\boldsymbol{G}$, respectively.

$$\begin{aligned} \boldsymbol{u_d}(t) =& K_4(-\frac{\boldsymbol{p}_d(t) - \boldsymbol{T}(t)}{\|\boldsymbol{p}_d(t) - \boldsymbol{T}(t)\|}) \\ &+ K_5\frac{\boldsymbol{p}_d(t) - \boldsymbol{T}(t)}{\|\boldsymbol{p}_d(t) - \boldsymbol{T}(t)\|^3} \\ &+ K_6\frac{\boldsymbol{p}_d(t) - \boldsymbol{G}}{\|\boldsymbol{p}_d(t) - \boldsymbol{G}\|} \end{aligned} \tag{7}$$

In this experiment, the control of the shepherd robot is calculated in MATLAB on an external PC based on the positional information of all the robots obtained from the motion capture system (OptiTrack (NaturalPoint Inc.)), and control is input from the parent XBee (Digi Inc.) to the child XBee mounted on the shepherd robot via serial communication. Please note that the sheep robot does not communicate with any external PC and moves based on autonomous distributed control using ultrasonic sensors and IR sensors.

4. NAVIGATION EXPERIMENTS AND RESULTS

A schematic diagram of the experimental system is shown in Fig. 7. We performed the navigation experiment on a 4.4 × 4.9[m] indoor plane. The goal position was set to $\boldsymbol{G} = [-1.0, -1.0]^T$, the initial position of the shepherd robot was set to $\boldsymbol{p}_d(0) = [0.2, 0.2]^T$, and the initial position of the sheep robot $\boldsymbol{p}_{s,i}$ was randomly set in a rectangular area ranging from $[0.5, 0.35]^T$ to $[0.95, 1.10]^T$. The gain values of the sheep robot were set to $K_1 = 0.1, K_2 = 0.001, K_3 = 0.01$, and the gain values of the shepherd robot were set to $K_4 = 0.2, K_5 = 0.02029, K_6 = 0.05$. The gain values of the shepherd robot's controller were designed to satisfy the condition that the induction converges $K_4 > K_6$ [6]. The upper limit of the induction time was set to 900 [s]. Table 1 shows the radius $\bar{L}$ of the goal area in each experiment. We set $\bar{L}$ to vary with the number of sheep robots as $\bar{L} = r_a n^{\frac{3}{2}} = 0.3n^{\frac{3}{2}}$ (r_a is the interaction radius of the sheep robot, $r_a = 0.3$ [m] in this case), following the reference [6]. Under these conditions, we conducted experiments by changing the number of sheep robots to 1, 2, 5, and 10, and performed five experiments for each case.

Fig. 8 shows the snapshots of the navigation experiment for 10 sheep robots. In addition, the trajectories of each robot in the case of the navigation for 10 sheep robots is shown in Fig. 9. In Fig. 9, the shepherd robot moves around the flock of sheep robots and successfully guides them from behind. The probability of successful navigation and the average navigation time for each experiment are shown in Table 2. The success rates of navigation were 100% in all cases, even when the number of sheep robots was increased while keeping the shepherd robot controller gains constant. This suggests that the controller of the shepherd robot is scalable. However, as the number of sheep robots increased, the navigation time increased. This is because as the number of sheep robots increased, the flock became dispersed, and the shepherd robot took longer to guide the flock.

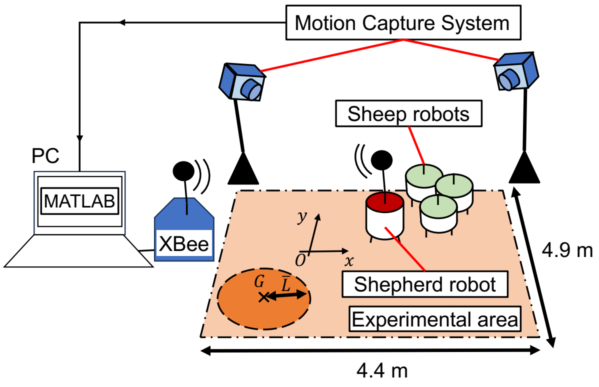


Fig. 7: Experimental environment

Table 1: The value of $\bar{L}$ in each experiment

Number of the sheep robots	1	2	5	10
$\bar{L}$ [m]	0.30	0.48	0.88	1.39

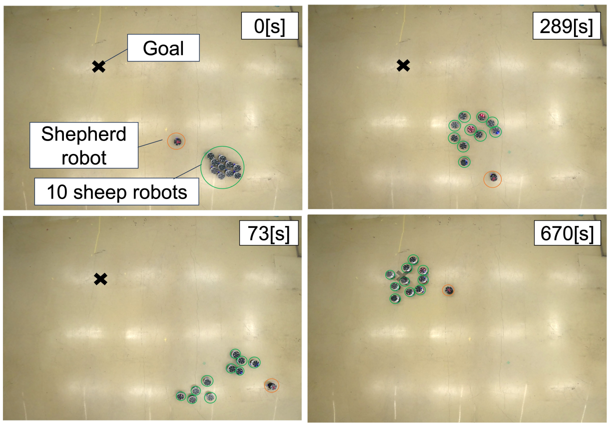


Fig. 8: Snapshots of the navigation for 10 sheep robots

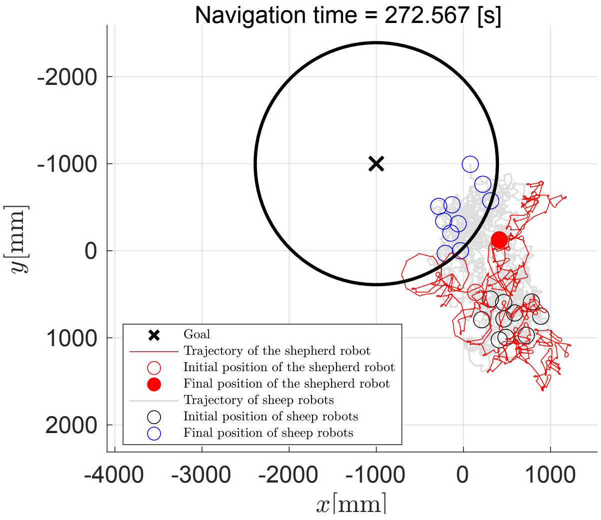


Fig. 9: Trajectories of the shepherd robot and 10 sheep robots during the navigation

5. CONCLUSION

We developed the local-sensing based sheepdog-type group robots navigation system and conducted the navigation experiments. Experimental results show that the shepherd controller can provide scalable navigation with respect to the number of sheep robots. In future work, we will examine the limitations of the scalability of the farthest-agent targeting control. Moreover, we will also desig an autonomous decentralized control of the shepherd robot based on local sensing.

Table 2: Success rate and average of the navigation time by number of the sheep robots

	$n = 1$	$n = 2$	$n = 5$	$n = 10$
Success Rate [%]	100	100	100	100
Time Ave.[s]	163.990	271.500	434.562	334.933

ACKNOWLEDGEMENTS

This research was supported by JSPS KAKENHI Grant Numbers JP22K14277, JP24H01439 and JP25K17629, and JST K Program Grant Number JPMJKP24G4, Japan. The authors express their sincere gratitude for the supports provided.

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