Information Diffusion by Local Communication of Multiple Mobile Robots

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Abstract

For the robot cooperation in a large system with many mobile robots, the locality and concurrence of communication must be taken into account. The time-delay in communication becomes important for task planning in such a robot environment. We analyzed the information diffusion among many mobile robots, and proposed a method to evaluate the time-delay and to control the diffusion using the logistic equation. The model is verified and the effectiveness of our method is verified by simulation which implements many mobile robots. Another simulation of cooperative task execution shows that the analysis allows us to make task planning more efficient. Utilizing this simple logistic function, the time-delay required so that the task information is transmitted to necessary number of robots is computed, and unnecessary diffusion of the information can be also avoided.

1 Introduction

In a multiple mobile robot system, robots need to communicate for such cooperations as collision avoidance or cooperative tasks. A number of protocols, e.g. Contract Net Protocol[1], have been proposed for the cooperation in multi-agent system. These models assume that information is transmitted to every agent without delay by broadcasting.

However, in a large system with many mobile robots, it becomes difficult for all of robots to exchange information at a time because of their limited communication capacities. In this case, the communication in the system must be regarded as local and concurrent. From another aspect of information processing, local information should not be spread too widely since each robot would have too much unnecessary information to handle. Local communication has an advantage in that this unnecessary diffusion of information can be avoided. From these reasons, this paper deals with the communication among many robots with a limited communication range.

As concerns cooperative task execution in such a system, tasks to be accomplished often require different numbers of robots. It then becomes important in task planning to estimate how long it takes for the appropriate number of robots to gather for each task. The essential part of this estimation is to analyze how the task information is diffused among robots, taking both the locality of communication and the robot motion into consideration. Although many communication systems for cooperation have been proposed[2][3], few studies take this issue into account.

In this paper, the information diffusion by local communication among mobile robots is analyzed. Employing probablistic model to represent the robot motion, we demonstrate a simple logistic function describes the diffusion process precisely enough. This logistic function model makes it possible to evaluate the time so that the information is diffused to the required number of robots. As an application of this analysis to task planning, a method is shown to control the degree of diffusion by specifying the diffusion time, according to how many robots are needed for a task.

2 Communication Model

In the field of multi-robot cooperation, Hara worked on spatial coverage and development of communication linkage by multiple mobile robots[4]. They dealt with the information diffusion in a static system without robot motion. Mataric carried some experiments such as gathering task or puck assembling using many robots[5]. Wang proposed a method to develop globally consistent order of discrete events using communication by signboards[6].

Local communication among moving robots, however, has not been analyzed although this type of communication is very likely to take place.

In this paper, we employ a simplified model to analyze the information diffusion as briefly described below:

Local Communication Information is passed among robots in limited communication

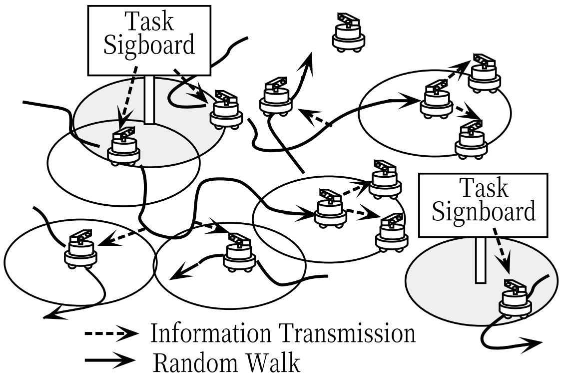


Fig. 1: Model of Information Diffusion by Local Communication

area.

Task Announcement Information about tasks is shown to robots from *task signboards.*

Motion of Robots Each robot walks randomly.

The random walking is adopted as a basic simple motion of a mobile robot that covers a wide area on the average. Task information is obtained from a task signboard by robots, and is spread to other robots as the effect of the random walk and local communication of each robot (we call this *information diffusion*) as shown in Fig. 1.

In this model, appropriate task groups can be formed in an environment where the configuration of robots is changing dynamically by robot motion.

3 Formulation of Information Diffusion

The information diffusion by local communication will be formulated in this section. Robots which have already obtained the task information are called *I-Robots* (Informed Robots), while robots without information are referred to by *N-Robots.* Variables are defined as follows:

$p(t)$: percentage of I-Robots at time t to all robots in the environment

p_0: initial value of $p(t)$ at time 0

R_c, A, ϕ: radius, area and visual angle of communication area

v: velocity of robot walking

ρ: density of robot population

ρ_{sign}: density of task signboards

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 shown in Fig. 2. First, the spatial distribution of randomly walking robots is modeled using Poisson distribution, from which a differential equation of $p(t)$ is derived.

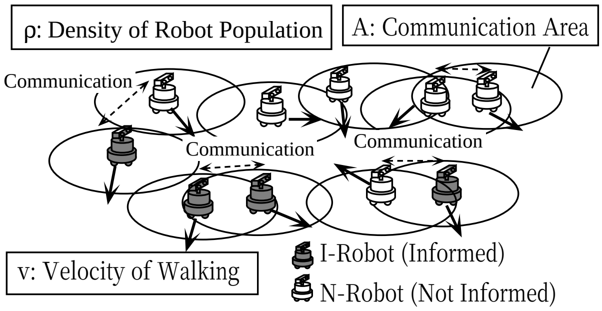


Fig. 2: Parameters of Information Diffusion

We secondly show this differential equation can be approximated by logistic function. This logistic function allows us to calculate easily the required time so that the information is diffused to certain percentage of robots.

3.1 Equation of Information Diffusion

In order to derive the equation of information diffusion, how $p(t)$ varies on time t is considered.

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. Defining *information acquisition probability* $I(t)$ as the probability that a robot obtains information at time t, $\Delta p(t)$ is calculated as the product of $I(t)$ and the percentage of N-Robots, $1 - p(t)$.

The spatial distribution of objects randomly disposed on a plane is represented by the Poisson distribution. If the density of objects is κ, the probability that x objects exist in the domain $S(T)$ with area T, $Prob[x \mid x \subset S(T)]$, is calculated using the Poisson distribution with mean κT as (1).

$$Prob[x \mid x \subset S(T)] = \frac{(\kappa T)^x}{x!} e^{-\kappa T} \quad (1)$$

Equation (1) can be satisfied when the distribution is static, but it can also be that the Poisson distribution (1) illustrates the spatial distribution of dynamically moving objects by computer simulation. In our case, the mean number of I-Robots within the communication area of a robot is $\rho A p(t)$. Thus, the probability that a robot finds x other robots in its communication the area $S(A)$, $Prob[x \mid x \subset S(A)]$, is written as follows using the Poisson distribution of mean $\rho A p(t)$:

$$Prob[x \mid x \subset S(A)] = \frac{\{\rho A p(t)\}^x}{x!} e^{-\rho A p(t)} \quad (2)$$

We use (2) to derive the information acquisition probability, which equals to the probability of existence of more than one I-Robot or task signboard within the communication area of a robot.

The probability that a robot finds at least one robot in its communication area is computed as that of the complementary event to the case that there is no robot found, as in (3).

$$1 - Prob[x = 0 \mid x \subset S(A)] = 1 - e^{-\rho A p(t)} \quad (3)$$

In the same way, the probability that a robot obtain information directly from task signboards is calculated as a constant value C_{sign} as follows:

$$C_{sign} = 1 - e^{-\rho_{sign} A} \quad (4)$$

We assume communication areas of task signboards do not overlap one another. Adding (3) and (4), information acquisition probability $I(t)$ is given by

$$I(t) = 1 - e^{-\rho A p(t)} + C_{sign} \quad (5)$$

The derivative of $p(t)$ is proportional to $I(t)$ and percentage of N-Robots, $1-p(t)$, as mentioned before. Thus, the differential equation of $p(t)$ is derived as follows:

$$\begin{aligned}\frac{dp(t)}{dt} &= \alpha\{1 - p(t)\}I(t) \\ &= \alpha\{1 - p(t)\}\{1 - e^{-\rho A p(t)} + C_{sign}\} \quad (6)\end{aligned}$$

where α is a constant.

The velocity of walking v also affects the way how $p(t)$ varies on time t. As the frequency with which N-Robots encounter I-Robots increases proportionally to v, the derivative of $p(t)$ is also supposed to be proportional to v. Therefore, introducing another constant β and replacing α by βv, the *equation of information diffusion* is derived as (7).

$$\frac{dp(t)}{dt} = \beta v\{1 - p(t)\}\{1 - e^{-\rho A p(t)} + C_{sign}\} \quad (7)$$

3.2 Calculation of Diffusion Time

In this section, we introduce a logistic function for the approximation of the equation of information diffusion in order to evaluate time-delay of information diffusion among robots. This time-delay, *diffusion time*, represents how long it takes for certain percentage of robots to obtain the information.

The equation of information diffusion (7) includes an exponential term, which makes it difficult to understand the characteristics of $p(t)$ clearly. A linear approximation is introduced so that we can deal with (7) in a more comprehensible way. If ρA, which is the average robot number in communication area, is small enough, (7) can be rewritten as (9) using linear approximation of exponential function as in (8).

$$1 - e^{-\rho A p(t)} \simeq \rho A p(t) \quad (8)$$

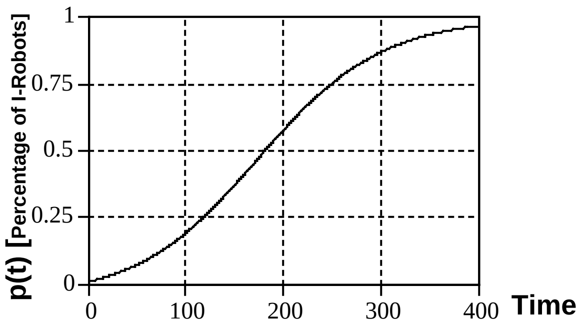


Fig. 3: Logistic Function. (β=0.1, v=0.1, ρ=0.1, ρ_{sign}=0.005, R_c=1.0)

$$\frac{dp(t)}{dt} = \{ap(t) + b\}\{1 - p(t)\} \quad (9)$$

where

$$a = \beta v \rho A, \; b = \beta v C_{sign}$$

Here the density of task signboards ρ_{sign} is supposed to be smaller than the density of robot population ρ. The approximation (8) usually holds only if ρA nearly equals to 0. Nevertheless, for the equation of information diffusion (9), the maximum relative error between approximation (9) and (7) still remains about 5 % even though $\rho A = 0.5$. It is an extreme case that 50 % of all the robots find other robots in their communication areas. This means that the approximation is applicable to relatively crowded robot population.

Equation (9) is an extended form of the *logistic equation*, used for modeling of growth curve or diffusion of infection, whose solution is the *logistic function* as follows:

$$p(t) = \frac{1 - C\frac{b}{a}e^{-(a+b)t}}{1 + Ce^{-(a+b)t}} \quad (10)$$

where C is a constant given by

$$C = \frac{1 - p_0}{p_0 + \frac{b}{a}}$$

The logistic function (10) has a S-curve as shown in Fig. 3.

The derived logistic function (10) allows us to calculate the diffusion time T_w so that the information is diffused up to the percentage w of all robots using (10) as follows:

$$T_w = \frac{1}{a+b} \log \frac{\{1 - w\}\{p_0 + \frac{b}{a}\}}{w + \frac{b}{a}q_0} \quad (11)$$

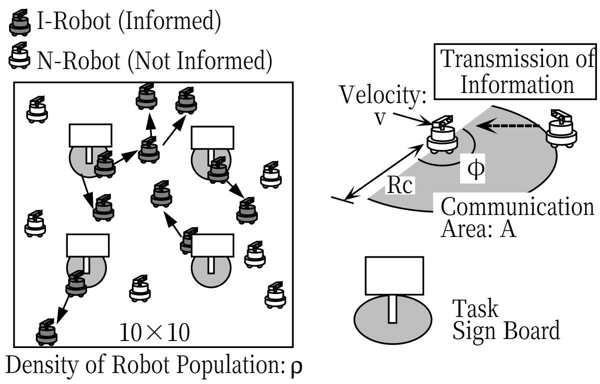


Fig. 4: Environment of Computer Simulation

Table 1: Parameters of Simulation

ρ (Density of Robot Population)	0.2
v (Velocity of Random Walking)	0.1 $\sim$ 0.5
ρ_{sign} (Density of task signboards)	0.01
R_c (Radius of Communication Area)	1.0
ϕ (Visual Angle of Communication Area)	180[deg]
β (Constant in (7))	1.0

4 Information Diffusion Simulation

We derived a logistic function in the previous section as a simple model of the information diffusion. The formulation is verified by computer simulation in this section.

Robots that walk randomly and communicate one another as shown in Fig. 4 are implemented in the simulation to see how information is diffused in a multi-robot system. The random walk of robots is implemented as the movement that changes its direction by certain interval. Parameters of simulation are as in Table 1. The error of the approximation (9) is small enough (2% with parameters in Table 1) to be able to regard the logistic function (10) as the solution of the information diffusion model (7) in this case.

Simulations have been undertaken 30 times with different initial robot positions, using parameters in Table 1. The simulations output the mean value of the percentage of I-Robots $p_{sim}(t)$ at every step t. These results $p_{sim}(t)$ are compared with the theoretical values $p_{logist}(t)$ calculated using logistic function (9). These $p_{sim}(t)$ and $p_{logist}(t)$ obtained with different velocity v are shown in Fig. 5.

From Fig. 5, we can see the information diffusion are precisely described by the logistic function through all steps. This allows us to evaluate the time-delay of information diffusion by local communication.

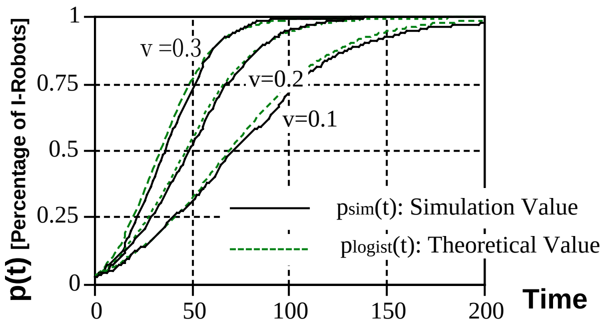


Fig. 5: Percentage of Informed Robots $p(t)$ (ρ = 0.3, $R_c = 0.1$)

Table 2: Parameters of Cooperative Tasks Simulation

ρ (Density of Robot Population)	0.1
v (Velocity of Random Walking)	0.1
T_{ann} (Task Announcement Period)	50 $\sim$ 300
T_{exe} (Task Execution Time)	20
w (Required Percentage of Robots for Each Task)	11% (10 robots)

5 Cooperative Task Simulation

Tasks performed cooperatively by mobile robots are simulated in this section. This gives an example of usage of our analytical results.

The detailed specifications of the cooperative task simulation are as follows:

(1) Tasks are consecutively announced from task signboards installed in the environment during the period T_{ann}.
(2) Task signboards show the points where tasks will be executed and the remaining announcing duration to robots.
(3) Informed robots continue random walking until the remaining task announcement duration expires.
(4) After the termination of the task announcement, robots change their motion and start moving straight to the task point.
(5) Tasks start as soon as the required number of robots gather to the task point.

Information about tasks is propagated among robots by local communication as analyzed so far. The analytical results in previous sections are utilized to determine the period during which tasks are announced.

Task signboards in the simulation environment are disposed with the constant density ρ_{sign} as in Fig. 6, and different periods of task announcement T_{ann} are tested. Task information holds valid only while announced on task signboards. Parameters of the simulation are shown in Table 2, and those not indicated are same as Table 1.

Four tasks in Fig. 6 are announced consecutively

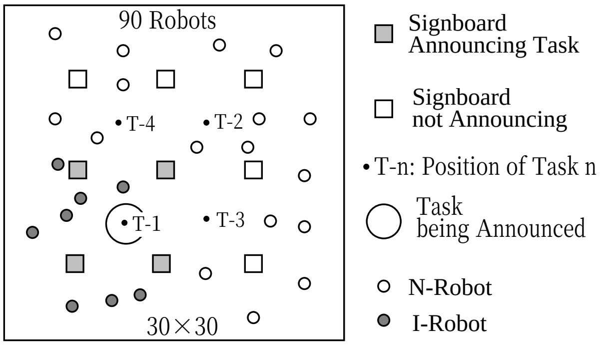


Fig. 6: Environment of Simulation of Cooperative Tasks

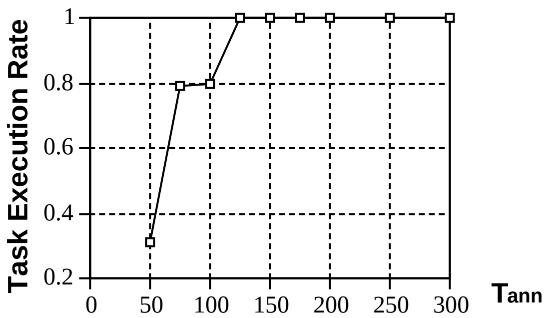


Fig. 7: Task Execution Rate

on the four nearest task signboards during the period T_{ann} and simulations are executed for different T_{ann}'s. Fig. 9(a)∼(d) show the motion of robots. the dispersion of the group after finishing the task.

A task is indicated in Fig. 9 by the mark ◯ when it is announced and remain visible until finished. Different gray levels of robots and task signboards express different information. In Fig. 9(a), the information of Task 1 is being diffused among robots from four task signboards near the task point. When the task announcement terminates, I-Robots for Task 1 start gathering to the task point as in Fig. 9(b), and Task 2 begins to be announced. In Fig. 9(c), Task 1 is being executed after the required number of robots gathered. Robots complete Task 1 and resume random walking, while the information of Task 2 still continues to be diffused in Fig. 9(d).

Ten different cases are simulated with different initial positions of robots. We will analyze *task execution rate* and *total information transmission* in this simulation. The task execution rate is the ratio of executed tasks to all the announced tasks. If tasks not executed are left because of lack of robots, this value becomes lower than 1. The total information transmission stands for how many times information is passed among robots per task. The relationships between these two indices and the announcing period T_{ann} are shown in Fig. 7 and Fig. 8.

From Fig. 7, it is observed that all the tasks are

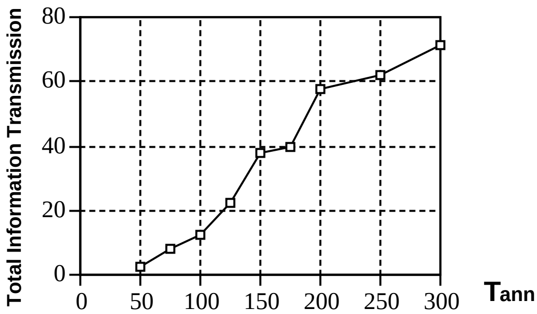


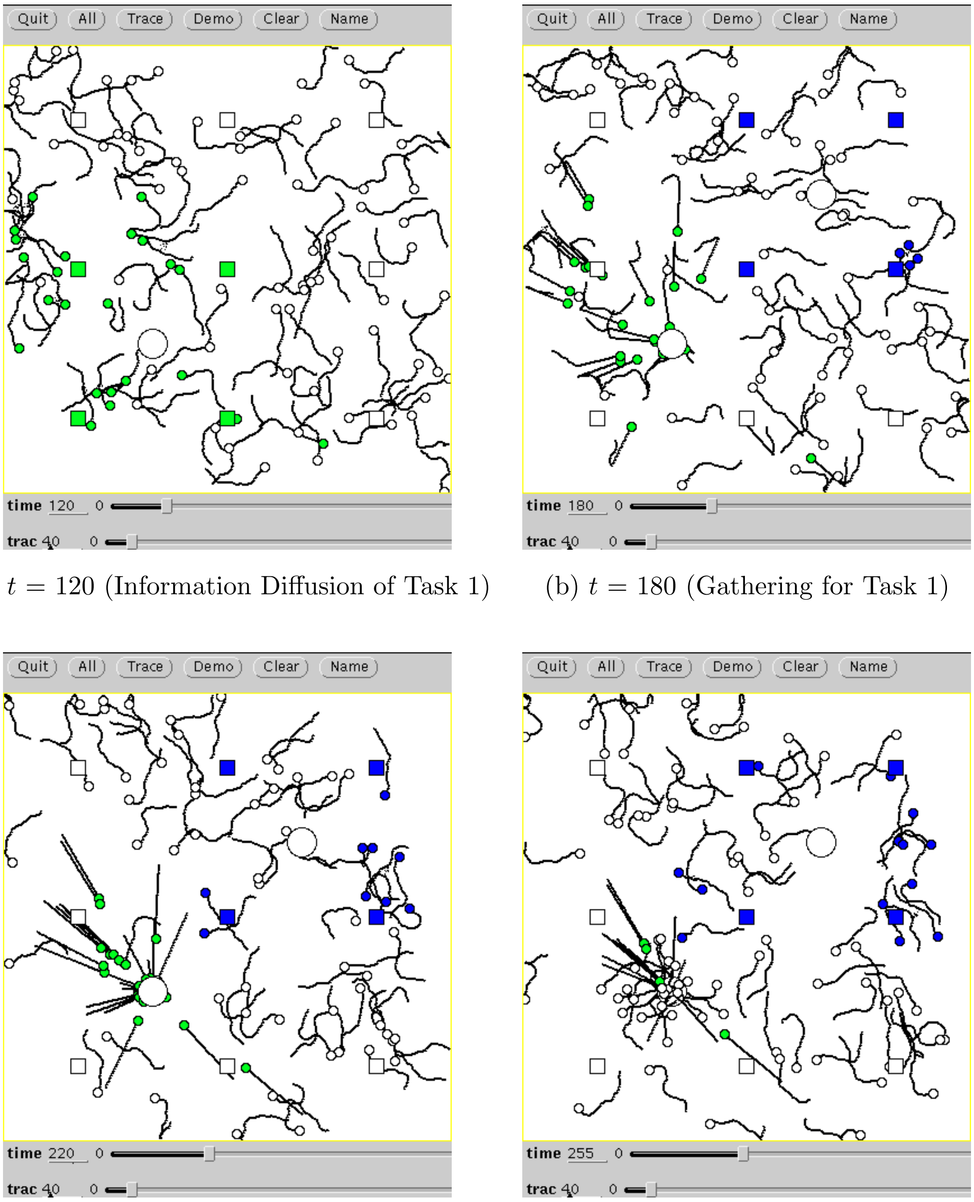
Fig. 8: Total Information Transmission per Task

executed if T_{ann} is longer than 125. The theoretical value of the diffusion time T_{logist}, which is necessary for the percentage $w(= 11\%)$ of robots to get the information, is calculated at 74.5 from (11). Since the value of $p(t)$ deviates from the theoretical value in each simulation, there are possibilities that the information is not transmitted to sufficient robots and that tasks are not executed if the announcing duration T_{ann} is not longer than T_{logist}. Thus, adding $3\sigma_w$ to w as the safety factor, we use $p(t) = w + 3\sigma_w$ as the percentage to calculate T_{ann} where σ_w is the standard deviation of w in this simulation. In this case, T_{ann} is the diffusion time for $p(t) = 26\%$, since σ_w is 5%. T_{ann} turns into 127.1 from (11), which is about the same as the value obtained from the simulation.

It can be concluded that the announcement time T_{ann} must be long enough to make tasks performed surely by robots from the analysis of task execution rate. However, the longer we take T_{ann} for reliable execution of tasks, the more total information transmission becomes as Fig. 8 indicates. This leads to higher cost of communication because of unnecessary information diffusion. Task announcement time obtained using our model of logistic function has also effectiveness from this point.

6 Conclusion

We modeled and analyzed in this paper the information diffusion among mobile robots by local communication. The analysis concluded that the diffusion process is represented by a simple logistic function, and its validity was verified by the information diffusion simulation. A method is proposed using the derived logistic function to evaluate the diffusion time so that the information is diffused up to the percentage of robots required by each task. From the cooperative task simulation, this method of evaluation of diffusion time turned out to be very useful in order to control the range of diffusion according to the task requirement of robots.



(a) $t = 120$ (Information Diffusion of Task 1)

(b) $t = 180$ (Gathering for Task 1)

(c) $t = 220$ (Execution of Task 1)

(d) $t = 255$ (End of Task 1)

Fig. 9: (a)∼(d) Simulation of Cooperative Task ($T_{ann} = 150$)

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