A Design Method of Local Communication Range in Multiple Mobile Robot System

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Abstract

Local communication system is considered appropriate when many mobile robots should achieve cooperation, from the standpoint of cost and capacity of communication. This paper presents a design method of the optimal communication range for efficient local communication system. The analyses of optimization are made by minimizing the information transmission time, first in case of transmission to an arbitrary robot, and next, to multiple robots. Computer simulations have been undertaken to verify the analytical results.

1 Introduction

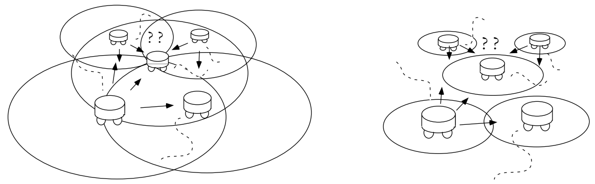
Mobile robots are now expected to execute complicated and sophisticated tasks by intelligent cooperation. This cooperation needs communication, which can be classified into (1) global communication [1]–[3] and (2) local communication [4]–[8].

Global communication is effective for small number of robots. However, when the robot number increases, this becomes difficult to be realized because of limited communication capacity and increasing amount of information to handle. Thus we are studying robotic systems based on local communication in which each robot transmits information locally, as we human beings usually do.

One of the advantages of local communication system is controllable communication range. Let us suppose each robot can adjust the range of information output. If this range is too large, the efficiency of information transmission decreases because all the information from others cannot be treated (Fig. 1(a)). The efficiency is also low if the output range is too small (Fig. 1(b)). It is therefore essential to develop a methodology for decision of the optimal communication range. In this paper, we refer to this output range by the term "communication range" hereafter.

Authors have been working on analysis of local communication such as information diffusion and group behavior for efficient information transmission [7][8]. However, these studies have not dealt with an environment rather crowded with robots where the efficiency must be optimized by adjusting communication range.

Although some other researches can be found on local communication [4]∼[6], the design of communication range has hardly been discussed. In communication theory there are studies on this optimization [9], but they are for radio network system and did not take account of information acquisition from multiple robots in an environment changing dynamically by robots' movement.



(a) Output range is too large (b) Output range is too small

Fig. 1: Control of Local Communication Range

To make the local communication system efficient, we must minimize the time it takes for a robot to obtain necessary information successfully from others. We propose in this paper a design method of optimal local communication area which realizes the minimal transmission time. This optimization will be done first for transmission from one robot to another, and next, transmission to multiple robots considering information diffusion by local communication. This method is based on "information transmission probability", which represents the probability of successful information transmission. Analyses are carried out in two cases, communication with and without transmission interference. The results obtained through the analyses enable us to obtain the optimal communication range with simple calculations.

We have undertaken simulations of local information transmission among many robots to verify the effectiveness analytical results.

2 Communication Model

We will explain the model of local communication used in the following chapters. We employ a simplified model as briefly described below (Fig. 2):

(i) Each robot outputs information within a limited area with certain probability.
(ii) Each robot moves randomly.
(iii) There is an upper limit in number of robots

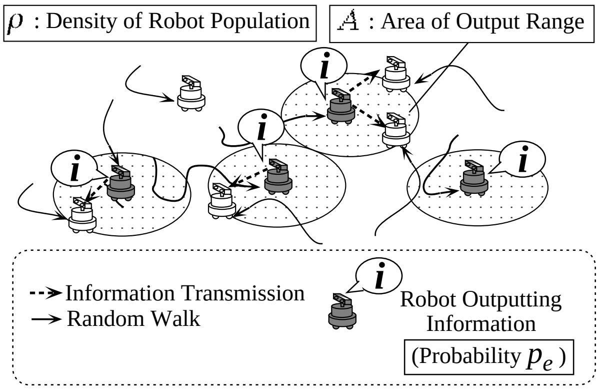


Fig. 2: Local Communication Model

from which each robot can obtain information.

(iv) Each robot executes information reception process at every time unit which is long enough for acquisition. If there are any reachable information, the robot receives it.

For example, this model corresponds to an environment where robots collect map information by moving randomly and update their internal map data when they detect some change of environment or receive information about it from other robots.

We define the upper limit in (iii) as "information acquisition capacity" c, which is an integer. If a robot finds more than c robots that output information, two cases are possible:

(a) The robot cannot receive information from any robots.

(b) The robot can receive information from c robots.

We call the case (a) "communication with interference," and the case (b) "communication without interference."

Information about a cooperative task is diffused among robots by repetition of local communication. The transmission time can be defined as the number of time units described in (iv) before the number of robots required for the task receive the information.

Principle parameters of the model are listed together:

ρ: Density of robot population
p_e: Probability of information output from a robot
A: Area of output range of information
c: Information acquisition capacity
x: Average number of robots in output range ($=\rho A$)

We will minimize the transmission time as the performance index in the following analyses. As a fundamental analysis, the optimization is done for transmission to an arbitrary robot from a robot in chapter 3. In chapter 4, it is extended to transmission to multiple robots taking account of information diffusion.

3 Optimal Communication Range for Transmission to an Arbitrary Robot

This chapter presents the derivation of the optimal communication range for transmission from a robot to an arbitrary other.

We first calculate the probability that the information is successfully transmitted to other robots. As mentioned in chapter 1, we call this probability "information transmission probability" P and it will be utilized to derive the information transmission time. The optimal communication range will be given by minimizing the transmission time in both cases, communication with and without interference.

3.1 Information Transmission Probability

We will compute the information transmission probability P for two types of communication, (a) P_I with interference and (b) P_N without it.

Each robot has two standpoints, "receiver" and "transmitter" of information. In the next section, the information transmission probability is calculated from the "receiver" standpoint of each robot, as how much of information emitted from other robots can be received successfully by a "receiver".

From the "receiver" standpoint of each robot, we classify the information transmission into exclusive events E_i ($i = 0 \sim 3$) as follows. Obviously, information transmission probability P is equivalent to Prob(E_3), and it can be represented in terms of x, c and p_e as $P_I(x, c, p_e)$ or $P_N(x, c, p_e)$.

E_0: No other robots find the "receiver" robot in their output range.

E_1: Some robots find the "receiver" robot in their output range, but none of them output information.

E_2: There are robots that output information to the "receiver," but the transmitted information is *not* successfully obtained by the "receiver".

E_3: There are robots that output information to the "receiver," and the transmitted information is successfully obtained by the "receiver".

For communication with interference, P_I is computed in the form of infinite series [11]:

$$P_I(x, c, p_e) = \sum_{n=1}^{c} \sum_{m=1}^{n} Q(n, m, x) + \sum_{n=c+1}^{\infty} \sum_{m=1}^{c} Q(n, m, x) \tag{1}$$

$$Q(n, m, x) = {}_nC_m p^m (1-p)^{n-m} \frac{x^n}{n!} e^{-x} \tag{2}$$

For communication without interference, P_N can be given through similar consideration.

$$P_N(x, c, p_e) = \sum_{n=1}^{c} \sum_{m=1}^{n} Q(n, m, x) + \sum_{n=c+1}^{\infty} \sum_{m=1}^{c} Q(n, m, x) + \sum_{n=c+1}^{\infty} \sum_{m=c+1}^{n} \frac{c}{m} Q(n, m, x) \tag{3}$$

So far the information transmission probabilities in local communication are represented in the form of infinite series. However, it is not preferable that robots should carry out numerical computations to obtain the optimal output range when they must adjust their communication range in real time.

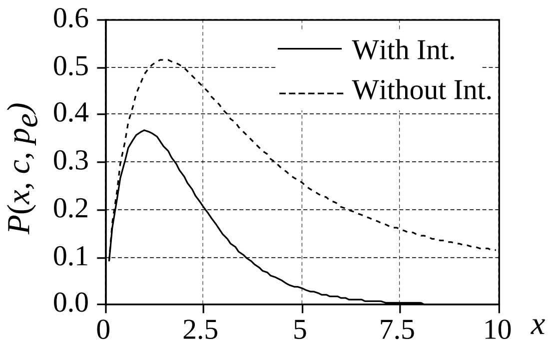


Fig. 3: Information Transmission Probabilities P_I, P_N

To reduce the computation load, the equations of information transmission probability (1) and (3) will be rewritten into more simplified formulae.

(a) Communication with Interference

Through several transformations of equation utilizing exponential series and binomial distribution, P_I in (1) is reduced into the form of (4).

$$P_I(x, c, p_e) = e^{-p_e x}(\sum_{n=0}^{c} \frac{(p_e x)^n}{n!} - 1) \tag{4}$$

(b) Communication Without Interference

Similarly, $P_N(x, c, p_e)$ can be rewritten as:

$$\begin{aligned} P_N(x, c, p_e) &= e^{-p_e x}(\sum_{k=0}^{c} \frac{p^k x^k}{k!} + c \sum_{k=c+1}^{\infty} \frac{1}{k} \frac{p^k x^k}{k!} - 1) \\ &= P_I(x, c, p_e) + c e^{-p_e x} \sum_{k=c+1}^{\infty} \frac{1}{k} \frac{p^k x^k}{k!} \end{aligned} \tag{5}$$

We can see $P_N(E_3)$ is obtained by adding a term of summation to $P_I(E_3)$ in (4). This is a part of an infinite series known as exponential integral $E_i(p_e x)$[1].

The values of P_I and P_N are plotted in terms of x in Fig. 3 for parameters $p_e = 1$, $c = 1$. These parameters can be thought to represent a fundamental case in which robots output information continuously and can receive information from one robot at each time unit. In Fig. 3 we can see the information transmission probability has one maximal value in each case.

3.2 Derivation of Optimal Communication Range

In order to make local communication systems efficient, the time required for information transmission should be made as short as possible, so that the system can follow dynamic environmental changes.

We define the transmission time W as how many time units it takes for an arbitrary robot to receive the information after output of the information. This W will be computed using probabilities P_I and P_N in (4) and (5).

Let x_{opt} be the value x ($= \rho A$) minimizing W. Then the optimal output range A_{opt} is calculated as:

$$A_{opt} = \frac{x_{opt}}{\rho} \tag{6}$$

Our goal is now to obtain this x_{opt}, and we will call x_{opt} the "optimal communication range" hereafter.

In this section, first we will show that the transmission time W is minimized by calculating the maximum of the information transmission probability P. And next, the optimal communication range will be obtained.

3.2.1 Calculation of Transmission Time

The transmission time W denotes the time required so that a "receiver" robot receives information from others. "Transmitter" robots keep outputting the information until successful transmission, and the reception is supposed to be detected using acknowledgment scheme. We give another assumption that the probability of information output p_e includes retransmitted information [9].

We define W_I and W_N as the transmission time for communication with and without interference respectively. Please note that, for large x, W_N is related to the efficiency of information acquisition from its neighborhood, while W_I is computed considering whether a robot can get information or not.

The mean value of transmission time W can be computed using geometric distribution as $W = 1/P$ [12]. From this, the problem of obtaining the optimal output range x_{opt} minimizing W_I and W_N is equivalent to that of obtaining x_{opt} maximizing P_I and P_N.

Fig. 4 shows the transmission time W_I and W_N plotted versus x, for the same paramaters (p_e=1, c=1) as in Fig. 3. W_I takes the minimum at the same x (=1) where $P_I(E_3)$ takes the maximum. This x is the optimal output range x_{opt} for communication with interference. As to W_N, we can see x_{opt} (=1.5) is greater than x_{opt} (=1) of W_I.

3.2.2 Calculation of Optimal Output Range

We will derive the optimal output range x_{opt} in this section. While x_{opt} can be derived analytically for

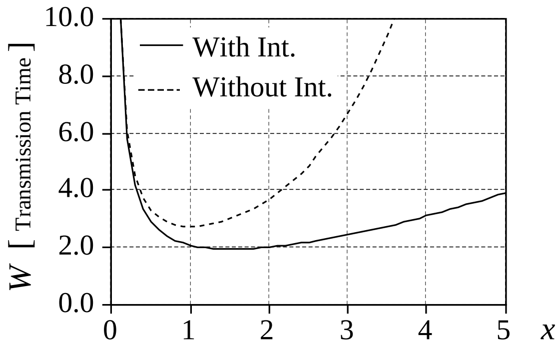


Fig. 4: Transmission Time W_I and W_N (p_e=1, c=1)

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[1] $E_i(p_e x) = \int_{-\infty}^{p_e x} \frac{e^t}{t} dt = C + \log p_e x + \sum_{k=1}^{\infty} \frac{1}{k} \frac{p^k x^k}{k!}$

communication with interference, it is not the case for communication without interference because of the existence of infinite series in (5). Thus we will show a method that makes it possible to reduce computation cost using a lookup table.

(a) Communication With Interference

Let us compute the optimal output range x_{opt} from (4). By solving $dP_I/dx = 0$, we can derive x_{opt} that maximizes $P_I(E_3)$ in a simple formula such as:

$$x_{opt} = \sqrt[c]{\frac{c!}{p^c}} = \frac{\sqrt[c]{c!}}{p} \tag{7}$$

In (7), x_{opt} is in inverse proportion to p_e, which is the probability of information output of each robots. As to the relationship between $p_e x_{opt}$ and information acquisition capacity c, we show a graph of $p_e x_{opt}$ versus c in Fig. 5.

We can see that x_{opt} has approximately linear relationship with c in Fig. 5. However, we must pay attention to the fact that it is not simply proportional to c like $x_{opt} = c/p_e$.

(b) Communication Without Interference

The value of x_{opt} maximizing P_N cannot be derived analytically because of the infinite series $E_i(p_e x)$. But on the analogy of communication with interference, we can prove x_{opt} is inversely proportional to p_e [11].

We can obtain the relationship between $p_e x_{opt}$ and c from numerical computation, as shown in Fig. 5. We can see the value $p_e x_{opt}$ has approximately linear relationship with c also in case of communication without interference, and is always greather than $p_e x_{opt}$ of communication with interference.

Since the information aquisition capacity c is an integer, the relationship between $p_e x_{opt}$ and c in Fig. 5 can be stored in each robot as a lookup table without consuming large memory. When robots need to calculate their information output range, they have only to refer to this table and get the value of $p_e x_{opt}$, then multiply it by p_e.

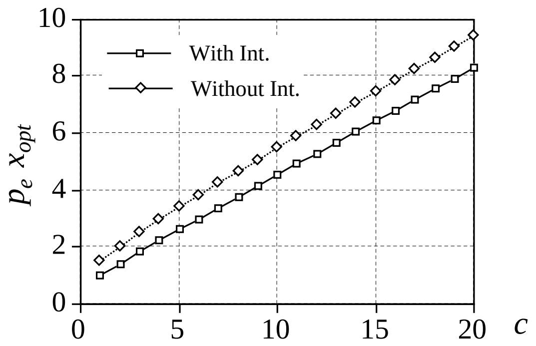

Fig. 5: The Value $p_e x_{opt}$ veusus c (With and Without Interference)

4 Optimal Communication Range for Transmission to Multiple Robots

We will derive the optimal communication range for the transmission to multiple robots by extending the analysis in the previous chapter.

4.1 Equation of Information Diffusion

The information about tasks is diffused among robots as it is transmitted repeatedly by local communication. Robots which have already obtained the task information are called *I-Robots* (Informed Robots), while robots without information are referred to as *N-Robots* (Not Informed). Let $p(t)$ be the percentage of I-Robots at time t, where t is the time from generation of information.

The increment of $p(t)$ per time Δt, $\Delta p(t)$, corresponds to the percentage of newly generated I-Robots at time t. $\Delta p(t)$ is calculated as the product of the information transmission probability P and the percentage of N-Robots, $1 - p(t)$. Since P is dependent of time t here, it can be written as $P(t, x, c, p_e)$.

Then the "equation of information diffusion" is derived as as follows [7].

$$\frac{dp(t)}{dt} = \beta(v)\ \{1 - p(t)\}\ P(t, x, c, p_e) \tag{8}$$

where $\beta(v)$ represents the effect of velocity v.

P_I and P_N can be computed as follows as an extension of procedures in the previous chapter, using the percentage of I-Robots $p(t)$.

$$P_I(t, x, c, p_e) = e^{-p_e x} \sum_{i=0}^{c} (p_e x)^i \frac{1 - (1 - p(t))^i}{i!} \tag{9}$$

$$P_N(t, x, c, p_e) = e^{-p_e x} \sum_{i=0}^{c} (p_e x)^i \{ \frac{(1 - p(t))^c}{i!} - \frac{(1 - p(t))^i}{i!} \} + 1 - (1 - p(t))^c \tag{10}$$

4.2 Derivation of Optimal Communication Range

The optimal communication range x_{opt} is given as the value minimizing the transmission time. In this section, x_{opt} will be derived by analyzing the equation of information diffusion (8) without directly computing the transmission time.

In this equation (8), if $P(t, x, c, p_e)$, the sole part dependent on x, is maximized, the derivative $dp(t)/dt$ also takes the maximum. As the transmission time can be minimized in this way, the optimal communication range x_{opt} is the value x which maximizes P.

The value x_{opt} can be determined in case of communication with interference. Since it can be proved that x_{opt} is inversely proportional to p_e by differentiating $P_I(t, x, c, p_e)$ in terms of x, we can make a lookup table between $p_e x_{opt}$ and c in the same manner as in chapter 3.

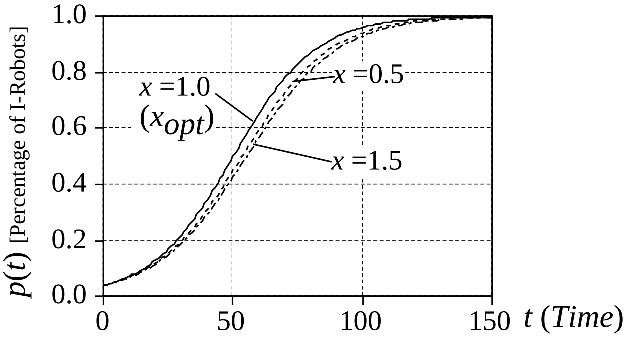

Fig. 6: Diffusion $p(t)$ with Interference (p_e=1, c=1)

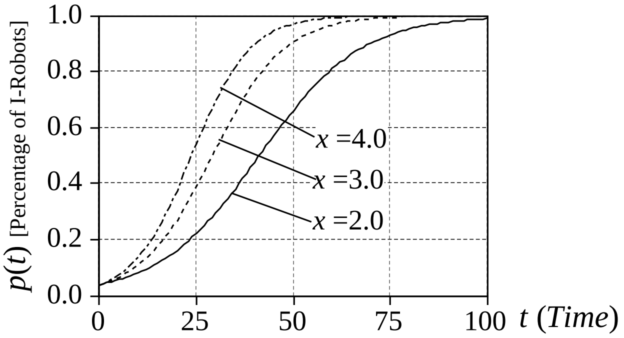

Fig. 7: Diffusion $p(t)$ without Interference (p_e=1, c=1)

Unlike this, P_N is a monotonously increasing function of x for communication without interference, and converges to $1-(1-p(t))^c$ as $x \to \infty$. That is to say the greater the value x becomes, the faster the information is diffused. Therefore, the communication range must be given taking account of factors such as communication cost in this case.

The percentage of I-Robots $p(t)$ calculated from (8) are shown in Figs. 6 and 7, for communication with and without interference respectively.

In case of communication with interference, Fig. 6 shows the information diffusion is the fastest at x=1, which equals to the computed value of x_{opt} from (10). Without interference, the information is propagated more rapidly with larger x.

In this way, the communication range is optimized for transmission to multiple robots.

5 Simulation for Analysis Verification

In order to verify the optimal output range derived in previous sections, several simulations have been executed. We implemented an environment where many robots moves randomly and communicate locally as shown in Fig. 8. In the environment 10×10, we implemented 50 robots moving randomly with velocity 0.2 at each time unit. The information output probability p_e is set to 1, which implements an environment where each robot outputs continuously such information as dynamically changing map.

We will verify the optimal communication range for transmission to an arbitrary robot in 5.1, and to multiple robots in 5.2.

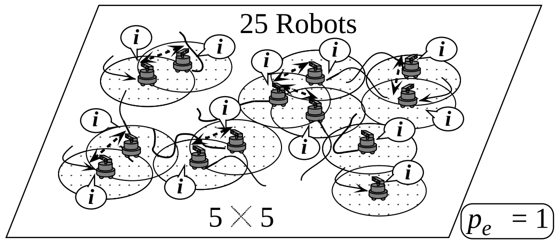

Fig. 8: Simulation Environment

5.1 Optimal Range for Transmission to an Arbitrary Robot

Figs. 9 and 10 show the transmission time W_I and W_N for the same parameters as in 3.2.

The theoretical value of x_{opt} is 1 and 1.5 for each case. In these graphs, W_I and W_N take the minimal values at almost the same x as theoretically predicted x_{opt}, it is therefore shown that the communication is optimized using the optimal output range.

For W_I, the difference between theory and simulation becomes large as x increases. This is because in very crowded situations with very large x, robots keeps information output continuously but hardly received, while the theory estimates certain value of transmission time. However this effect does not have much significance because the model is precise enough near around the x_{opt} derived from the analysis.

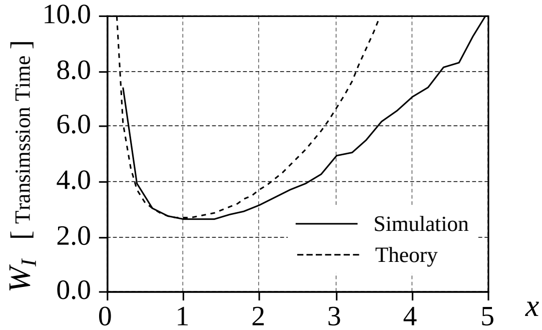

Fig. 9: Transmission Time W_I (With Interference)

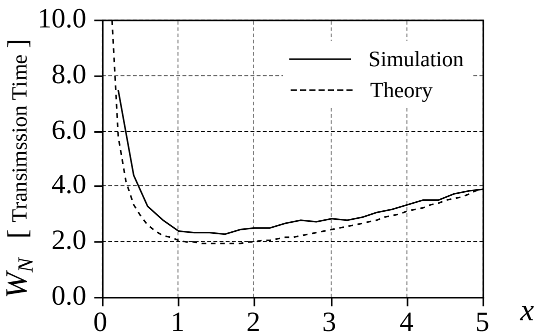

Fig. 10: Transmission Time W_N (Without Interference)

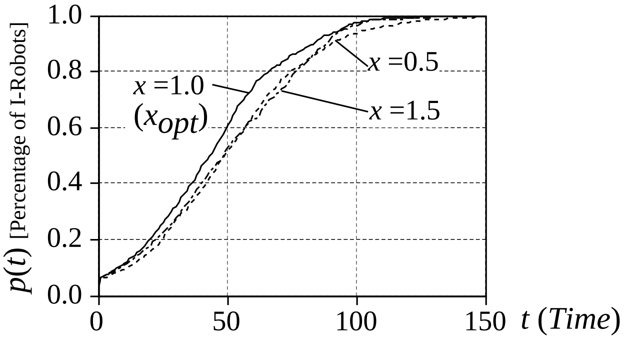

Fig. 11: Diffusion $p(t)$ with Interference (p_e=1, c=1)

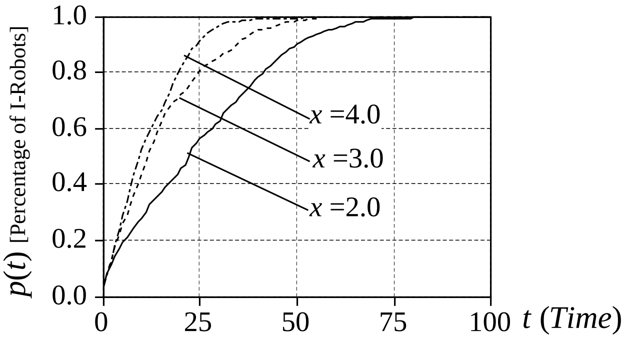

Fig. 12: Diffusion $p(t)$ without Interference (p_e=1, c=1)

5.2 Optimal Range for Transmission to Multiple Robots

The information diffusion processes to multiple robots are shown in Figs. 11 and 12 for communication with and without interference respectively. The same parameters are used as in Figs. 6 and 7.

In Fig. 11, information is diffused the most rapidly with x_{opt} (=1) derived from the analysis, which means the transmission time is minimized by x_{opt} for communication with interference.

In the case without interference, the information diffusion becomes fast with increasing value of output range x, as predicted by the analytical results.

From these simulation results, the effectiveness of the optimal output range is demonstrated.

6 Conclusion

We have shown a design method of the optimal communication range in local communication system for multiple mobile robots.

As the performance index, we use the transmission time, namely the number of time units required before the desired number of robots for task receive necessary information from other robots. The optimization is carried out transmission from one robot to an arbitrary other, and next, to multiple robots. From the analyses using the information transmission probability, we have obtained the optimal communication range.

The effectiveness of these analyses was verified by computer simulation of many robots. The derived design method of communication area can help to construct an efficient local communication system for many robots.

We intend to expand the analysis to obtain the optimal output range for various spatial distributions of mobile robots. As an application of the analyses in this research to real system, we are now implementing local communication system for mobile robots combining the relative position/orientation measurement system we have developed [10] and infrared communication device.

Acknowledgments

This research is supported by Casio Science Promotion Foundation.

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