Effect of Grouping in Local Communication System of Multiple Mobile Robots

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Abstract

For the cooperation in a large system with many mobile robots, local communication system is considered appropriate in terms of the cost and capacity of communication. The behavior of robots has a respectable effect on the efficiency of communication in such a local communication system and it is essential to know what kind of behavior robots should take to realize efficient information transmission for cooperative tasks.

We introduce a simple group behavior for the purpose of improving the communication efficiency. This paper analyses the effect of group behavior on the communication performance, and derives differential equations describing information diffusion among robot groups. The optimal group size to transmit information to desired number of robots is obtained from these equations. The effectiveness of the analysis is verified by computer simulation.

We also show a self-organization algorithm for group forming designed for local communication system.

1 Introduction

Recently researches on mobile robots have made remarkable progress and these robots are now expected to perform sophisticated and complicated tasks.

In a large system with many mobile robots, robot will often have to cooperate with many other robots to achieve such tasks as collision avoidance, transportation of heavy objects, or surveillance.

The communication among robots becomes important in order to realize such cooperation. Many researches on this subject are currently being made, which can be classified from the standpoint of the way of information transmission as follows:

(1) Global communication with wide-area media [1]~[4]
(2) Local communication with limited capacity [5],[6]

Global communication (1) works well for a system with about less than ten robots. However, the limit of communication capacity cannot be neglected in case of much greater number of robots and robots might receive too much information to handle if all the local information is propagated globally.

From these reasons, we adopted the local communication (2) which takes the limit of communication capacity into consideration. Robots communicate others within a limited distance from them. This type of communication can be called human-like "from-mouth-to-mouth" communication, and the information is diffused among robots with certain delay.

In such a local communication system, robots' behavior towards the environment and other robots has a great influence on the performance of communication. It is therefore important to know this effect from the viewpoint of efficient transmission of information to desired number of robots. This point is characteristic of local communication system.

Quite a few studies on robot behavior have mentioned the communication among robots [7]∼[12]. Many of these researches dealt with group behavior and showed that by computer simulations it improves the efficiency of such tasks as sample collecting. Since communication is a similar task in that it is collection and transmission of information in place of objects, group behavior is considered to be effective in improvement of communication performance. However, few researches made clear the effect of behavior on communication performance based on mathematical analysis.

In this paper, we will analyze the effect of group behavior on the efficiency of communication. We assume a general environment where events, the sources of information, take place randomly. The information should be transmitted fast and efficiently to necessary robots which treat these events cooperatively. The optimal group size must be known for the efficient information transmission.

As the preparatory step, chapter 2 presents a simple model of local communication and formulates information diffusion using that model.

In chapter 4, we show the model of group behavior in local communication system of multi-robots. The information diffusion process by this behavior is analyzed based on the formulation methodology in chapter 2. The analysis gives the optimal size of group to transmit information to desired number of robots. The effectiveness of the analysis is verified by computer simulation in chapter 4.

In chapter 5, an algorithm for self-organizing group forming using local communication is presented, and the effectiveness this algorithm is shown by simulations.

2 Fundamental Analysis of Local Communication System

In this chapter, we will present a simplified model of local communication system and the formulation of information diffusion. Although his has already been shown in [12], we give the outline since this method of analysis will be extended to that of communication among robot groups in the next chapter.

2.1 Communication Model

In this paper, we employ a simplified model as briefly described below:

Local Communication Information is passed among robots in limited communication area.

Events *Events* take place randomly in the environment and correspond to the sources of information.

Motion of Robots Each robot walks randomly.

"Events" represent faults or emergencies to be detected by surveillance robots, or such tasks as cooperative transportation, which are given at any point of the environment at any time and whose treatment requires cooperation of multiple robots. Mobile robots can detect events in their communication area. The information about an event should be transmitted from the detector robot to necessary number of robots so that the event is duly treated.

As to the robot movement, we have adopted random walking as a fundamental movement which covers relatively wide area.

Time is defined as 0 when an event occurs, and the event remains detectable to robots since then. Information about an event obtained by a robot is spread to other robots by the effect of random walk and local communication (we call this *information diffusion*) as in Fig. 1.

Robots which have already obtained the information are called *I-Robots* (Informed Robots), while robots without information are referred to as *N-Robots*. Variables of the model are as follows, as shown in Fig. 1:

$p(t)$: percentage of I-Robots at time t to all robots in the environment
R, A, ϕ: radius, communication area and visual angle

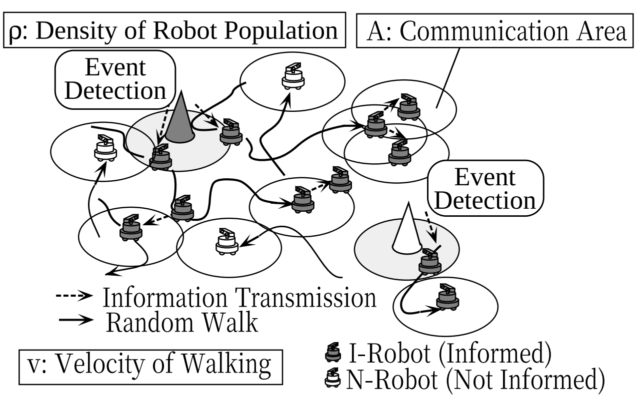


Fig. 1: Information Diffusion by Local Communication

v: velocity of robot walking
ρ: density of robot population
ρ_{event}: density of events

The goal of this section is to represent the percentage of I-Robots $p(t)$ in terms of parameters ρ, v, A and time t in Fig. 1. First, a differential equation of $p(t)$ is derived, and then we show this differential equation can be approximated by logistic function. This analysis allows us to calculate easily the required time so that the information is diffused to certain percentage of robots.

2.2 Equation of Information Diffusion

Robots change their state from N-Robot to I-Robot by obtaining the information. The increment of $p(t)$ per time Δt, $\Delta p(t)$, corresponds to the percentage of these newly generated I-Robots at time t. We define *information acquisition probability* $I(t)$ as the probability that a robot obtains information at time t. $\Delta p(t)$ is proportional to the product of $I(t)$ and the percentage of N-Robots, $1 - p(t)$ as in (1).

$$\Delta p(t) \sim \{1 - p(t)\}\ I(t) \tag{1}$$

The information acquisition probability equals to the probability of that a robot finds at least one robot or directly the event in its communication area. $I(t)$ is computed using Poisson distribution which describes the spatial distribution of randomly walking robots, as

$$I(t) = 1 - e^{-\rho A p(t)}\ e^{-\rho_{event} A} \tag{2}$$

The derivative of $p(t)$ is also considered proportional to the velocity of motion v, so introducing a constant coefficient β, the differential equation of $p(t)$, which we call the *equation of information diffusion*, is derived as

$$\frac{dp(t)}{dt} = \beta v\ \{1 - p(t)\}\ \{1 - e^{-\rho A p(t)}\ e^{-\rho_{event} A}\} \tag{3}$$

2.3 Calculation of Diffusion Time

The equation of information diffusion (3) includes exponential terms, which make it difficult to understand the characteristics of $p(t)$ clearly. A linear approximation is introduced so that we can deal with (3) in a more comprehensible way.

Equation (3) can be rewritten as (4) using linear approximation of exponential function.

$$\frac{dp(t)}{dt} = \{ap(t) + b\}\{1 - p(t)\} \tag{4}$$
$$a = \beta v \rho A, \quad b = \beta v \rho_{event} A$$

Equation (4) is an extended form of *logistic equation*, which is often used for modeling of growth curve or diffusion of infection. Its solution is *logistic function* as follows:

$$p(t) = \frac{1 - C\dfrac{b}{a}e^{-(a+b)t}}{1 + Ce^{-(a+b)t}} \qquad \text{where} \quad C = \frac{1 - p(0)}{p(0) + \dfrac{b}{a}} \tag{5}$$

The derived logistic function (5) allows us to calculate the diffusion time T_w so that the information is diffused up to the percentage w of all robots using (5) as follows:

$$T_w = \frac{1}{a+b} \log \frac{\{1-w\}\{p(0)+\frac{b}{a}\}}{w+\frac{b}{a}(1-p(0))} \tag{6}$$

The validity of this formulation was shown by computer simulation that implemented the information diffusion of randomly walking robots in [12].

3 Formulation of Information Diffusion by Group Behavior

We have analyzed the information diffusion by local communication among robots moving independently and randomly. However, the independent random motion is not very suited for the efficient information transmission and causes some difficulty in going into cooperation phase.

As mentioned in chapter 1, considering simulation results of other researches, group behavior is expected to improve the communication performance. We introduce group behavior to the local communication system of mobile robots for the purpose of transmitting more efficiently the information to necessary robot for event handling.

Group behavior is considered to have such advantages as:

(1) Group of robots can detect events faster by its coordinated motion.
(2) Robots can smoothly go into cooperation phase from event searching.

Nevertheless, it has drawbacks as:

(1) Too large groups may delay the detection of events, thus lower the communication efficiency.
(2) Overlap of communication area reduces the effective communication area in a large group.

Hence it is important to decide the optimal size of group for the information to be passed to desired number of robots in the light of task planning for the efficient cooperation. In this chapter, we will analyze the information diffusion among mobile robots moving based on the introduced group behavior.

The analysis consists of two parts. First, we will formulate the information diffusion among robot groups using the analytical method in chapter 2 by regarding one robot group as one robot. Secondly, the we model how information is transmitted within a group, and derive differential equations of information diffusion. From these differential equations, the optimal group size is obtained.

3.1 Model of Grouping Behavior

A line-up motion is selected among various forms of group behavior in this paper, because it can be easily implemented using only local communication and has an advantage in sweeping a large area for detection of events and other robots.

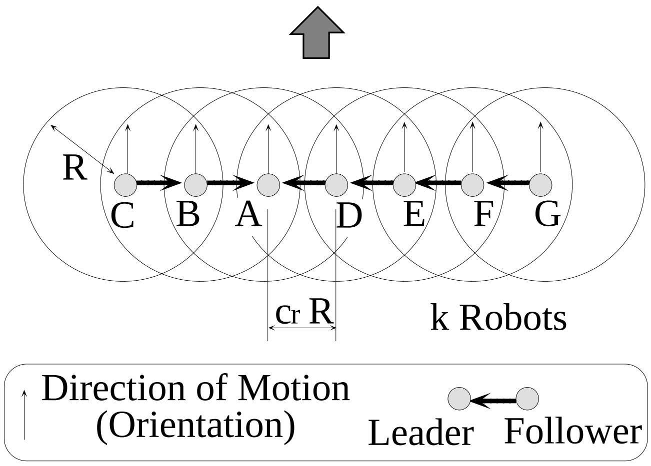


Fig. 2: Model of Group Behavior

We assume that the visible area of robots is 360[deg]. and robots moves straightforward in the environment, for simplicity. The group behavior is illustrated in Fig. 2, and defined as follows:

- Robots move in line formation keeping their orientation vertical to that line. The orientation is equal to the direction of motion (the thin arrows in Fig. 2).
- A robot looks at only one robot on its either side to keep the same orientation (the thick arrows in Fig. 2). We call following and followed robots *followers* and *leaders* respectively. In Fig. 2, Robot B is the follower of A and the leader of C.
- A group is formed by robots connected by this leader-follower relationship. Consequently, there exists only one robot without a leader (Robot A in Fig. 2).
- The size of group is defined as the number of robots k. The relative distance between two adjacent robots is $c_r R$, where c_r ($c_r < 1$) is the ratio of following distance to communication radius R.
- The next position to go to is calculated by linear interpolation from the current relative position and velocity of its leader.
- The size of group k is uniform in the system.

This group behavior should be realized without any central managers. We will discuss a decentralized algorithm for group forming later in section 5.1. The main interest in this chapter resides in the information diffusion by the group behavior. We assume an environment where events occur randomly as in the previous chapter.

3.2 Analysis of Information Diffusion among Groups

The same procedure of analysis in chapter 2 will be applied to lined-up robot groups. The analysis will be proceeded by regarding a group as one robot.

A robot group can be modeled as one robot with communication area which is like a line segment as in Fig. 3. The communication between two robot groups is possible when the two groups overlap.

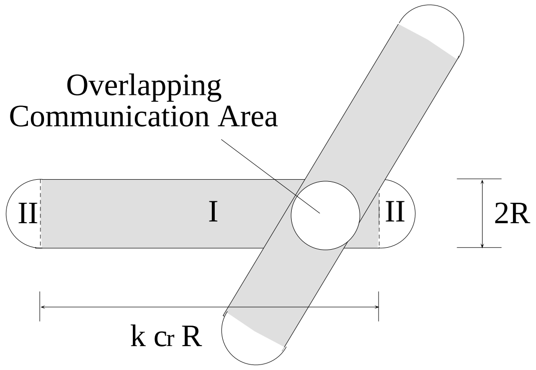


Fig. 3: Communication Area of Robot Groups

The communication area A_g of a robot group can be obtained as the sum of areas I and II in Fig. 3. Area of I is approximated by a rectangle. A_g and the density of robots ρ_g inside the group is calculated as:

$$A_g = R^2(2c_r(k-1)+\pi), \rho_g = \frac{k}{A_g} \tag{7}$$

If $k = 1$, eq. (7) becomes $A_g = A = \pi R^2, \rho_g = 1/A$, which represents the case of independent random motion.

Here groups including at least one I-Robot are called "I-Groups", and in contrast, and "N-Groups" are groups without any I-Robots. $p_g(t)$ is defined as the percentage of I-Groups to all groups in the environment, and this $p_g(t)$ describes how information is diffused among robot groups. Here also $p(t)$ represents the percentage of I-Robots as defined in chapter 2.

In following analysis, we will apply the methodology used in section 2.2 to derive differential equations on $p_g(t)$.

Let us consider the information acquisition probability $I_g(t)$ for robot groups. We define $I_g(t)$ as the probability that at least one robot in the group can obtain the information from other overlapping groups. The overlapping area is considered to equal to the communication area of a robot, namely A, and the density of groups in the environment is ρ/k. Therefore, the average number of robot in the intersection area is computed as:

$$\frac{\rho}{k} A_g \ \rho_g A \ p(t). \tag{8}$$

Replacing the average number of I-Robots in the communication range $\rho A p(t)$ with (8), and A with A_g for

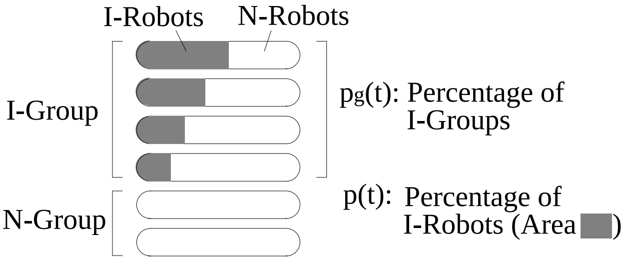


Fig. 4: The Diffusion Process within Robot Groups

event detection respectively in (2) which represents the information acquisition probability of randomly walking robots, we obtain

$$I_g(t) = 1 - e^{-\frac{\rho}{k} A_g \ \rho_g A \ p(t)} \ e^{-\rho_{event} A_g}. \tag{9}$$

And in the same way as in section 2.2, we derive the equation of information diffusion among robot groups by introducing a proportional coefficient β_g as:

$$\frac{dp_g(t)}{dt} = \beta_g v\{1 - p_g(t)\} \ \{1 - e^{-\frac{\rho}{k} A_g \ \rho_g A \ p(t)} \ e^{-\rho_{event} A_g}\} \tag{10}$$

Please note that this is an extended form of equation of information diffusion (3). If we set

$$k = 1, \quad \beta_g = \beta, \quad p_g(t) = p(t),$$

equation (10) is transformed to the same equation as the equation of information diffusion for randomly walking robots (3).

3.3 Analysis of Information Diffusion Within a Group

We will discuss the information diffusion within a group in this section. The index of diffusion $p(t)$ should be derived in such a way that the diffusion within a group is taken into consideration as shown in Fig. 4. Here, $p(t)$ is obviously smaller than $p_g(t)$, and $p(t)$ increases towards the value of $p_g(t)$.

We will model the process of how $p(t)$ varies towards $p_g(t)$. The percentage of N-Robots in the group at time t is given by $1 - p(t)/p_g(t)$.

The average number of robots found in the communication area of each robot is $\rho_g A$ since the density of robot inside a group is ρ_g. As the proportion $\rho_g A/k$ of N-Robots out of $1 - p(t)/p_g(t)$ in a group are supposed to get the information at time t, how $p(t)$ increases is described as

$$\frac{dp(t)}{dt} = p_g(t) \frac{\rho_g A}{k} \left(1 - \frac{p(t)}{p_g(t)}\right). \tag{11}$$

Equations (10) and (11) are the equations that express the information diffusion among robot groups.

Since eqs. (10), (11) are nonlinear simultaneous differential equations, we cannot obtain the analytical solutions. Nevertheless we can compute their numerical solutions by such a method as Runge-Kutta method. Information diffusion process in case of group size $k = 4$

Table 1: Parameters of Robot System

ρ (Density of Robot Population)	0.024
k (Size of Robot Group)	4, 12, 24
v (Velocity of Random Walking)	0.2
ρ_{event} (Density of event)	0.001
R (Radius of Communication Area)	1.0
c_r (Ratio of following distance)	0.8
ϕ (Visual Angle of Communication Area)	360[deg]
β_g (Constant in Equation (10))	0.5

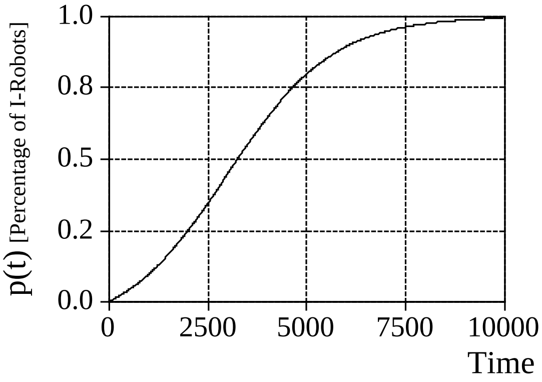


Fig. 5: Information Diffusion by Group Behavior ($k = 4$)

calculated from eqs. (10), (11) is shown in Fig. 5. The parameters for these calculation are given in Table 1.

3.4 Calculation of Diffusion Time and Optimal Group Size

As the purpose of forming group is to transmitting the necessary information to desired robots, we define the optimal group size as that allowing the information to be passed to desired number of robots the fastest. This section will show the analysis about the diffusion time and the optimal group size (Fig. 6).

What we have derived so far is the diffusion process (Graph A in Fig. 6). Except for very congested environments, when the information is transmitted from one group to another, the time required for the information acquisition of the first robot in another group from a group, e.g. the diffusion time between groups T_a, is much greater than that within a group T_b in Fig. 6.

Therefore the graph representing the diffusion time for given robot number looks like Graph B in Fig. 6. Fig. 7 shows calculated diffusion time T_n for given robot number n in cases of different group size k.

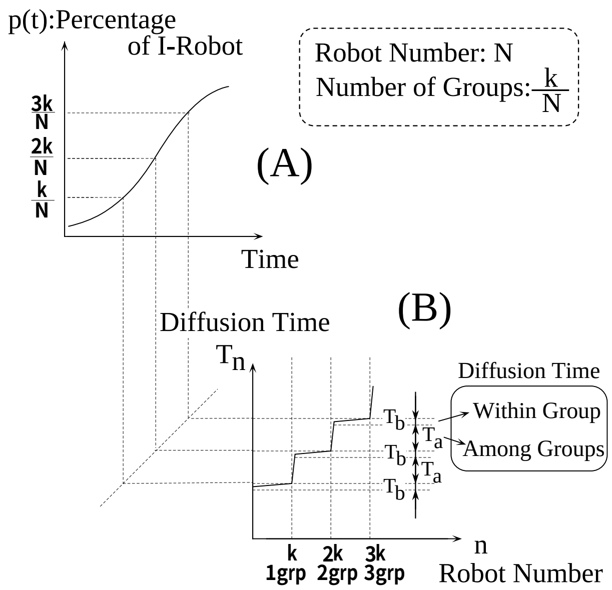


Fig. 6: Calculation of Diffusion Time

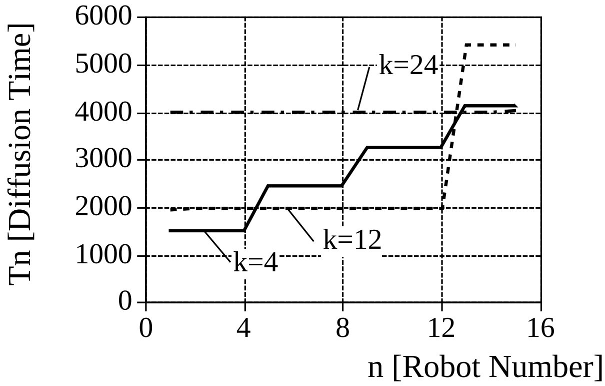


Fig. 7: Calculated Diffusion Time by Group Behavior

In Fig. 7, for example to transmit the information to 4 robots, the diffusion time is the shortest in case of group size $k = 4$. This also holds for other robot numbers.

It can then be concluded that the optimal group size for the fast information transmission to k_e robots equals to k_e, for instance in case where a task requires k_e robots to be executed.

4 Simulation for Verification of Analysis

We implemented robots moving based on the analyzed group behavior in an environment as Fig. 8 and simulated the information diffusion among robots to verify the effectiveness of the analysis.

Groups are supposed to be already formed in the initial state, and the simulation starts when events take place at time 0. The parameters of simulations are the same as those in Table 1.

Twenty simulations have been undertaken and the mean value is used as simulation results. Simulation results are compared with theoretical values about the diffusion process and the optimal group size.

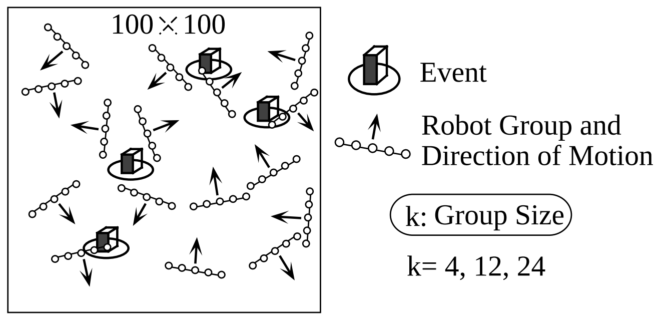


Fig. 8: Simulation environment

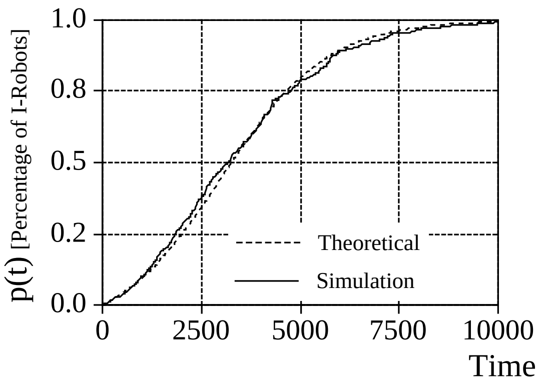


Fig. 9: Simulation Results of Diffusion Process (k=4)

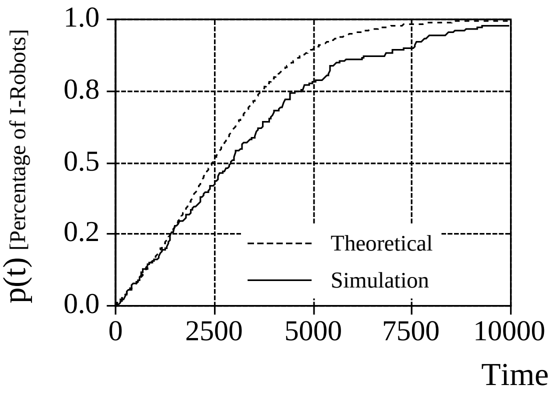


Fig. 10: Simulation Results of Diffusion Process (k=8)

4.1 Verification of Equations of Information Diffusion

Simulation results of diffusion process $p(t)$ are compared with theoretical values obtained using the equations of information diffusion (10) and (11). Figs. 9, 10 show the case of group size $k = 4, 8$ respectively.

Although some modeling error is observed, the theoretical values correspond with the simulation well in different size of groups. These simulation results show that the analytical method in this chapter is effective and that the derived differential equations models precisely the information diffusion of robots with group behavior.

4.2 Verification of Diffusion Time and Optimal Group Size

We will verify the analysis on diffusion time and optimal group size. Simulation results of diffusion time T_n for given robot number n are shown in Fig. 11.

The simulation results in Fig. 11 correspond well with the theoretical values in Fig. 7 in the relationship between robot number n and diffusion time T_n. We can see that group size k_e is optimal to transmit the information to k_e robots the fastest. The effectiveness of the analysis has been validated also on the diffusion time and optimal group size.

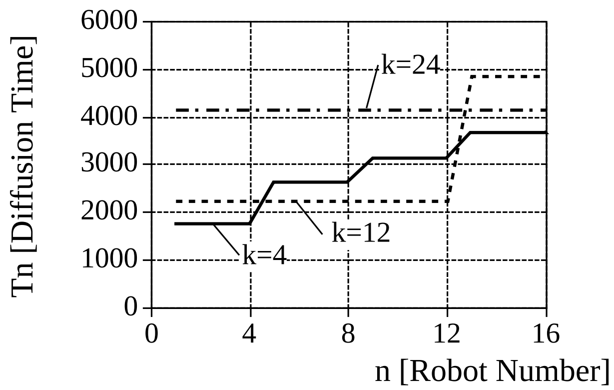


Fig. 11: Diffusion Time by Group Behavior

It has been shown that we can determine the appropriate group size according to the robot number required by cooperation for event handling using analytical results.

5 Realization of Group Forming

The analyses in chapter 3 was made on the assumption that robot groups have been already formed in advance. But this must be done in a decentralized manner since we are working on distributed robotic systems. In this chapter will explain an algorithm for group forming. This algorithm allows robots to form line-up groups using only local communication. The effectiveness of the algorithm is verified by computer simulation.

After discussing the validity of the group forming algorithm, we will demonstrate the efficiency of information transmission is improved when robots act according to the algorithm.

5.1 Algorithm for Group Forming

We will explain an algorithm for group forming that allows robots to make up groups in a decentralized way using local communication.

Before describing the algorithm, the following are given as assumptions about the environment and the internal state information of robots.

- Each robot has an identification number ID and can be identified by this ID.
- Robots have such internal states as the desired group size k_d, current group size k_c, and the identification number of the group ID_g.
- At the initial state,
  - k_c and ID_g are set to 1 and its own ID respectively.
  - k_d is given to every robot.
  - Robot moves randomly without leader.
- Robots can read other robots' internal states (k_c, ID_g) of other robots only from its adjacent robots, i.e. their leader and followers.
- Only robots at the edge of a lined-up group can quit his group. When a robot enters another group, it is disposed between appropriate robots of the group.

A simple algorithm is shown for self-organization of robot group by local communication.

When a robot X quits a group A and enters another group B, the group-forming procedures are as follows. A->ID means the ID number of robot or group A.

```
quit-group(A):
    reset X->k_c to 1
    reset X->ID_g to X->ID
    (the former adjacent robots of group A
     decrements k_c)
enter-group(B):
    read k_c and ID_g from the new adjacent robots
    set incremented value to X->k_c
    set X->ID_g to B->ID_g
    (the new adjacent robots of group A
     increments k_c)
```

The following algorithm shows how a robot X at the edge of group A acts when it encounters another robot Y of group B. We must pay attention to the fact that there can be more robots than desired number k_d in a group because of the delay of information transmission within the group.

```
if Y->k_c < Y->k_d      [k_d not achieved in grp B]
  if X->k_c < X->k_d    [k_d not achieved in grp A]
    if X->k_c < Y->k_c [grp A smaller than B] - Case 1
      X calls quit-group(A) and enter-group(B)
    else if X->k_c == Y->k_c [same grp size] - Case 2
      X or Y calls quit-group() by probability 0.5
      and enter-group() for the group of the other
  else if X->k_c > X->k_d [k_d surpassed in grp A]
                                             - Case 3
    X calls quit-group(A) and enter-group(B)
```

In this algorithm, we can see there are three cases where a robot quit its group. They are illustrated in Fig. 12.

Using this method, there must be only one random walking robot in a group as a result. The change of such internal states as ID_g or k_c is propagated from the point where it happens. Clearly, delay of propagation of information becomes more important in a large group.

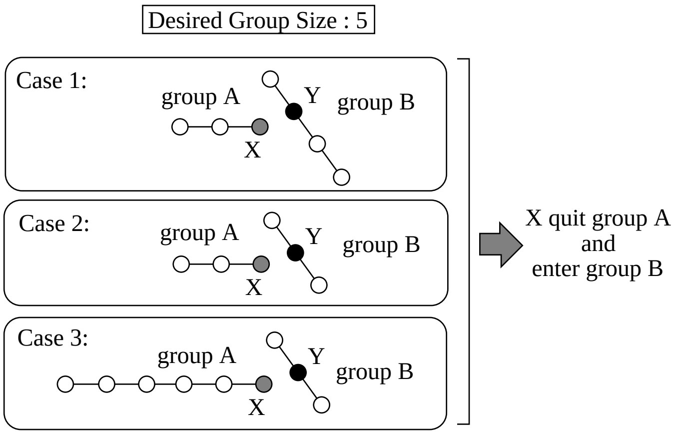


Fig. 12: The three Cases of Changing Group

5.2 Simulation of Group Forming

We will show groups of desired size are actually formed using the explained algorithm by computer simulation, starting from the initial state where all robots are randomly distributed in the environment. The parameters are the same as in Table 1, except that robot number is augmented to 160 to see the group forming well.

Fig. 13(a)$\sim$(c) show the group forming process of desired group size $k = 10$. These simulation results show that groups of desired size are formed using our algorithm. Starting from initial state at time 0 in Fig. 13(a), almost all groups are completed at time 600 in Fig. 13(c). These simulation results show the effectiveness of the group forming algorithm.

5.3 Simulation of Information Diffusion using Group Forming Algorithm

We derived the optimal group size for the efficient transmission of information to given number of robots in chapter 3. Now that we know the group forming behavior works, let us verify the effectiveness of this behavior for information diffusion. We simulated the information diffusion among the robots moving according to the group forming algorithm. The parameters of simulation are the same as in Table 1. Robots are distributed randomly in the environment at the initial state, and events are supposed to occur at time 0.

Fig. 14 shows the diffusion time for different desired group size k_d as 4, 12, 24. Similarly to the results in Fig. 11, the optimal group size is k_e if the information is to be passed to k_e robots. The effectiveness of the analysis on optimal group size is also shown for the case where robots are continuously reorganizing groups.

6 Conclusion

In this paper, we have made following analyses and evaluations to clarify the effect of group behavior on the performance of local communication system of multi-robots.

- The information diffusion among randomly walking robots was formulated as a basic mathematical anal-

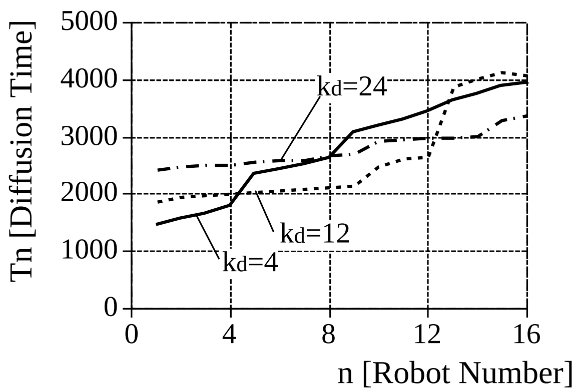
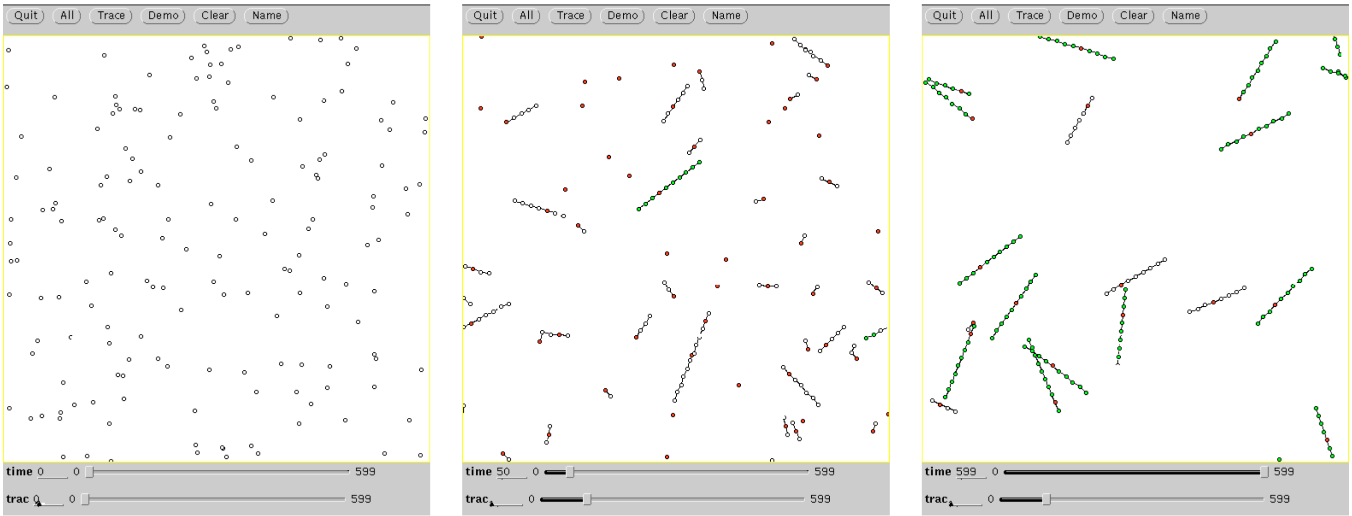


Fig. 14: Diffusion Time with Group Forming Behavior



(a) $t = 0$ (b) $t = 50$ (c) $t = 600$

Fig. 13: (a)∼(c) Simulation of Group-Forming Behavior

ysis.

- Using the basic analytical methodology, we analysed the effect of group behavior on information diffusion and derived the optimal group size for the efficient information transmission to desired number of robots.
- The validity of the analysis was verified using computer simulation.
- A group forming algorithm is proposed for the realization of group behavior. We demonstrated the the analysis are effective also when robots reorganize groups.

As future work, we intend to apply this analysis to various cooperative tasks. Another subject to be studied is the development of learning scheme of grouping adaptive to unknown environments where desired number of robots are changing.

References

[1] A. Matsumoto, H. Asama, Y. Ishida, K. Ozaki and I. Endo: "Communication in the Autonomous and Decentralized Robot System ACTRESS", *Proc. IEEE Workshop on Intelligent Robots and Systems*, pp.835-840, 1990.

[2] S. Yuta and J. Iijima: "State Information Panel for Inter-processor Communication in an Autonomous Mobile Robot-Controller",*Proc. IEEE Workshop on Intelligent Robots and Systems*, 1990.

[3] F. R. Noreils: "An Architecture for Cooperative and Autonomous Mobile Robots", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp.2703-2709, 1992.

[4] J. Wang: "Establish A Globally Consistent Order of Discrete Events in Distributed Robotic Systems," *Proc. IEEE Int. Conf. on Robotics and Automation*, pp.853-858, 1993.

[5] F. Hara and S. Ichikawa: "Effects of Population Size in Multi-Robots Cooperative Behaviors,"*Proc. of Int. Symp. on Distributed Autonomous Robotic Systems, DARS '92*, pp.3-9, 1992.

[6] T. Ueyama, T. Fukuda, F. Arai: "Approach for Self-Organization - Behavior, Communication and Organization for Cellular Robotic System -"*Proc. of Int. Symp. on Distributed Autonomous Robotic Systems, DARS '92*:pp.77-84, 1992.

[7] L. Steels: "Cooperation between Distributed Agents through Self-Organization", *Decentralized AI*, Y. Demazeau and J. -P. Muller, eds., North Holland, pp.175-196, 1990.

[8] M. Mataric: "Minimizing Complexity in Controlling a Mobile Robot Population", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp.830-835, 1992.

[9] R. C. Arkin, T. Balch and E. Nitz: "Communication of Behavioral State in Multi-agent Retrieval Tasks", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp.588-594, 1993.

[10] D. W. Gage: "Sensor Abstractions of Support Many-Robot Systems", *Proc. of SPIE Mobile Robots VII Conference*, Vol. 1831, pp.235-246, 1992

[11] A. Drogoul, J. Ferber: "From Tom Thumb to the Dockers: Some Experiments with Foraging Robots", *Proc. 2nd Int. Conf. on Simulation of Adaptive Behavoir, "From Animals to Animats 2"*, pp. 451-459, 1993

[12] E. Yoshida, T. Arai, J. Ota: "Information Diffusion by Local Communication of Multiple Mobile Robots", *Proc. IEEE Int. Conf. on Systems, Man and Cybernetics*, Volume 4, pp. 535-540, 1993.