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複数移動型作業ロボットの空間共有のための情報伝達および協調戦略に関する研究

A Study of Communication and Cooperative Strategies among Multiple Mobile Robots for Solving the Sharing Area Problem

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1. Introduction

At a first glance it looks very difficult to work with multiple robots. We can build one robot that is capable of doing everything but it highly depends upon the nature of the task. Here we argue that following are some reasons why two robots (or more) can be better than one:

- task distribution: Some part of the task is allocated to each robot
- parallelism: Many robots can perform the task at the same time
- simplicity: It is easy to construct a robot with partial capability as compared to a single comprehensive robot
- fault tolerance: Task can be completed even any member is unable to perform the task··

These are the reasons, why we prefer multiple robot system. The big problem with multi robot system is how their motions can be harmonized and how proper coordination at each stage of the task among them can be realized. This degree of difficulty depends heavily upon the task and the communication and strategies chosen to solve the problem. Thus in this study different strategies for realizing cooperation and coordination among multiple robots and affects of different information over system performance will be discussed.

1.1 Task for this research

Intelligent Robot Contest [6)] is held every year in Sendai, Japan. Different kind of objects like empty coffee cans, soap and tennis balls are scattered in the field. These all objects are of different shape, size and colors. The task is first to search these objects, collect and finally dump them to their respective waste baskets after identification. No doubt this task can be accomplished with a single robot as well. Main objective to introduce the multi robot system is to investigate and evaluate different strategies to achieve the coordination among the multi robots by exchanging different information among them.

When multi-robots use some shared resources like same work area or same goal area then there is need of coordination and cooperation without which completion of task is highly impossible and system can come across some collision. Intelligent Robot Contest provides some interesting, common and popular topics of cooperation in the field of multiple robot system. These are

- Cooperation among the robots when they share time and area to avoid collisions
- sequence action cooperation when more than one robot perform some task
- Coordination of robots in the common sweep area

In this work we wish to study cooperation and coordination required by the robots when more than one robots share some common area or perform the task which requires time sharing. Keeping this problem in view we present different strategies based on different information. These strategies will lead towards an efficient and collision free robot system. Here below common area to be used by two robots is shown in Fig.1. There

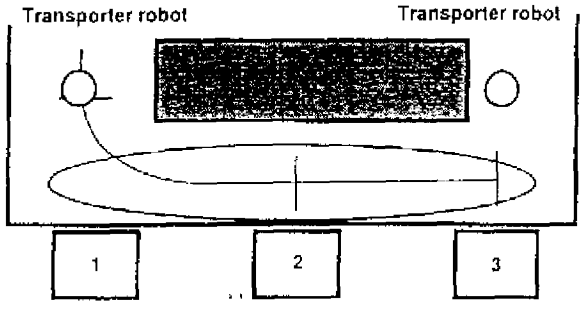

Fig. 1 Task for the transporter robots

are number of ways to solve the problem. Here below a brief survey of related literature in cooperation and coordination of multi robots and the works which are directly related to this task is given.

1.2 Related works

Needs of communication in multi-agents system are discussed by Balch and Arkin [2]. An example of cooperation of multi-agents is described by Balch et al.[1]. On distributed manipulation using different information Donald et al [3] have shown the effectiveness of information invariants. A considerable amount of research has been conducted in the contest of coordinating multiple automatic guided vehicles using road or path networks in the context of manufacturing environments [4]. Jiang et al. [5] has discussed the problem of coordination of multi robots in the manufacturing industry for parts assembly using off line planning.

1.3 Research Targets

Reviewing all the works related to this task we see that there is no profound research that provides a comprehensive solution by discussing cooperation and coordination of multi robots along with an analysis of effects of different information over the performance of the multi robot system in the common sharing area problem.

Different methods based on different information can solve the problem but each has some merits and demerits. Here basic thinking is to analyze the effects of different information over coordination and cooperation when robots share common areas. These information may be time, position, velocity, goal or state of a robot etc. For the common sharing area problems, first of all it is tried that only one robot should use the resource. In case more than one robot use the resource there must be some specific pattern to avoid any conflict.

Here below different solutions will be presented in two stages. The first solution uses only explicit communication. Second solution relies on real time sensor information but also uses some explicit communication in certain cases.

Analyzing these strategies we conclude that there are two types of information. These are static and dynamic information. Some static information (like goal information) and dynamic information (like distance information by sensor) always improve the system performance in all aspects showing a tight relation with the common sharing area. At the same time there is a group of static information like velocity which have loose relationship with common sharing area. This kind of information introduce some bad effects (e.g. fault tolerance point of view) along with improved performance.

1.4 Robot system

Robot system to be used is comprised of two robots named as transporter robot (robot used to transport object from one place to another). Hardware architecture of the system is shown in Fig.2.

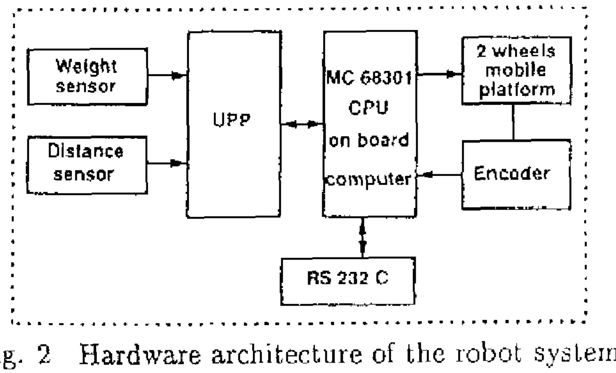

Fig. 2 Hardware architecture of the robot system

Assumptions of robot system

1) The robots are autonomous one
2) The robots use communication for information exchange
3) Both robots start the task almost at the same time.
4) Both robots use distance sensors for real time information.

Fig. 3 presents a view of real robot system i.e. 2 robots 3 goals.

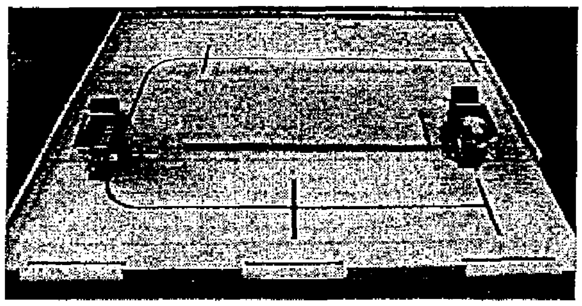

Fig. 3 A view of the practical robot system

1.5 Report organization

First of all a strategy using explicit communication (strategy A) in three steps will be given in section 2. Section 3 discusses the performance evaluation of strategy A. Strategy B which is based on real time sensor information is presented in section 4. Next section (section 5) is reserved for evaluation of strategy B like section 3. Comparison between strategy A and B is presented in section 6 whereas in section 7 summary and future work has been described.

2. Strategy A: An explicit communication based strategy

In strategy A robots rely on explicit communication for coordination in common area to be shared. In strategy A robots transmit starting time, goal and velocity information in three steps. Sub strategies of strategy A are discussed in the following paragraphs.

2.1 Strategy A1

In strategy A1 task starting time information is transmitted by the high priority robot. Only high priority robot can perform the task in the commonly shared area. Robot gets high priority only either there is no other robot in the commonly shared area or when other robot finishes the task in the common area.

The highlights of this strategy are

- Task starting time information based strategy
- If no robot is using any goal, high priority to first robot
- Low priority robot will wait during this time
- High priority robot delegates its priority to other robot after completion of the task

In strategy A1 only single bit information is used. High priority robot shown in Fig. 4 as H. Priority release from high priority robot enables the low priority robot L in Fig. 4 to perform the task. This solution does not fulfill the purpose of using multi robot system as we have only one robot working at a time.

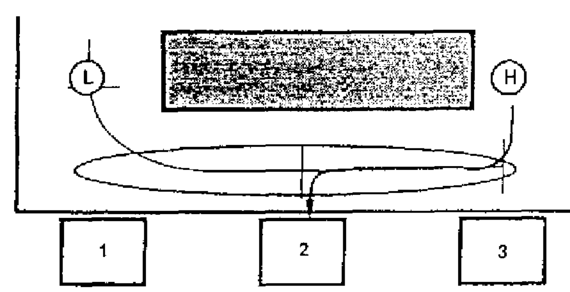

Fig. 4 Strategy A1

2.2 Strategy A2

In strategy A2 there is a trick to utilize the system resources in a better way. High priority robot transmits two information. One is starting time (about priority) and second is goal information. Goal information from high priority robot enables the low priority robot to perform the task in some area which is not under the use of high priority robot.

- Same as strategy A1
- Addition of goal information
- In some cases different goals can be approached by two robots at a time
- Low priority robot will wait when either both robots want to use the same goal or all area is under the use of high priority robot

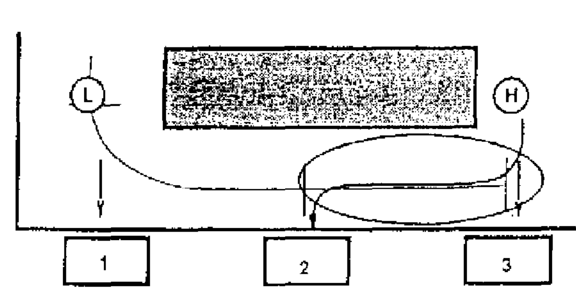

Fig. 5 Strategy A2

When goal of high priority robot is goal 2, low priority robot is free to go to goal 1. Area for high priority robot is marked as ellipse in fig. 5. Thus increase of information from single bit to 3 bits (66% more) provides some chances to low priority robot to use the common area.

2.3 Strategy A3

Strategy A3 is different from A1 and A2. As low priority robot can also perform the task before high priority robot. But for this purpose there should be some other information which can help low priority robot to estimate the time of high priority robot to perform the task and its own lagging time. This can be achieved from velocity information. The highlights of strategy A3 are

- Same as strategy A2

- Addition of velocity information

Adding velocity information to the strategy A2 makes possible for the system to share the goal 1 and goal 3 at a time. The strategy can be understood by considering the following case as an example. The high priority robot got the object

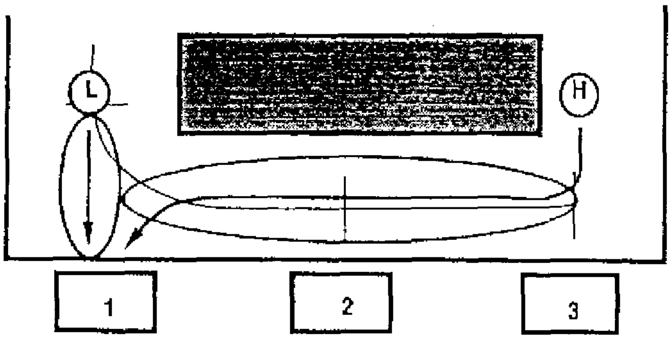

Fig. 6 Strategy A3

for goal 1 and according to A3 transmitted starting time, goal and velocity information to other robot. In the mean time low priority robot also got the object for the same goal. Low priority robot from the information it already has will estimate whether it is possible for it to complete the task before high priority robot reaches there as shown in Fig. 6. If not possible to perform the task, it will estimate when goal will be released and finally perform the task at that time.

3. Performance evaluation of strategy A

Time taken by required by the two robots to dump two objects simultaneously and fault tolerance will be discussed to evaluate the performance of strategy A

3.1 Time calculation

Different assumptions for time calculation are:

1) Both robots start the task almost at the same time.
2) The robots always move forward/backward with the same velocity
3) Dumping time (t_d) for each robot is same.
4) The time required by each robot from positions A, B or C to goal 1,2 or 3 respectively is included in t_d .

In strategy A1 time taken by two robots is sum of the average time taken by high priority robot for all 3 goals and average time taken by low priority robot for 3 goals. For strategy A2 and A3 time taken by robots is calculated for all possible 2 robots 3 goals combinations i.e. 9 cases and then average is calculated. Different time variables are shown in Fig. 7. The results are as follows.

- Strategy A1

$$\bar{t}_{total} = \bar{t}_l = 4t_1 + 4t_2 + 2t_d \qquad (1)$$

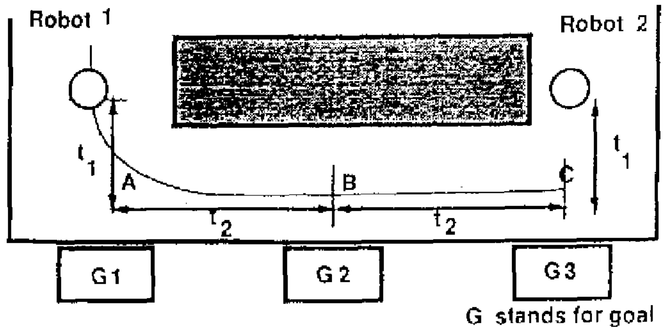

Fig. 7 Time indication diagram

- Strategy A2

$$\bar{t}_{total} = \begin{cases} 2t_1 + \frac{32}{9}t_2 + \frac{14}{9}t_d & (2t_2 > t_d) \\ \frac{19}{9}t_1 + \frac{10}{3}t_2 + \frac{5}{3}t_d & (2t_2 < t_d) \end{cases} \qquad (2)$$

- Strategy A3

$$\bar{t}_{total} = \begin{cases} 2t_1 + \frac{28}{9}t_2 + \frac{4}{3}t_d & (2t_2 > t_d) \\ 2t_1 + \frac{8}{3}t_2 + \frac{14}{9}t_d & (2t_2 < t_d) \end{cases} \qquad (3)$$

Two conditions $2t_2 > t_d$ and $2t_2 < t_d$ specifies certain cases related to waiting time of low priority robot. This depends upon the selection of t_d.

In the real robot system average time taken by two robots to dump two objects can be calculated by using following values of different times.

$t_1 = 10, t_2 = 13$ and $t_d = 30$ ($2t_2 < t_d$)

- Strategy A1 $\bar{t}_{total} = 152.0$ sec
- Strategy A2 $\bar{t}_{total} = 122.9$ sec (80.8% of A1)
- Strategy A3 $\bar{t}_{total} = 104.7$ sec (68.9% of A1)

3.2 About fault tolerance

Another parameter that can affect the system performance is the fault tolerance. Different possible faults in the system may occur but here only a typical case i.e. when any one of the two robots dies will be presented.

- Strategy A1: As per strategy only high priority robot can perform the task in the common area. If high priority robot dies during performing the task, it will never be able to release the priority and low priority robot will remain in waiting state. But when low priority robot dies high priority robot continues to perform the task. In this regard strategy A1 is a robust one as we don t see any sort of collision in the common area.
- Strategy A2: Case is same like A1 when low priority robot dies. In case high priority robot dies during task performance, in some cases it leaves some area for which low priority robot may continue. Thus addition of goal information improves fault tolerance capability.

- Strategy A3: In strategy A3 robots estimate to find the area free. This creates some risks of collisions in the common area. Thus we conclude that it is always not true that increase of information always improve the performance. No doubt, in A3 time taken by the robots is reduced up to 67% but on the other hand we have some risks of collisions.

4. Strategy B: Sensor information based

Strategy A relies totally on explicit communication. In strategy B the robots are equipped with distance sensors which can detect the presence of any robot or obstacle at a certain distance. Using this information required coordination can be achieved in the common sharing area. For this purpose total area to be shared

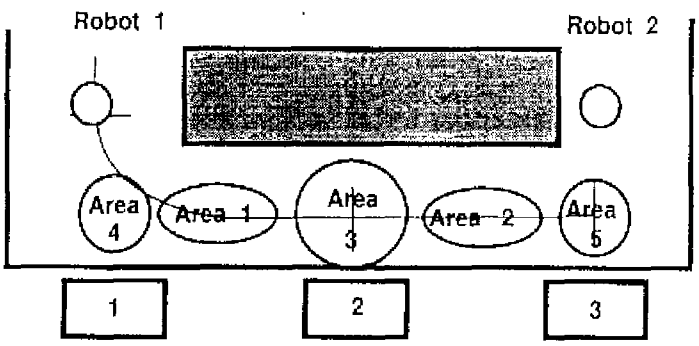

Fig. 8 Strategy B

is divided in two groups, common road area and common goal area. Fig. 8 shows area 1, area 2 as common road area (where robot can cross) whereas area 3, area 4 and area 5 are common goal area (crossing not allowed).

Like strategy A strategy B will be discussed in three steps.

4.1 Strategy B1

Strategy B relies only on sensor information is used to achieve the coordination in the common area. Using distance sensor information two different behaviors have been devised. Low priority robot always maintains a distance d_1 from high priority robot. High priority robot will always stop at a distance d_2 whenever it detects low priority robot.

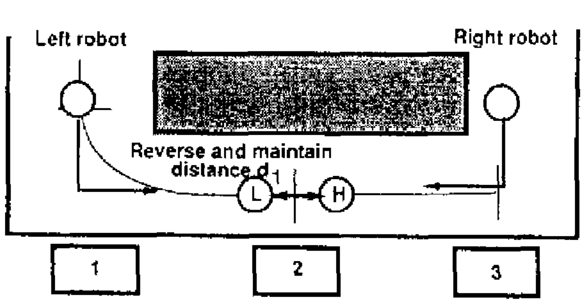

Fig. 9 Strategy B1

The highlights of strategy B1 can be described as follows.

- No explicit communication
- High priority to right robot
- Low priority to left robot
- For the common goal area
  1) Low priority robot maintains the distance d_1 in case robots come face to face.
  2) High priority robot will stop at a distance $d_2, (d_2 < d_1)$ if it detects low priority robot at some goal area.

High and low priority is at the time when robots meet each other. Robot coming from right side of Fig. 9 will be of high priority (H) whereas the robot from left side will be low priority (L) robot. Here when low priority robot sees the high priority robot, it will reverse itself until it comes in the common road area where it can cross the other robot to proceed further without disturbing high priority robot. Here priority is only to manage the crossing.

4.2 Strategy B2

It is very similar to strategy B1. Two bits goal information is added to strategy B1. High priority robot at the start of task transmits 2 bit goal information. In this case low priority robot having knowledge of goal of high priority robot and his own can manage the crossing. The main features of strategy B2 (Fig. 10) are

- Same as strategy B1
- Addition of goal information by high priority robot
- Low priority robot will manage crossing in the common road area

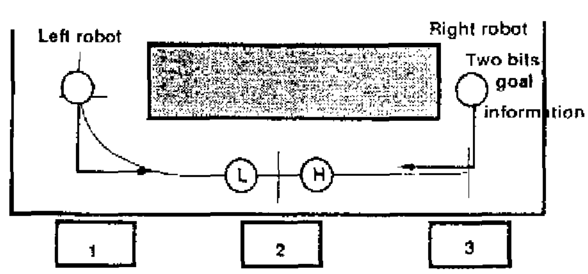

Fig. 10 Strategy B2

This goal information is helpful for crossing in common goal area as it avoids extra reversing of low priority robot.

4.3 Strategy B3

In strategy B3 both robots transmit goal information at the starting of the task. This method is helpful in the case when high priority robot goes to goal 2 and low priority robot's goal is 3. High priority robot will let the low priority robot to cross before it enters in the goal 2 region for dumping. This also improves only one case as compared to strategy B2.

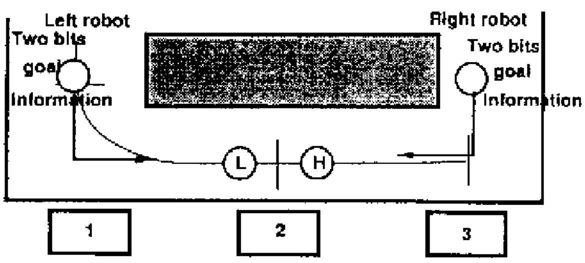

Fig. 11 Strategy B3

The highlights of strategy B3 are:

- Same as strategy B2
- Low priority robot also transmits goal information
- High priority robot will arrange crossing for different goals of the robots in common goal area.

Fig. 11 explains these characteristics.

5. Performance evaluation of strategy B

Like strategy A time taken by two robots and fault tolerance will be discussed to evaluate the system performance.

5.1 Time calculation for strategy B

Time taken by the robots to cover the distances d_1 and d_2 is $2t_{d_1}$ and $2t_{d_2}$ respectively. t_3 is the time taken by the high priority robot to come out from common goal area to common road area. t_4 is the difference of time taken by the robot on curved trajectory and straight line. In strategy B time for all possible 2 robots 3 goals combinations will be calculated and then average will be given. In strategy B there are 3 conditions on dumping time t_d because of t_{d_1} and t_{d_2}. Here below only one case will be described to show the results.

General time taken by two robots in strategy B for the case $2t_2 - t_d < 2t_{d_2}$

- Strategy B1 $2t_1 + \frac{20}{9}t_2 + \frac{13}{9}t_d + \frac{4}{9}t_3 + \frac{4}{9}t_4 + \frac{10}{9}t_{d_1} + \frac{2}{9}t_{d_2}$
- Strategy B2 $2t_1+\frac{20}{9}t_2+\frac{13}{9}t_d+\frac{4}{9}t_4+\frac{2}{3}t_{d_1}+\frac{2}{9}t_{d_2}$
- Strategy B3 $2t_1+\frac{20}{9}t_2+\frac{12}{9}t_d+\frac{5}{9}t_4+\frac{5}{9}t_{d_1}+\frac{2}{9}t_{d_2}$

The time taken by two robots considering the following numerical values is presented here below.

In case $2t_2 - t_d < 2t_{d_2}$ taking $t_d = 30$, $t_1 = 10, t_2 = 13, t_3 = 2t_4 = 5, t_{d_1} = 1.5$, $t_{d_2} = 1$

- Strategy B1 $\bar{t}_{total} = 97.2$ sec
- Strategy B2 $\bar{t}_{total} = 96$ sec
- Strategy B3 $\bar{t}_{total} = 92.89$ sec,

These results show that even addition of goal information by high priority robot in B2 and by low priority robot as well in B3 does not affect the time taken by two robots too much. The reason is that system is already using real time sensor information. Therefore out of nine possible cases each time only one or two cases are affected and that difference may be very small when average is taken. As sensor information plays a role of implicit communication and in the presence of implicit communication explicit communication does not improve the performance too much.

5.2 Fault tolerance for strategy B

Here under this title we shall analyze all solutions presented in strategy B using sensory information alone or along with explicit communication. The purpose of this analysis is to observe the fault tolerance of the system. Such analysis may be helpful to provide some solution for different nature of faults. System can face different nature of faults but here we shall only analyze a typical one i.e. when any one of the two robots cannot perform the task.

5.2.1 Strategy B1

In this case, the system relies of sensor information. In strategy B high or low priority is assigned when there is need of coordination or when robots are face to face. Thus during the process of task performance, if any robot dies, sensors of the other robot make possible for it to avoid the collision in the common sharing area. For example if low priority robot dies during work in the common road area, as per behavior of high priority robot it will stop at a distance of d_2 and will remain waiting until the dead robot is not removed physically. The same is the case when high priority robot dies. The behavior of low priority robot is that it will maintain a distance d_1 from the high priority robot. Thus it will again stop at this specified distance. In both of the cases there is not any danger of collision.

5.2.2 Strategy B2

In strategy B2 there is an addition of goal information from high priority robot. Goal information from high priority robot does not provide any means of avoiding collision but it only reduces some time taken by low priority robot to reverse itself. Fault tolerance capability may be improved in this case if robots use sensor information along with goal information to avoid collision. This is because that low priority robot having goal information of high priority robot will be a collision conscious robot in that area.

5.2.3 Strategy B3

As both robots transmit goal information at the time they start the task. In case anyone of them dies, other robot can perform its task if dead robot is removed from the way. Goal information from both robots improve the fault tolerance capability as both robots can use this information to be conscious to collision in that area. Thus addition of goal information from both robots improves the fault tolerance capability.

6. Comparison between strategy A and B

In the above sections different ways to share the common area and avoiding the collisions between the robots have been discussed. Every solution has some advantages and some disadvantages. In strategy A all solutions were relied on explicit communication, initially from one bit starting time information in A1 to 6 bits information in A3. Increase of quantity of information reduces the time taken by the system up to 67% but at the same time it was observed that fault tolerance capability was not improved from strategy A2 to A3. This concludes that different information play different roles. Here velocity information has the loose relation with coordination whereas goal information has tight relationship with coordination. Thus we observe improvement in performance from A1 to A2 but a risky system from A2 to A3.

Strategy B mostly relies on real time sensor information for coordination in common area sharing problem. Using real time information average time of strategy B is less than that of strategy A. An interesting thing is that even increasing the quantity of information within strategy B does not show any specific reduction of time. On the other hand it provides a robust system when we consider fault tolerance. This also proves that in the presence of implicit communication explicit communication does not improve the system performance too much as it is always expected.

7. Conclusion and future work

Two strategies were presented and different aspects were analyzed. In Strategy A stepwise different information were exchanged using explicit communication and different solutions for common area sharing problem were devised. For strategy B we used the hammer of real time sensor information for solution of the problem. From this discussion it is concluded that there are two types of information, static information and dynamic information. Some static information for example goal information improve the system performance both time and fault tolerance point of view showing a tight relation with common sharing area. At the same time dynamic information (real time) not only reduce the time of the system but also make the system more fault tolerant. On the other hand velocity information introduce the risks of collisions (fault tolerance point of view) along with improved efficiency.

For future first of all we want to implement these described strategies to the present robot system. These strategies were presented for two robots 3 goals. How different information affect coordination if there are n ($n > 2$) robots and m goals ($m > 3$), is the next step of this work.

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