CONF-9011115--1

DE91 001491

SAFE MOTION PLANNING FOR MOBILE AGENTS —A MODEL OF REACTIVE PLANNING FOR MULTIPLE MOBILE AGENTS—*

Kikuo Fujimura

Center for Engineering Systems Advanced Research
Oak Ridge National Laboratory
P.O. Box 2008
Building 6025, MS-6364
Oak Ridge, TN 37831-6364

Submitted to: The 1990 SPIE Symposium on Advances in Intelligent Systems, Mobile Robots V, Boston, Massachusetts, November 4-9, 1990

* This work is supported in part by the Office of Engineering Research Program, Basic Energy Sciences, of the U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. and in part by an appointment to the U.S. Department of Energy Postgraduate Reasearch Program administered by Oak Ridge Associated Universities.

Safe Motion Planning for Mobile Agents *

– A Model of Reactive Planning for Multiple Mobile Agents –

Kikuo Fujimura
Center for Engineering Systems Advanced Research
Oak Ridge National Laboratory
P.O.Box 2008, Oak Ridge, TN 37831-6364

Abstract

The problem of motion planning for multiple mobile agents is studied. Each planning agent independently plans its own action based on its map which contains a limited information about the environment. In an environment where more than one mobile agent interacts, the motions of the robots are uncertain and dynamic. A model for reactive agents is described and simulation results are presented to show their behavior patterns.

1. Introduction

Motion planning to achieve a given task is one of the fundamental abilities required by intelligent mobile robot systems. There has been much research on motion planning for a single mobile robot in known environments containing stationary obstacles [Loza79, Yap84] as well as moving obstacles [Reif85, Erdm87, Kant86, Fuji89, Warr90]. There is also research on sensor-based planning systems for a robot in unknown environments [Elfe89, Weis89]. We envision that in the future a situation will arise where multiple autonomous robots must carry out their tasks concurrently in the same environment. We would like the autonomous robots to work cooperatively without interfering with each other. In such a multi-robot environment, one of the requirements for each agent (i.e., mobile robot) is to coordinate its motion with those of others. This requires an agent to have a higher level of ability than simply planning a motion in the presence of obstacles that move along known trajectories, since the motions of other agents are, by nature, not known ahead of time. This paper introduces a model of such dynamic reactions for multiple mobile agents in dynamic domains.

The few previous authors dealing with multiple mobile robots [Sait89, Tour86, Lee90] consider a set of *homogeneous* robots, i.e., all robots are identical in the sense that they are operated under an identical set of simple rules. Realistically, however, the workspace may contain robots of different capacities. For example, visual processing abilities as well

* This work is supported in part by the Office of Engineering Research Program, Basic Energy Sciences, of the U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. and in part by an appointment to the U.S. Department of Energy Postgraduate Research Program administered by Oak Ridge Associated Universities.

as mobility may vary for all robots. Motivated in this manner, we consider *heterogeneous* multiple robots, i.e., a set of agents with different capabilities with respect to their sensors, planning algorithms, etc. We would like the mobile agents to be completely autonomous, determine their actions on their own, and react properly to the actions of other agents.

When several mobile agents with various degrees of intelligence interact, the resulting scenario can be quite complex. To cope with this situation, we have built a simulation system that enables us to observe various behaviors of heterogeneous mobile agents of a set of different capacities at various settings. We consider two factors to model the mobile agent: (i) planning algorithms and (ii) knowledge about the environment. Our study is distinguishable from other approaches for multi-robot coordination in that our aim at this stage is to observe how planning and knowledge about the environment affect the overall performance of coordination of the agents, rather than designing a set of robots that simply follow predetermined rules of action. In this preliminary study, we report some experimental results obtained through simulation of such autonomous mobile agents. Our simulation results reveal some interesting facts about the roles of planning and knowledge for a reactive system in dynamic domains.

The rest of this paper is organized as follows. Section 2 briefly reviews previous research in the area of coordination of multiple robots. Section 3 describes our models of mobile agents used for simulation. Section 4 presents simulation results and Section 5 contains a few concluding remarks.

2. Previous Work

A survey of previous work on coordination of multiple robots shows that the motion planning problem for multiple robots is usually stated as follows. Given a set of objects B, a set of obstacles, initial and goal positions for the objects of B, plan a motion of the objects of B from their initial positions to the goal positions such that they do not collide with the obstacles or with each other.

There have been two formulations for the problem based on the form of computation: centralized approaches and distributed approaches. In centralized approaches, all computation is performed at a single site (called *central planner*) that has all information about the shapes of the robots and geometry of the environment. Motions for all robots are completely determined by the central planner at one time. After the solution is found, each robot follows the motion determined by the central planner. This problem is also called the "many body problem" [Hopc84, Yap84]. The planner determines exactly whether or not there exists a solution for the given set of robots, and plans such motion if it exists. The planning process usually terminates before the execution of the motions begins. For central approaches, see [Yap84, Hopc84, Erdm87, Buck89, Warr90].

On the other hand, distributed approaches do not have such a central planner. Instead, each robot acts as an independent agent and determines its motion based on a limited amount of information about each agent. The agent needs to revise its plan as new information arrives. Usually, each agent makes use of local information (typically obtained through its sensors) to plan its motion to the goal location. Our approach fits in this category. As opposed to the centralized approach where global information about the environment is completely known, only partial information of other agents is known to each agent. Planning is reactive in the sense that a plan will have to be revised as new information invalidates the old plan. In a distributed approach, a general strategy for resolving conflicts when two robots get near is to move away from each other so as to avoid collision. Tournassoud [Tour86] uses separating planes for obstacle avoidance. Saito and Tsumura [Sait89] use velocity vector modification together with risk evaluation functions. Lee and Bien [Lee90] use neural networks to handle multiple mobile robots. A drawback of distributed approaches is that solutions are usually not globally optimal. Also, it is possible for robots to be trapped in a deadlock situation.

Some researchers propose use of a hybrid of these two approaches. A central planner determines global routes for the robots, while local conflicts are resolved by independent robots [Yeun87, Pape90]. In such a system, the central planner is evoked when an event occurs that can not be resolved between the agents (e.g. deadlock). None of these approaches discuss multiple distributed agents that have different sets of capabilities.

3. Mobile Agents

This section describes the model of mobile agents that is used for our simulation. An agent is modeled by the combination of two factors: a planning algorithm and knowledge about the environment. These factors respectively represent how well the agent can navigate to the destination point based on knowledge about the environment and how much the agent knows about the current status of the environment. At this initial phase of our study, the agent model is limited in the sense that the agents only take into consideration a set of relatively simple factors for determining their actions. There are many factors that are not considered in this model. For example, the agents are not able to infer other agents' mental processes.

In our system, each robot is assumed to have a local map through which knowledge about its surroundingsis obtained. The map is assumed to be constantly updated as the agent moves. Each map has a scope such that objects that are inside the scope of the map are precisely known to the agent, while objects outside the scope are not. This models a situation where each agent is equipped with a sensor with a limited scope that enables the agent to acquire information around itself[1]. Given a destination point to be reached, each agent plans its future action based on the map information surrounding the agent and generates a plan so as to minimize its own motion (e.g. with respect to time, distance) to the destination point. The agents are completely independent and do not communicate with each other (other than seeing each other). In this paper, we restrict ourselves to the interaction of two robots that meet on their way to destination points. This type of interaction happens in multi-robot domains frequently. Now we describe the three factors that define the agent model.

Planning algorithms: The agents use one of the two planning algorithms described here. The first one uses the concept of visibility. Two points on the plane are said to be visible if

[1] A priori knowledge about the environment may also be contained in the scope.

the line segment connecting the two points is not intersected by any object. Making use of the concept of visibility, the visibility graph is defined for a set of polygons as follows. The vertices of the graph are the vertices of input polygons plus start and goal points. An edge exists between two vertices of the graph when the two vertices are visible to each other. The visibility graph is often used for path planning among stationary obstacles [Loza79] together with configuration spaces in which the robot is treated as a point. It is known that a shortest-length path is obtained as a sequence of edges of the visibility graph. Note that in a dynamic environment, the graph must be constantly updated.

Another algorithm we have adopted for our simulated agent is based on the concept of accessibility. The agent computes a future location of other agents. Each agent moves in the direction in which a future collision can be avoided. Suppose that the robot moves at a constant speed. All directions around the start point can be decomposed into subsets of directions in which the robot will meet or not meet an obstacle. The robot is moved to a direction in which it does not meet any of the obstacles.

More formally, the concept is defined as follows. A point V is said to be accessible, if there exists a direction of motion of the agent such that the agent meets V without prior interception by any other movement.[2] The set of accessible points corresponding to all points on an obstacle forms a segment. The robot is moved to an endpoint of the segment. Making use of the concept of accessibility, we can construct a graph called the accessibility graph. It is known [Fuji89] that a time-minimal motion is obtained as a sequence of edges in the accessibility graph. Both algorithms are known to run quite fast (i.e., a low degree of polynomial time). Therefore, it does not pose any computational problem even if an agent must compute the whole motion to the goal each instant of time. The two planning algorithms are contrasted by the fact that both try to optimize the motion using different quantities (time or distance). We presume that the one based on accessibility is "smarter" than the one based on visibility since accessibility takes the motions of other objects into consideration, while visibility does not. As a result of this choice, each agent avoids collision by changing the direction of motion, while moving at a constant speed. Alternately, we could have adopted other planning algorithms among moving obstacles such as the ones described in [Kant86, Warr90].

Knowledge about the environment: Each robot needs to plan its motion based on its map information. The map represents the current information available to each agent. Each map has a limited amount of information around the agent. The shapes and locations of objects that lie within a given scope are assumed to be correct. However, an agent may not have any information about objects outside the scope, or even if it does, the information about the objects outside the scope of the map may not correctly reflect the status of the environment. For example, objects that were previously inside the scope and not in the current scope may or may not be in the same location. In the future when communication is possible between agents, an agent may have information local to other agents as well.

[2] Note that the accessible point of a particular point varies for different values of the speed and the initial location of the agent

The scope of the map is a variable that can be changed in our model. The larger the scope is, the more information is available to the agent. The speeds and moving directions of other agents can be computed from their locations in two consecutive maps (assuming that map updates are frequent enough).

All agents compute an optimal solution with respect to either distance (based on visibility) or time (based on accessibility) for their motions toward their goals based on their maps at each instant of time. When planning a motion, an agent assumes that objects that are not currently in its map (i.e., unknown obstacles) do not exist and that the current status of the world will hold in the future (until told otherwise). However, the world will change because (i) a new object enters its map, (ii) the course of motion of the other agent changes, and (iii) an optimal solution at an instant of time may not be optimal at another instant. In these cases, the plan must be revised. As a result of the revision, other agents may also be affected and may need to revise their plans.

Even with this simple model of a mobile agent, when two robots interact, the resulting motion can be complex. We have built a simulation system that simulates behaviors of independent mobile agents with different capabilities. Our preliminary results show that there may arise a counter-intuitive scenario when agents interact. This suggests that we need to be careful before any algorithm is implemented for multiple independent mobile agents working in the same environment.

Our simulation system assumes the following for each mobile agent. Each agent needs to plan its motion based on its local map information. The map contains exact information about the shapes and locations of objects that lie within a certain distance from the agent (called scope of the map). It plans its motion, moves, and acquires information from the outside world iteratively. Each robot avoids collision by changing the direction of motion, while moving at a constant speed (alternately, it could slow down, etc).

4. Simulation Results

This section presents some of our simulation results. As we have shown in the previous section, there are three parameters that define a mobile agent. We can change each of them (or two or three of them at a time) to see the effect on the performance of the agents. We first show that deadlock is possible with two identical mobile agents. Next, we show two agents that are identical except for their planning algorithms. Then, we compare two identical agents except for the scopes of their maps. Then, we illustrate somewhat counter-intuitive scenario for two robots that are different both in their planning algorithms and scopes of the map. Finally, we show two agents with different action intervals.

Agents with different planners: Figure 1a contains a result of two mobile agents with different planning algorithms. Agent 1 uses accessibility, while agent 2 uses visibility to plan their motions. As a result, two agents move to their respective goals smoothly. Agent 2 (with visibility) starts moving straight toward its destination point, as its destination point is visible from its start point. For Agent 1 (with accessibility), the destination point is not accessible from the start point, as Agent 2 will be in its way. Thus, Agent 1 has a choice as to whether it moves toward the right or the left to avoid Agent 2. Agent 1 chooses to go toward the right, since it turns out to be faster. As a result, for Agent 2 (with visibility), the destination point remains visible throughout its motion, and it ends up having a straight line motion. Agent 1 changes its direction of motion when the destination point becomes accessible. In this example, none of the agents needed to change the plans that they created in the beginning.

Figure 1b contains a similar set-up of the environment with the difference being that the start point of Agent 1 is in the left hand side instead of the right hand side. The resulting motions, however, differ qualitatively from that of Figure 1a. Here is our explanation. Agent 2 starts moving straight toward its destination point as before, while Agent 1 starts heading toward the right, trying to avoid Agent 2, soon after it leaves the start point. Agent 2 does not react to Agent 1 until Agent 1 comes near location X, where the destination point of Agent 2 becomes no longer visible due to Agent 1(i.e., Agent 1 is in its way). This requires Agent 2 to revise the current plan. Agent 2 chooses to move toward the left, since it turns out to be shorter, assuming the current motion of Agent 1. This action of Agent 2 affects Agent 1. It requires Agent 1 to reconsider its course of action when it comes to point X. At X, going around Agent 2 from the right becomes no longer time-minimal for Agent 1. As a result, Agent 1 revises its action and determines to move toward the left to avoid Agent 2.

Agents with different scopes of the map as well as different planners: We have seen in the previous example that the one that uses accessibility is the key agent, since it takes action toward resolving a potential conflict between the two agents. An interesting question is: what happens if the agent with a better planner has a narrower scope of the map? Figures 2a-c show a set of motions generated by the two agents, one of which has a better planner and the other has a larger scope of the map.

Agent 1 uses accessibility while Agent 2 uses visibility. The scope of the map for Agent 1 is varied from 2 to 5, while that of Agent 2 is fixed to 10. In other words, Agent 2 always has more information about the environment than Agent 1. As we vary the scope of the map of Agent 1 from 3 to 10, we expect that the performance of Agent 1 will continually improve. However, the results don't show this.

We observe from Figure 2a and 2b that the performance of Agent 1 certainly improves as its scope of the map gets wider. However, when we move to Figure 2c where the scope of the map is even wider, the motion of Agent 1 is qualitatively different from those of Figures 2a and 2b and its performance degrades. It exhibits a behavior pattern shown in the previous examples (Figure 1). This phenomenon follows from the fact that Agent 1 with the scope of the map 5 was too far away from Agent 2 when it perceived Agent 2 and thought going around Agent 2 in the right would still work.

One explanation is that Agent 1 had a greater amount of information only about what the environment is now, but it did not have any information about what the environment was going to be in the future. In other words, it was not able to infer the future from the available information at present. This results in a poorer performance despite the fact that the amount of available information was greater.

A similar result was obtained by Lumelsky and Skewis [Lume88]. They have investigated how vision affects the efficiency of maze search in comparison with a robot with a tactile sensor. Our intuition is that the robot with a visual sensor will outperform the robot with only a tactile sensor. They have shown that for some environments, however, the performance of the robot with vision is poorer than the robot with tactile sensor.

5. Concluding Remarks

We have considered a model of autonomous mobile agents in dynamic domains. The agents differ in their planning algorithms, knowledge about the environment, etc. We have built a simulation system which provides a testbed for conducting experiments using mobile agents with various capabilities. In some cases, the behavior of the agents is shown to be quite different from what we normally expect.

Our model for the mobile agents can be extended so as to achieve more versatile agents. The following are a few directions in which extensions are possible. In our model, we have used two algorithms for planning a motion. We can adopt various planning algorithms in dynamic domains. It remains of interest to see how an agent that makes use of other motion planning algorithms (e.g., [Kant86], [Warr90]) copes with those in our model.

References

[Buck89] - S. J. Buckley, Fast motion planning for multiple moving robots, *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale, AZ, May 1989, 322–326.

[Elfe89] - A. Elfes, Using occupancy grids for mobile robot perception and navigation, *Computer 22*, 6(June 1989), 46–57.

[Erdm87] - M. Erdmann and T. Lozano-Pérez, On Multiple Moving Objects, *Algorithmica 2*, 4(1987), 477–522.

[Fuji88] - K. Fujimura and H. Samet, Time-minimal paths among moving obstacles, *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale, AZ, May 1989, 1110–1115.

[Hopc84] - J. E. Hopcroft, J. T. Schwartz, and M. Sharir, On the complexity of motion planning for multiple independent objects: PSPACE hardness of the 'ware houseman's problem', *International Journal of Robotics Research* **3**,(4) (Winter 1984), 76–88.

[Kant86] - K. Kant and S. W. Zucker, Toward Efficient Planning: The Path-Velocity Decomposition, *International Journal of Robotics Research* **5**,(3) (Fall 1986), 72–89.

[Lee90] - J. Lee and Z. Bien, Collision-free trajectory control for multiple robots based on neural optimization network, *Robotica 8*, 3(July-September 1990), 185–194.

[Loza79] - T. Lozano-Pérez and M.A. Wesley, An Algorithm for Planning Collision Free Paths Among Polyhedral Obstacles, *Communications of the ACM* **22**(10) (October 1979), 560–570.

[Lume88] - V. Lumelsky and T. Skewis, A paradigm for incorporating vision in the robot navigation function, *Proceedings of 1988 IEEE International Conference on Robotics and Automation*, April 1988, Philadelphia, PA, 734–739.

[MacN90] - C. MacNish and F. Fallside, Temporal reasoning: A solution for multiple agent collision avoidance, *Proceedings of 1990 IEEE International Conference on Robotics anc Automation,* May 1990, Cincinatti, OH, 494–499.

[Pape90] - C. L. Pape, A combination of centralized and distributed methods for multi-agent planning and sccheduling, *Proceedings of 1990 IEEE International Conference on Robotics anc Automation,* May 1990, Cincinatti, OH, 488–493.

[Reif85] - J. Reif and M. Sharir, Motion Planning in the Presence of Moving Obstacles, *Proceedings of the 26th Annual IEEE Symposium on Foundations of Computer Science,* Portland, OR, October 1985, 144–154.

[Sait89] - M. Saito and T. Tsumura, Collision avoidance between mobile robots, *Proceedings of IEEE/RSJ International Workshop on Intelligent Robots and Systems,* September 1989, Tsukuba, Japan, 473–478.

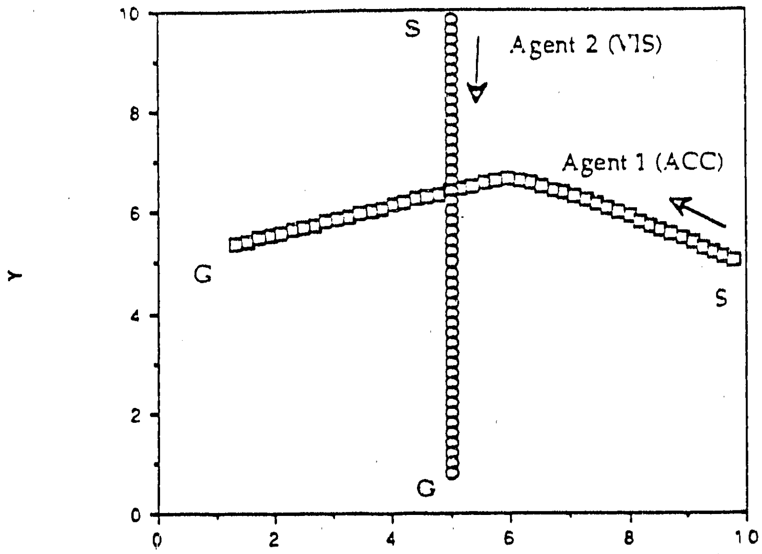
[Tour86] - P. Tournassoud, A strategy for obsacle avoidance and its application to multi-robot systems, *Proceedings of IEEE International Conference on Robotics and Automation,* San Francisco, CA, April 1986, 1224–1229.

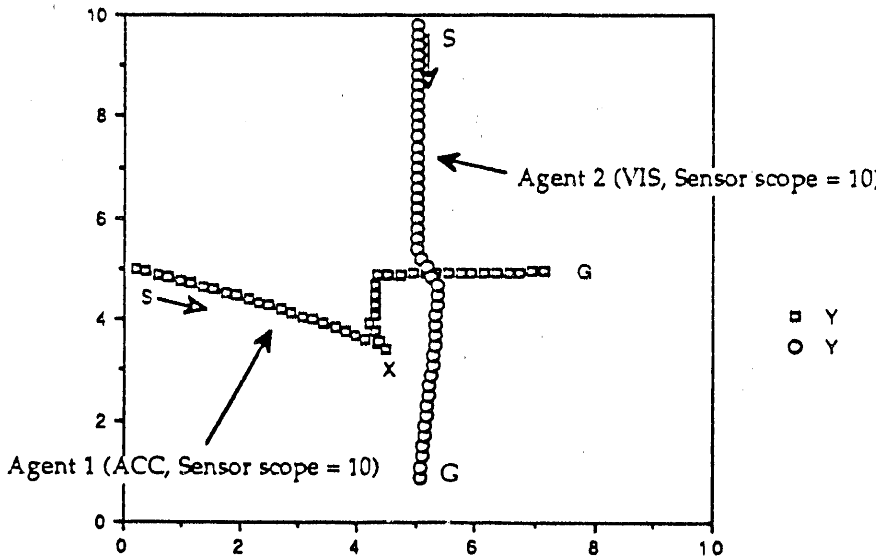
[Warr90] - C. W. Warren, Multiple robot path coordination using artificial potential fields, *Proceedings of IEEE International Conference on Robotics and Automation,* Cincinatti, May 1990, 500–505.

[Weis89] - C. R. Weisbin, G. de Saussure, J. R. Einstein, F. G. Pin, and E. Heer, Autonomous mobile robot navigation and learning, *Computer 22*, 6(June 1989), 29–35.

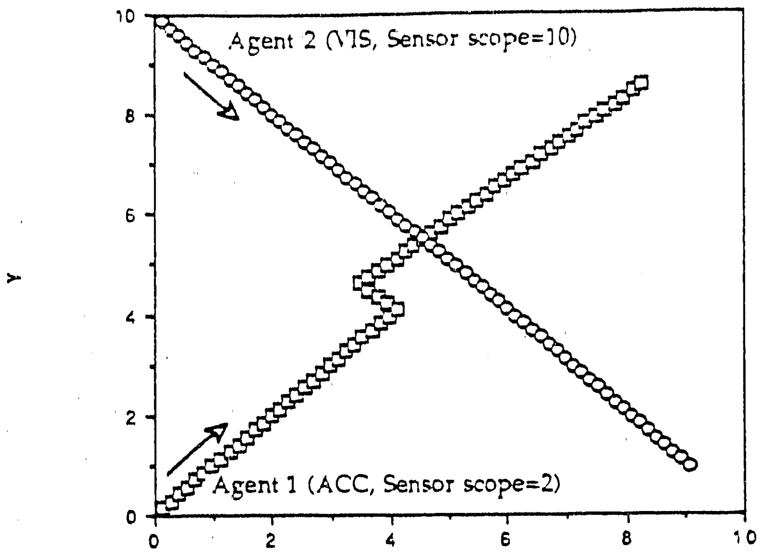
[Yap84] - C. Yap, Coordinating the motion of several discs, TR-105, Computer Science Department, Courant Institute, New York University, February, 1984.

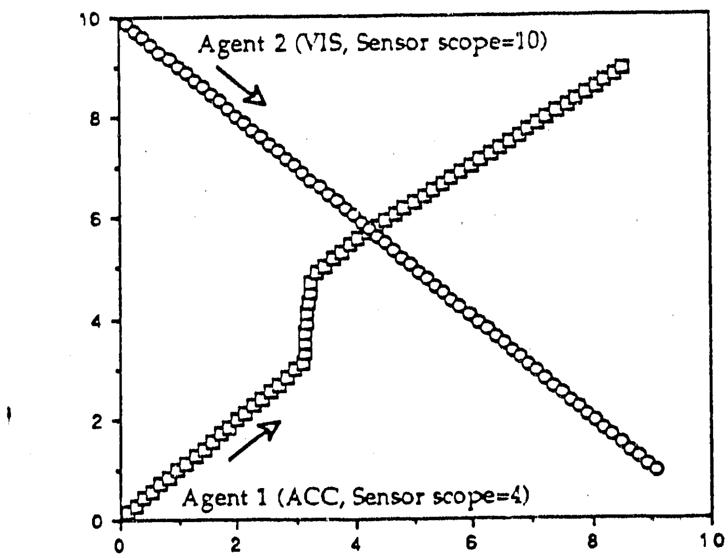
[Yeun87] - T. Yeung and G. A. Bekey, A decentralized approach to the motion planning problem for multiple robots, *Proceedings of IEEE International Conference on Robotics and Automation,* Raleigh, GA, March 1987, 1779–1784.

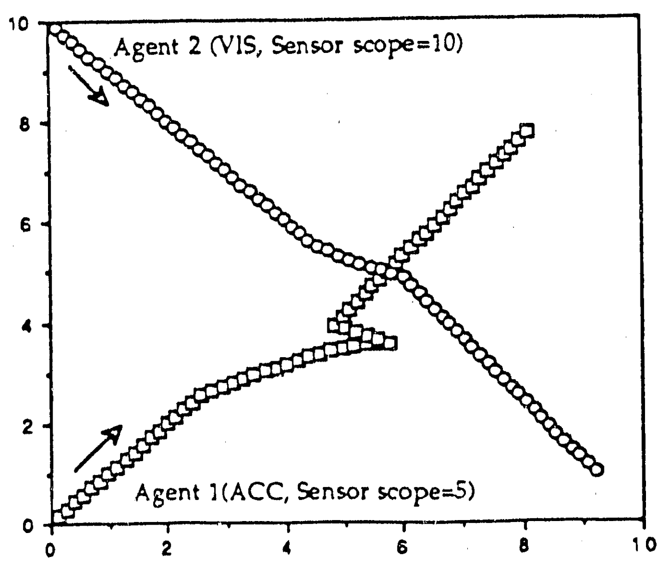




Agent 1 changes its plan at location X.
After X, its optimal plan is to move
behind Agnet 2.


Agent 2 (VIS, Sensor scope=10)
Agent 1 (ACC, Sensor scope=2)
Y
0
2
4
6
8
10


Agent 2 (VIS, Sensor scope=10)
Agent 1 (ACC, Sensor scope=4)
0
2
4
6
8
10


Agent 2 (VIS, Sensor scope=10)
Agent 1(ACC, Sensor scope=5)
0
2
4
6
8
10

END

DATE FILMED

11 / 21 / 90