Evaluating the Efficiency of Local and Global Communication in Distributed Mobile Robotic Systems

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Abstract

One of the major emerging problems of distributed mobile robotic system is what kind of inter-robot communication to use, because of increasing robots integrated in the system. This paper aims to give an analytical view of this issue. The efficiency of local and global communication is compared based on the analysis of information transmission time to multiple robots. We will show that local communication is effective in environments where cooperative tasks are executed by multiple mobile robots in distributed fashion.

1 Introduction

Communication between robots is currently an essential issue for multiple mobile robot cooperation. Global communication has been often utilized in previous studies for robotic systems consisting of only a few robots [1]∼[3]. However, distributed robotic systems require much greater number of robots for the sake of flexibility and robustness of cooperative task execution. Recent progress in robotic technology has made it possible to realize systems integrating many robots [4] [5]. There are mainly two kinds of communication in such a distributed system with many mobile robots as shown in Fig. 1:

(1) Communication for notification of a task to the number robots required by the task.
Content of information: attributes of multiple task (e.g. the place and type of task)
(2) Communication for task execution.
Content of information: status of task execution (e.g. the map being constructed in the case of cooperative map generation task)

In both types of communication, the information needs transmitting to necessary robots in minimum time for efficient task execution.

Global communication has the following problems when applied to distributed many-robot system:

- The efficiency of information transmission becomes low when a single communication medium is assigned to many robots, like radio network.
- If a central station manages the communication in the system, increasing load may cause communication bottleneck and insufficient fault-tolerance.

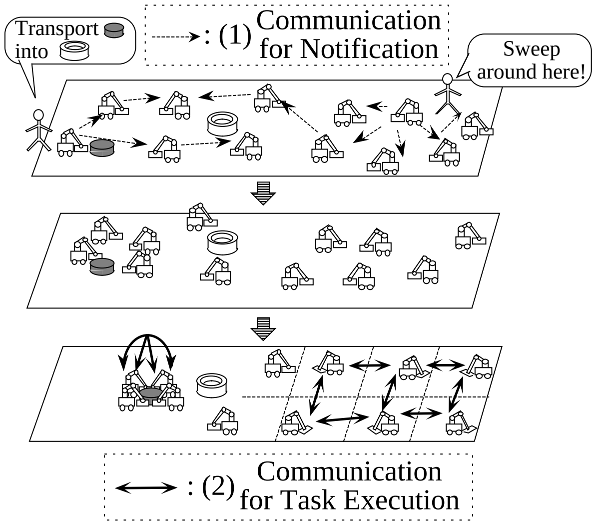

Fig. 1: Two types of communication for cooperation

For these reasons, local communication has been frequently brought into use in recent research [5] [6]. Authors have also introduced local communication to many mobile robot system and analyzed information diffusion process among robots by repeated local transmission [7]. This analysis allows us to know the time period required for transmission to necessary number of robots in a simple manner. We have furthermore proposed a methodology for design of optimal communication area minimizing the transmission time [8].

Although these studies give the analytical guidelines on the design of local communication, they did not clarify its effectiveness as against global communication. In this paper, we will compare the efficiency of local and global communication using average information transmission time T as a performance index. The index T will be calculated as:

The time period it takes for n_f robots to transmit information to n_e robots respectively

This analysis will make clear on what conditions local communication is more efficient than global one, and vice versa.

2 Analysis on Local Communication

2.1 Local Communication Model

We will employ a simplified model of local communication as shown in Fig. 2. Principal parameters of the model are listed together:

ρ:	Density of robot population
R_c, ϕ, A:	Radius, visible angle and area of output range of information ($A = 0.5R_c^2\phi$)
x:	Average number of robots in output range ($=\rho A$)
p_e:	Probability of information output from a robot
c:	Information acquisition capacity
$r(t)$:	Ratio of informed robots at time t
v:	Velocity of motion
m:	Total number of robots in the system
n_e:	Number of robots the information is transmitted to
A_E:	Total area of workspace

In this model, communication takes place as described below:

(i) Each robot outputs information in the form of a "packet" within a limited area A, with certain probability p_e.

(ii) There is an upper limit in number of robots from which each robot can obtain information.

(iii) 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.

This simple model has such advantages as load distribution and easy implementation. The parameter x, given as the product of ρ and A, represents the average number of robots in output area A. We refer to x by the term "communication area" since it is clearer than using the surface A directly.

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

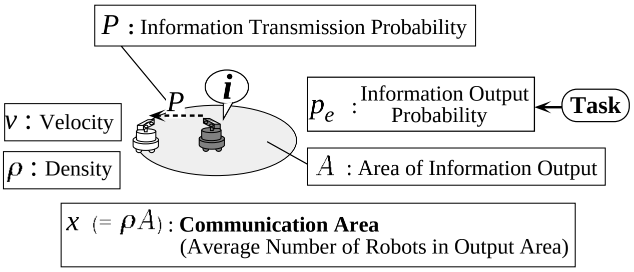

Fig. 2: Local communication model

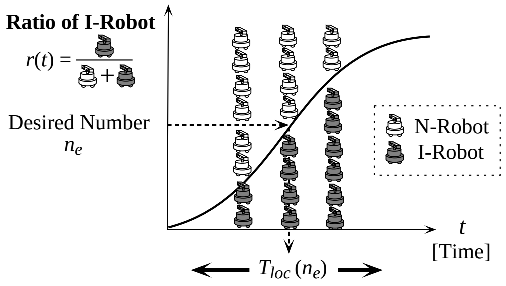

Fig. 3: Information diffusion among robots

(a) The robot cannot receive information from any robots.
[interfering communication]

(b) The robot can receive information from c robots.
[non-interfering communication]

Information used in cooperative tasks is diffused among robots by repetition of local communication as shown in Fig. 3. As explained in chapter 1, a packet contains such information as set of attributes (type, place,...) of several tasks in (1) communication for notification; and the status of task execution updated by each robot in (2) communication for task execution. Then repeated transmission of a packet leads to diffusion of information about multiple tasks or status updated by multiple robots. We will therefore proceed the analysis assuming that the information about each task or about the status change made by each robot is diffused independently.

Paying attention to a specified content of information $\mathcal{I}$, we define "I-Robots" as the robots received that content, and N-Robots as those not received. The ratio of I-Robots at time t is represented by $r(t)$.

The transmission time can be defined as the number of time units described in (iv) before the information is received by the number of robots determined by the task.

2.2 Analysis of Transmission Time [8]

Previous studies have shown a design method of optimal communication area x_{opt} minimizing the transmission time [8]. In this paper, random search of the environment is dealt with as cooperative task since it is always used in the notification process (1), and is the most basic and simple motion applied to many tasks such as map generation [9] or sample collection [10] [11].

We give only an overview of optimization described in [8] here. The increase of $r(t)$ per time Δt, $\Delta r(t)$, corresponds to the percentage of newly generated I-Robots at time t. We define the information transmission probability P as the probability that a robot can successfully obtain information from others at time t, which is a function of c, p_e, x and t. The increment $\Delta r(t)$ is in proportion to ratio of N-robots $1-r(t)$ and $P(c, p_e, x, t)$. Then the diffusion process is modeled by the following differential equation:

$$\frac{dr(t)}{dt} \;=\; \beta(v,x)\;P(c,p_e,x,t)\;\{1-r(t)\} \qquad (1)$$

where $\beta(v,x)$ stands for the effect of robot motion. The optimal communication area x_{opt} can be calculated by maximizing the part $\beta(v,x)\;P(c,p_e,x,t)$ to have the maximum diffusion velocity $dr(t)/dt$ [8].

We consider the lowest capacity of local communication in order to demonstrate its effectiveness. That is, interfering communication with information acquisition capacity c=1. Information output probability p_e is set to 1.0 for simplicity.

For random search task, the information transmission probability $P(c,p_e,x,t)$ is given as follows.

$$P(c,p_e,x,t) = e^{-p_e x}\sum_{i=0}^{c}\frac{(p_e x)^i\{1-(1-r(t))^i\}}{i!} \qquad (2)$$

In our case of c=1, p_e=1.0 and x=x_{opt}, $P(c,p_e,x,t)$ is reduced to $P(t)$ as:

$$P(t) = p_e x e^{-p_e x} r(t) = x_{opt}e^{-x_{opt}}r(t) \qquad (3)$$

We adopt a random motion in which robots change its orientation within the range θ at every τ time units. The coefficient $\beta(v,x)$ in (1) is given using the area $S(v)$ swept per time unit as:

$$\beta(v,x) = \frac{1-e^{-\rho S(v)}}{1-e^{-x}} \qquad (4)$$

$$\text{where } S(v) = 2R_c v\frac{(\tau-1)+a(\theta)}{\tau}$$

$$a(\theta) = \frac{1}{\theta}\int_0^{\theta}\cos\alpha d\alpha$$

The radius R_c of information output can be easily calculated as $\sqrt{\frac{x}{\rho\pi}}$.

The optimal communication area x_{opt} is calculated based on the design method in [8] when the velocity v is given. From (3) and (4), the equation (1) is transformed into the following equation.

$$\frac{dr(t)}{dt} = \beta(v,x_{opt})x_{opt}e^{-x_{opt}}r(t)\;\{1-r(t)\} \qquad (5)$$

The solution of (5) is a simple logistic function as shown in (6). The validity of the analysis of information diffusion has shown in [7] by computer simulation of many robots.

$$r(t) = \frac{1}{1+\dfrac{1-r(0)}{r(0)}\exp{(-\dfrac{\beta x_{opt}}{e^{x_{opt}}}t)}} \qquad (6)$$

where $r(0)$ is the ratio of I-Robot at time 0

From (6), we can evaluate analytically the transmission time $T_{loc}(n_e)$ required before n_e out of total m robots receive the information, by solving $r(t) = \frac{n_e}{m}$ in terms of t:

$$T_{loc}(n_e) = -\frac{e^{x_{opt}}}{\beta x_{opt}}\log{\{\frac{m-n_e}{(m-1)n_e}\}} \qquad (7)$$

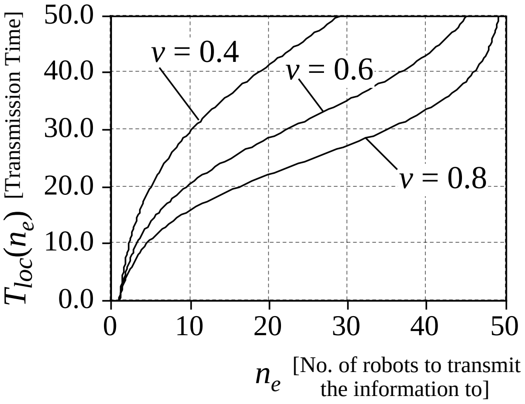

Fig. 4: Transmission time $T_{loc}(n_e)$ (m=50)

Note that in local communication the transmission time $T_{loc}(n_e)$ is independent of n_f since information from multiple robots can be contained in a packet.

An example of calculated $T_{loc}(n_e)$ versus n_e with is given in Fig. 4 for various velocities v, where total robot number m=50, total area of workspace A_E 400.

The diffusion time $T_{loc}(n_e)$ increases monotonously as n_e becomes greater. We can also see in Fig. 4 that greater velocity v leads to smaller $T_{loc}(n_e)$, namely rapid information diffusion. The derived transmission time will be compared with that of global communication in chapter 4.

3 Analysis on Global Communication

3.1 Global Communication Model

Most of the studies utilizing global communication is based on time-division multiple access (TDMA) to a single medium like radio communication [2] [4] [12] . So we will compare the performance of local communication analyzed in the previous chapter with that of TDMA-type global communication modeled as:

- Information is transmitted per packet.
- Robots can output information when assigned a time slot, which is a period of time enough for outputting a packet. Time slots are assigned to robots in turn, by centralized manager or token passing method.
- A packet output from a robot is transmitted globally to all m robots.
- The length of a time slot is same as a time unit used in local communication.
- Communication is completely synchronized in all robots.

The model is illustrated in Fig. 5. As described in chapter 1, the objective of communication here is for n_f robots to be assigned time slots since the output information is broadcasted globally. Figure 5 is the

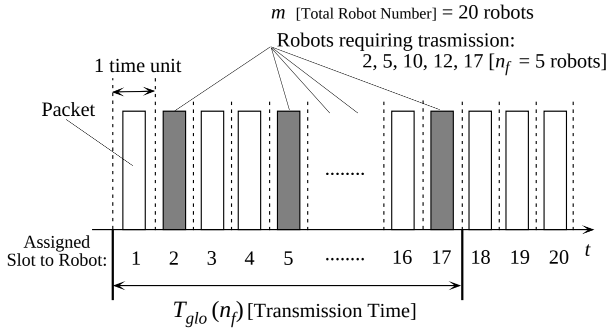

Fig. 5: Model of global communication

case of $(m,\ n_f)$ = (20, 5) and robots #2, #5, #10, #12, #17 have the information to send out. In this example, time slots are assigned from robots #1 by turns, and the transmission time T_{glo} is 17.

3.2 Analysis of Transmission Time

We will calculate the average time $T_{glo}(n_f)$ needed so that n_f out of m robots are assigned time slots. $T_{glo}(n_f)$ is the expectation of the number of time units required until n_f robots finish outputting information when a slot is assigned to an arbitrary robot at time 1,2,…,m (time unit). This can be computed as:

$$T_{glo}(n_f) = \sum_{i=n_f}^{n} \Pr\left[n_f \text{ robots finish at time } i\right] \times i$$

$$\sum_{i=n_f}^{n} \underbrace{\Pr\left[n_f - 1 \text{ robots finished by time } i-1\right]}_{\text{A}} \times \underbrace{\Pr\left[n_f\text{th robot transmits at time } i\right]}_{\text{B}} \times i \qquad (8)$$

The part A in (8) is given by hypergeometric distribution in (9).

$$\Pr\left[n_f - 1 \text{ robots finished by time } i-1\right] = \frac{{}_{i-1}C_{n_f-1} \cdot {}_{m-i-1}C_{n_f-(n_f-1)}}{{}_{m}C_{n_f}} \qquad (9)$$

The part B in (8), the probability that the last n_fth robot is chosen from $m-(i-1)$ robots not yet assigned time slots, equals to $\dfrac{1}{m-(i-1)}$. By substituting this and (9) for the parts A and B in (8), the average transmission time $T_{glo}(n_f)$ is derived as follows.

$$T_{glo}(n_f) \quad = \quad \sum_{i=n_f}^{m} \frac{{}_{i-1}C_{n_f-1}}{{}_{m}C_{n_f}} \times i \qquad (10)$$

In global communication, $T_{glo}(n_f)$ is independent of n_e, the number of robots to transmit the information to. The relationship $T_{glo}(n_f)$ and n_f is shown in Fig. 6 for total robot number m. The transmission time does not exceed m=50 as seen in Fig. 6. However, we can also observe the tendency that $T_{glo}(n_f)$ increases very sharply towards m at small n_f.

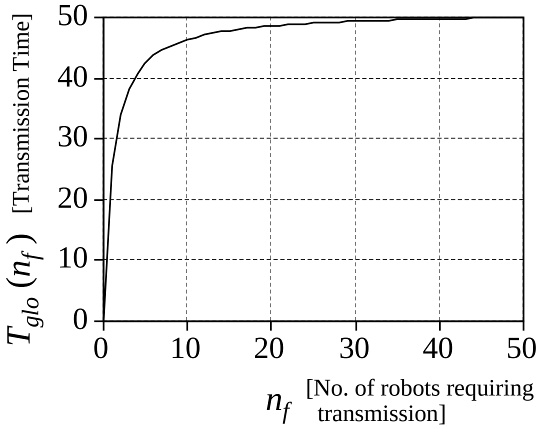

Fig. 6: Transmission time $T_{glo}(n_f)$ (m=50)

4 Evaluation using Transmission Time

As mentioned in chapter 1, we will compare local and global communication by evaluating:

The time period T it takes for n_f robots to transmit information to n_e robots respectively

From the analyses so far, it has been shown that in local communication the transmission time T_{loc} is the time needed until the information is diffused to desired number of robots n_e. Thus T_{loc} depends only upon n_e, and can be represented as $T_{loc}(n_e)$.

In global communication on the other hand, T_{glo} represents how many time units it is before n_f robots requiring transmission output the information. The transmission time T_{glo} is the function of n_f merely.

4.1 Parameters of Evaluation

The evaluation here will be made by comparing $T_{loc}(n_e)$ and $T_{glo}(n_f)$. We consider the lowest capacity for local communication as mentioned in section 2.2 to validate its effectiveness. This is interfering local communication with parameters shown in Table 1.

The values of parameters m, n_f and n_e used for evaluation are shown in Table 2. In this case, the percentage 20%, 40% (n_f=10, 20) of total m (=50)

Table 1: Parameters of local communication

A_E	: Area of workspace	400 (20×20)
c	: Information acquisition capacity	1
p_e	: Information output probability	1.0
x (=ρA)	: Communication area	optimal area x_{opt}
ϕ	: Visible area	360[deg]
v	: Velocity of motion	0.5, 0.8
θ, τ	: Parameters of random search	3,90[deg]

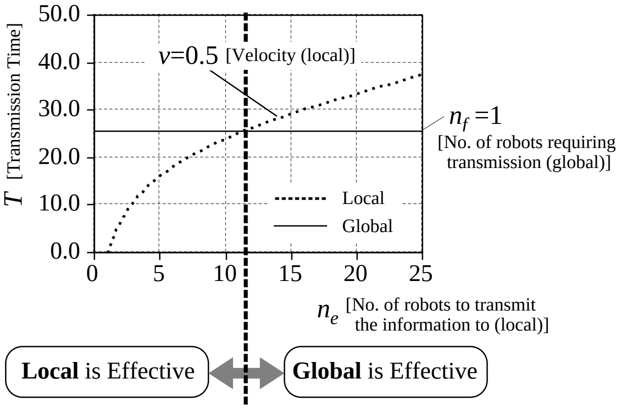

Fig. 7: Evaluation of local and global communication

robots transmit the information to 20%, 40% (n_e=10, 20) of robots respectively. The case of n_f=1 is also dealt with in global communication.

4.2 Comparison of Transmission Time

Let us see how to compare the transmission time here before starting the evaluation. As illustrated in Fig. 7, $T_{loc}(n_e)$ for local communication is plotted versus n_e in thick dotted line (indicated by "Local"). The transmission time $T_{glo}(n_f)$ for global communication is indicated by thin solid line ("Global"). Plotted $T_{glo}(n_f)$ is a parallel line to n_e axis since it is not dependent on n_e, but only on n_f.

Fig. 7 describes that if n_e is smaller than the intersection of $T_{loc}(n_e)$ and $T_{glo}(n_f)$, local communication is more effective. In contrast, for greater n_e than this intersection, global communication is effective.

Figs. 8 and 9 show the transmission time computed using parameters in Table 1 and 2.

The transmission time $T_{glo}(n_f)$ for global communication is calculated using (10) for $n_f = 1$ and 20%, 40% of total $m = 50$ robots. Even if there is only one robot requiring transmission, namely n_f =1, it takes about 25 ($\sim m/2$) time units and when n_f = 20%, 40% of m (= 50), $T_{glo}(n_f)$ is nearly equal to m.

As to $T_{loc}(n_e)$ in local communication, it increases monotonously as n_e increases and larger velocity v makes $T_{loc}(n_e)$ smaller at the same value of n_e, as stated in section 2.2.

It can be concluded from these analyses that:

(1) **Local communication is effective** when many robots transmit the information to relatively small number of robots (in the above example, to about 20% of total m).

Table 2: Parameters for evaluation

m	(Total robot number)	50
n_f	(No. of robots requiring transmission)	1, 10, 20
n_e	(No. of robots to be transmitted)	10, 20

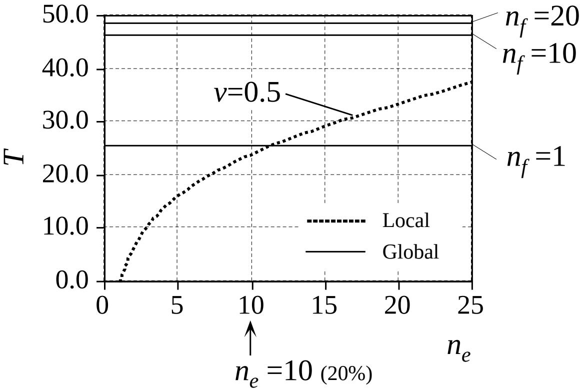

Fig. 8: Comparison of transmission time (v=0.5)

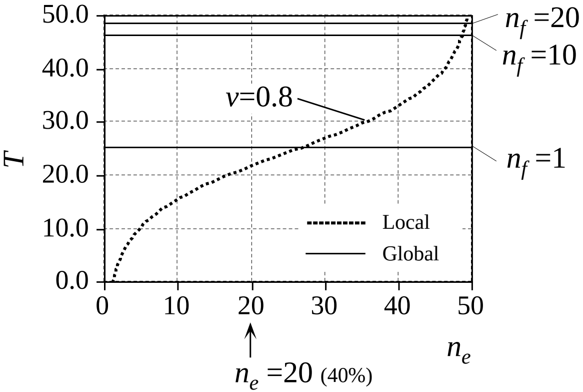

Fig. 9: Comparison of transmission time (v=0.8)

(2) **Global communication is effective** when a few robots transmit to many robots (in the above example, to more than 40% of total m).

The statement **(1)** means that local communication is suited for environments as shown in Fig. 1 where many robots form several groups according to given tasks and execute them cooperatively in a distributed manner. In Fig. 8, local communication transmits the information to 10 robots (20% of m) more rapidly with velocity v=0.5 than global communication of n_f = 1. The area of workspace A_E 400 corresponds to the environment 20×20. Assuming the workspace is 20[m] × 20[m] and a time unit equals 1[sec], this velocity v is 0.5[m/sec], which is realizable enough.

In contrast, from the above **(2)**, global communication is considered to be effective if it is utilized in centralized environments where a few managing robots give command to many robots. As seen in Fig. 8, even if the velocity v is elevated to 0.8, global communication with n_f = 1 still leads to shorter transmission time compared to local communication when transmitting to more than 25% of all 50 robots.

Even if the statements **(1)**, **(2)** look trivial, we would like to emphasize the fact that we have shown this "common sense" from an analytical viewpoint, which has hardly been realized before.

Especially in communication for notification (1) in Fig. 1, if tasks are given frequently in many different

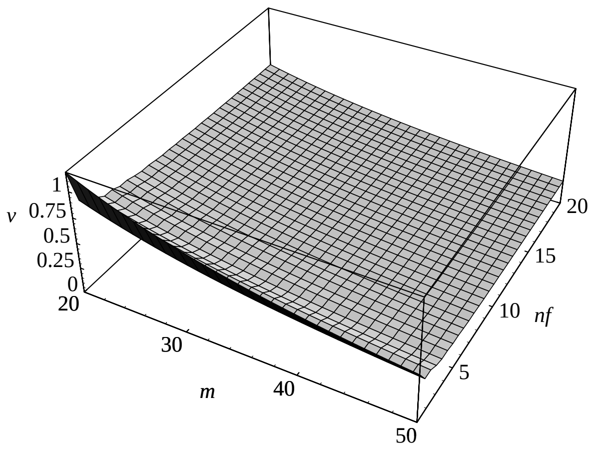

Fig. 10: Critical velocity v ($n_e = 0.2m$)

places distributively, local communication might be appropriate. In an environment where tasks appear rather rarely, in contrast, global communication had better be chosen.

4.3 Critical Velocity in Local Communication

As seen in Figs. 8 and 9, the velocity of robot motion in local communication, v, plays an important role in the evaluation of transmission time.

When n_e and n_f are determined from the given task, we can compute the critical value of velocity v which decides the more effective communication type, by equating $T_{glo}(n_f)$ in (10) and $T_{loc}(n_e)$ in (7). This critical velocity calculated by numerical computation is plotted versus total robot number m and n_f in global communication in Fig. 10 when the information should be transmitted to 20% of total m robots ($n_e = 0.2m$). Other parameters are the same as those in Table 1 and 2.

In Fig. 10, the critical velocity v decreases monotonously as either of m and n_f increases. This characteristics holds also for other values of n_e.

This graph allows us to know the minimum value v so that local communication is more efficient than global from the viewpoint of transmission time to n_e robots for given values of (m, n_f).

The average values of n_f and n_e can be known if a task is specified. Using the analytical results so far, we can determine which communication type is more efficient following the analysis so far. This helps the design of systems that consist of many cooperating mobile robots.

5 Conclusion

In this paper, we have evaluated the efficiency of local and global communication for distributed mobile robotic systems. The efficiency is compared based on the transmission time to desired number of robots from multiple robots.

As analytical results, the transmission time in local and global communication has been derived as analytical formulae. They simplify the comparison and allow us to know which communication type is more effective when given such parameters as total robot number, the number of robots which should output or receive the information and the motion velocity. The analysis has confirmed that local communication is suitable for distributed cooperating systems with many mobile robots, and also that global communication is fit for centralized task execution. Which communication to choose depends on the property of environment where cooperative tasks are given.

These results are very helpful to the design of efficient cooperative system according to the characteristics of tasks.

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