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ADVANCES IN INTELLIGENT SYSTEMS AND ROBOTICS

LAPTEC 2003

Edited by
Germano Lambert Torres
Jair Minoro Abe
Marcos Luiz Mucheroni
Paulo Estevão Cruvinel

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Dedicated to Professor Helmut Thiele, in Memoriam

Preface

It constitutes a great honor for us to present the approved and invited papers of the 4th Congress of Logic Applied to Technology – LAPTEC'2003 held in Marília city, Brazil, from November 10th to 12th, 2003. Logic (Classical and Non-Classical) is being increasingly related with almost every other scientific discipline and human activity. In this volume we have emphasized its role in Artificial Intelligence, Robotics, Informatics in general, Technology and correlated themes.

LAPTEC'2003 had as Chairs:

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On behalf of the Organizing Committee, we would like to express our gratitude to the members of the following committees:

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Also our special gratitude to the following additional scholars who helped us in refereeing papers: Gustavo E.A.P.A. Batista – USP (Brazil), Luiz Eduardo Borges da Silva – UNIFEI

(Brazil), Luiz Octávio Mattos dos Reis – UNIFEI (Brazil) and Ronaldo Cristiano Prati – USP (Brazil).

We would like to thank the numerous sponsors, particularly the Fundação Eurípides de Marília – UNIVEM, Marília city, São Paulo, Brazil. Also we would like to acknowledge the following entities: FAPESP, UNIFEI – Universidade Federal de Itajubá – Brazil, Institute For Advanced Studies – University of São Paulo, IEEE, Universtity of São Paulo – Campus São Carlos, Himeji Institute of Technology – Japan, Shizuoka University – Japan, Teikyo Heisei University – Japan, Federal University of Rio de Janeiro – Brazil, Sociedade Brasileira de Computação, Sociedade Brasileira para o Progresso da Ciência, ABJICA – Brazil, Hokkaido University – Japan, The University of British Columbia – Canada, Universität Dortmund – Germany, University of Liége – Belgium, Stanford University – U.S.A., University of the Ryukyus – Japan, SENAC-College of Computer Science and Technology, and IOS Press, the publisher of this Proceedings.

This Proceedings is dedicated to Professor Helmut Thiele, in Memoriam. Prof. Thiele, brilliant researcher and human being, was one of the most enthusiastic about the idea of doing the LAPTEC, collaborating since the beginning.

Last but not least, we wish to express our appreciation for the work of Cláudio Rodrigo Torres and Marcos Roberto Bombacini. Their efforts were the main organizing force behind the LAPTEC'2003.

Our undying gratitude again for all these gifted people, responsible for the success of LAPTEC'2003.

Jair Minoro Abe
Germano Lambert Torres
Chair and Vice-Chair LAPTEC'2003

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Hierarchical Path Planning Method For Autonomous Mobile Robots

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Abstract: In near future, autonomous robots will be used in factories and offices. Since there are many stationary/moving obstacles in these environments, autonomous robots are require to make the path plans that can avoid moving objects such as people and robots. In this paper, we propose the path planning method to avoid the collisions with these obstacles. The proposed method consists of two planning steps. In the first step, we can get "the global static path" that is determined based on the location map of the stationary obstacles. Then, in the second step, the static path is modified to "the dynamic local path" using a potential field of repulsion and attraction forces. Using our method we get rid of the parallel run phenomenon that is caused by the traditional Potential method.

Introduction

Mobile robots are expected to work in many places such as factories, offices and so on. In the near future, autonomous mobile robots will be used in the environment where many human beings are working cooperating with robots. In these environments, the collision-free path planning is one of the major problems to realize autonomous mobile robots. Since there are many stationary/moving obstacles in these environments, autonomous mobile robots should plan their own path that can avoid not only stationary obstacles but also moving ones such as human workers and other robots.

There are several research reports on path planning. For example, the "Roadmap method" and "Potential method" are promising. The Roadmap method sets up sub-goals in the environment, and then the method makes a path network whose nodes stand for the sub-goals. This method is useful for stationary obstacles, but this is helpless to avoid moving obstacles. The Potential method is another expecting method. In this method, robots are led to their final goals using potential powers; that is, the goal has an attraction potential, and all obstacles have repulsive ones. But, practically, this method has also some problems. The method may produce the stationary points of the potential as a result of all potential summation, and robots might not be led to their goals. We call it the "stationary dead-lock phenomenon". Besides, in some cases, plural robots might move on a parallel with each other under the influence of other robots' repulsion. We call it the "parallel run phenomenon".

In this paper, we propose a new path planning method. Our method plans an efficient path to avoid the collision with stationary/moving obstacles, and this planning is fast enough to apply real time control robots. By applying our new method, we can also solve the above problems. Finally, we show the evaluation results using virtual robot and real robot.

1. A study plan of autonomous mobile robot

For the study of autonomous mobile robot, we have to develop three functions; an environmental recognition, a path planning and a robot controlling. An environmental recognition measures positions of obstacles and the robot itself. Then, the shortest path to the final goal has to be planned without collisions against obstacles. Finally, the robot is controlled following the planned path. We will develop these functions step by step (Fig.1).

For the first step, we will propose a hierarchical path planning method. In the upper level, we take only static obstacles into consideration to make a skeleton of the shortest path. In the lower level, the planned path obtained in the upper level is modified dynamically to avoid collisions with moving obstacles. In this step, we assume that the environmental recognition and the robot control are performed ideally with no disturbance. For the second step, we extend the field with disturbances for robot control. As shown in Fig.1, we introduce a synthesized space combining the virtual space and the real space. For the final step, we consider the environmental recognition including all disturbances. In this paper, we will propose the first and the second step mentioned above. Since we are in the process of development, we will report the third step in another paper later.

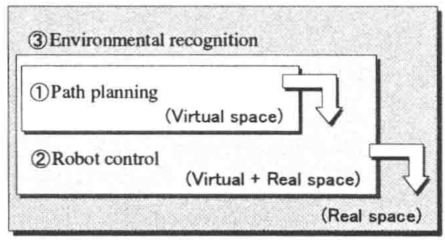


Fig.1 Study plan of autonomous robot

2. Robot path planning method

2.1 Basic idea of our method

Autonomous mobile robots should avoid two types of obstacles; the stationary obstacles and the moving ones. Some of the stationary obstacles can be recognized beforehand as map information, but all moving obstacles and some stationary ones are not known at the beginning. In this environment, the Potential method has been a simple and promising way for the path planning. However, the conventional method might cause the stationary point problem and the parallel run phenomena. As a result, sometimes the robot cannot reach the goal.

When we view the environment globally, we can neglect small changes. Therefore, at the first upper level planning, we take only stationary obstacles into consideration, and the shortest path to the final goal will be planned. We applied "roadmaps method" to this first upper level. To the contrary, when we take a local view of the environment, even a small change should be considered to avoid collisions. Therefore, the local dynamic path plan deals with not only stationary obstacles but also moving obstacles in detail. We applied "Potential method" to the second lower level.

This hierarchical division philosophy can produce efficient paths, because we can search for the local optimal path without forgetting our final goal. Since we applied the suitable method to each level of planning, our method can decrease the stationary points by setting up the sub-goals. Even if the robot falls into the stationary point by applying Potential method, the global path is planned again to escape from the stationary points. The method can also decrease the parallel run phenomena by applying a prediction potential. We named the upper level as the global statistic path planning, and the lower level as the local dynamic path planning. The details of the both level will be explained as follows.

2.2 Global static path plan

In the upper level of the planning, the sub-goals are setup along the shortest path to the final goal in consideration of only stationary obstacles in the map. First, the shortest path is searched based on the "Visible graph method" under the condition that assures no collision with stationary obstacles. Then, sub-goals are setup on the path as the milestones towards the final goal. The global path plan is formed at the following three kinds of the timing.

(a) The start point and the goal are decided, or the goal is changed to another one.

(b) The surrounding environment is changed. For example, if some stationary obstacles on the path are moved, the robot might not move along the planned path.

(c) The robot falls into a dead lock such as a stationary point at the local path planning.

This global path planning method consists of the following three planning steps. The planned results are handed to the lower level planning, or local dynamic path planning.

Step 1: Setting sub-goal candidate points The dangerous areas, where the robot might collide with obstacles, are set around each obstacle based on the map's information. The all vertexes of the area are sub-goal candidate points where the robot should pass by before the final goal (Fig.2(a)). The dangerous areas are defined as the area where the distance from the circumference of each obstacle is within a certain length. The length should be long enough not to collide with the obstacles; i.e., the radius of the robot body.

Though the vertexes of the dangerous areas form arcs according to this definition, we introduced representative points, shown in Fig.2(a), to simplify the algorithm. If the obstacles have acute angles, the representative point might be too far from the obstacle. So, we defined three representative points around acute angle vertexes of obstacles (Fig.2(b)). As shown in Fig.2(b), the line segment BC makes a right angle with the segment BG, and also the segment FE and FG cross at right angles. The length of AG, BG and GF are the same.

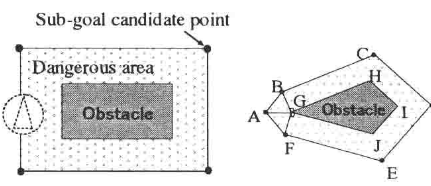


Fig.2 Sub-goal candidate points

Step 2: Drawing up a visible graph A path network, whose starting point is the robot start point and whose finishing point is the goal of the robot, is drawn up by connecting sub-goal candidate points using Visible graph method. This method allows to draw a line connecting two points, when the line crosses neither obstacles nor the dangerous areas. On this network, the distance of each line is calculated as an attribute of the arc. Visible graph method is a graph drawing method that connects mutual visible vertexes of obstacles.

Step 3: Searching the shortest path The obtained visible graph shows all possible path from the starting point to the goal. The shortest path to the goal is searched using conventional path searching method such as Dijkstra method. The sub-goal candidate points on the obtained shortest path are defined as the sub-goals towards the final goal. An example is shown in Fig.3. In this figure, points G_1, G_2 are selected as sub-goals. In the lower level planning, or the local dynamic path planning, the objective of the planning is to reach the sub-goals one by one. When the robot arrives at the current sub-goal, the next sub-goal will be a current sub-goal till the robot arrives at the final goal.

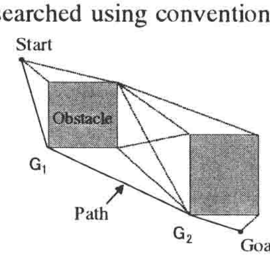


Fig.3 Visible graph

2.3 Local dynamic path plan

At the lower level of the planning, the local dynamic path planning makes a practical path to the next sub-goal. For this planning, we apply the Potential method to avoid known obstacles in the map information. The traditional Potential method pulls the robot to the current sub-goal. To the contrary, the obstacles have the repulsion potential keeping the robot away from the obstacles. When the robot arrives at the current sub-goal, the following one is adopted as the next current sub-goal. This cycle continues till the robot reaches its final goal.

Since this method uses only distances between the robot and the obstacles, it requires small amount of calculation. Therefore, the method is suitable for real-time robot control. However, this method sometime causes parallel run phenomena and stationary dead-lock phenomena. The parallel run phenomenon is an undesired situation where the robot and the other moving obstacle run in parallel under the influence of repulsion potential.

We introduced a new potential, or prediction potential, to decrease the undesired phenomena mentioned above. According to the predicted routs of the robot and the obstacles, the prediction potential is formed on their crossing point as an attractive one or a repulsive one. If the robot seems to pass the crossing point earlier than the obstacle, the prediction potential becomes attractive and vice versa. This prediction potential prevents the two moving things to reach the crossing point at the same time. The algorithms for making the three potentials will be shown below in detail; they are the attractive sub-goal potential, the repulsive obstacle potential and the attractive/repulsive prediction potential.

Step 1: attractive sub-goal potential We define the attractive sub-goal potential around the current sub-goal. This potential pulls the robot toward the current sub-goals. This attractive force U_a is defined by the following Eq.(1), and this has a constant value k_a.

$$U_a = -k_a \tag{1}$$

The typical three-dimensional shape of the potential field is shown in Fig.4. The robot will be pulled as if it falls into the current sub-goal.

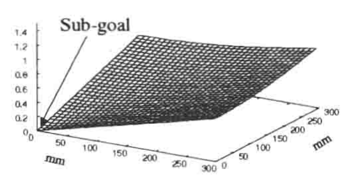


Fig.4 Attractive sub-goal potential

Step 2: repulsive obstacle potential We define the repulsive potential field around obstacles. When the robot comes close to obstacles, the repulsive potential works as a force to make the robot away from the obstacle. The repulsive potential U_r is defined by the following Eq.(2). This potential is the function of the distance x_p between the robot and the obstacle. As shown in this equation, the value x_s shows the effected distance of the repulsive potential. The value is a positive constant, and the robot movement is influenced when the distance x_p becomes less than x_s.

$$U_r = \begin{cases} k_r\left(\dfrac{1}{x_p} - \dfrac{1}{x_s}\right) & x_p \le x_s \\ 0 & x_p > x_s \end{cases} \tag{2}$$

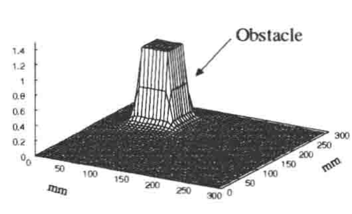


Fig.5 Repulsive obstacle potential

An example of the potential field is shown in Fig.5. The parameter k_r, that decides the power of the potential, is constant, and the value is decided based on the characteristics of the obstacles. For example, the value k_a for moving obstacles is much larger than the value for stationary obstacles because the moving obstacles are easy to collide with robots.

Step 3: attractive/repulsive prediction potential This potential fieldis formed around the crossing point of the robot path and the obstacle path to avoid simultaneous approach to the point. If the robot is predicted to pass the crossing point earlier than the obstacle, the predictive potential is attractive, and vice versa. If the situation is opposite, the potential is repulsive. When the approaching times of the both objects are almost the same, the power of the potential should be strong to strength the acceleration or the deceleration. Besides, the closer the robot is to the crossing point, the stronger the predictive potential becomes. Under the assumption of uniform linear movement, the predicted arriving point of the obstacle is predicted when the robot reaches the crossing point (Fig.6). The notations in this figure are defined as follows.

x_e : the distance between the obstacle's current position and the predicted arriving point
x_c : the distance between the obstacle's current position and the predicted crossing point
x_r : the distance between the robot's current position and the predicted crossing point
x_a : the influential area of the prediction potential
k_e : a constant value

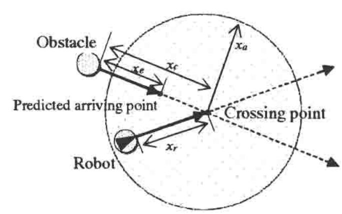
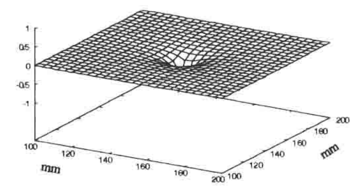


Fig.6 Field of Predictive potential

The prediction potential is calculated by Eq.(3) using the above notations.

$$U_e = \begin{cases} k_e \dfrac{1}{x_e - x_c}\left(\dfrac{1}{x_r} - \dfrac{1}{x_a}\right) & x_c \le x_a, x_e \ne x_c \\ 0 & x_c > x_a \end{cases} \quad (3)$$

An example of the potential field is shown in Fig.7. Fig.7(a) shows the attractive potential in the case where the predicted arriving point exists on this side of the crossing point. On the other hand, in the other case where the predicted arriving point exists on other side of the crossing point, the prediction potential is repulsive as shown in Fig.7(b). As you can see in these figures, the closer the robot comes to the obstacles, the stronger the repulsive power becomes. If we use only traditional Potential method, the robot might move inefficiently because of the parallel run or stationary dead-lock phenomenon. The value of parameter k_e is decided based on the characteristics of the obstacles.


(a) Attractive potential

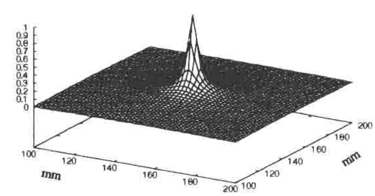

(b) Repulsive potential

Fig.7 Attractive/repulsive prediction potential

Step 4: Synthesized potential We have introduced three kinds of potentials, and the robot is controlled based on the summation field of the three as shown in Eq.(4). An example of the synthesized potential is shown in Fig.8.

$$U = U_a + U_r + U_e \quad (4)$$

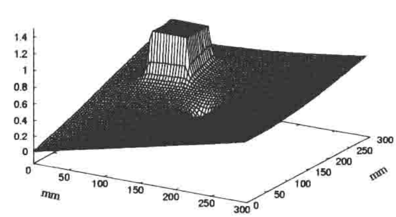


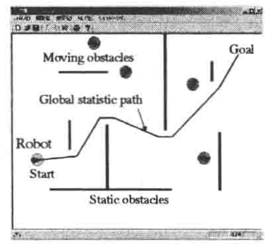
Fig.8 Synthesized potential

3. Evaluation experiment using virtual robots

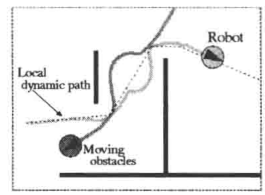
3.1 Objectives and method of evaluation

We built a virtual space as a simulation program. In the virtual space, we can control robots without being disturbed by errors in robot movement and environment recognition. We can evaluate the plan itself. Though we also have to decide the values of some parameters of potential functions adequately through lots of experiments, our virtual space experiment makes it easy to change environments of the robot control.

Our simulation program represents the robot control environments and the experiment results as Computer Graphocs as well as numerical data such as transit time and the travel distance. Using this CG, we can observe the robot movement. In our experiment, we performed 20 cases of experiment with different positions of robots and obstacles.



(a) Global static path



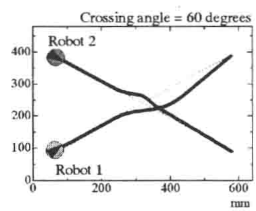
(b) Local dynamic path

Fig.9 Path planning example

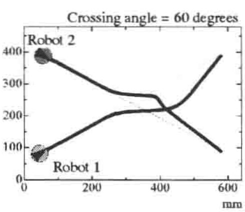
3.2 Evaluation results

In all our experiments, the robot could go to the final goal through efficient paths with no collision. Examples of the planning results are shown in Fig.9. Fig.9(a) represents the global path, and Fig.9(b) represents the dynamic path obtained based on the global path.

Then, the effectiveness of the prediction potential is evaluated from the viewpoint of reducing the parallel run phenomenon. Two virtual robots are prepared in the virtual space, and we set their starting points and final goals so as to cross their paths. We compared the total journey lengths planned by two methods; one is our proposed method with the prediction potential and the other is without the prediction potential. The angle of two path intersection is set 5 times at intervals of 30 degrees from 30 up to 150 degrees, and we compared the increasing rate of journey distance caused by the parallel run phenomena. The increasing rate is defined as the increased journey distance divided by the direct path distance that is described by the dotted line. Fig.10 shows an example of a dynamic path for the angle of 60 degrees. As you can see in this figure, the parallel run phenomena can be decreased by the prediction potential. Table 1 shows the results of the increasing rate, and in all cases the ratios are smaller for our proposed method. The average of the increasing ratio for no prediction potential case is 4.4%, and the average for prediction potential case is 1.8%. Therefore, the effect of the prediction potential is estimated to be 2.6% on average. Besides, no stationary dead-lock phenomenon was observed during the experiments.



(a) with predicted potential



(b) without predicted potential

Fig.10 Reduction of parallel run phenomenon

Table 1 Increasing rate of total journey length

Crossing angle	180°	150°	120°	90°	30°	Aver.
Including prediction potential	4.2	3.8	6.6	3.6	3.7	4.4
Excluding prediction potential	1.9	0.8	1.6	1,.1	3.5	1.8

4. Evaluation experiments using a real robot

4.1 Objectives and method of evaluation

In the virtual space, we confirmed the planned path itself is efficient and valid. However, a real robot cannot move accurately because of various disturbances. In case of controlling real robots in the real space, we have to decide the adequate values of parameters that are used for the potential field considering the control characteristics of the robots. As a result, a real robot should be controlled for determining the parameter values. If we can decide optimal values for a robot, we think we can decide the values for other robots in the same manner. We will also evaluate our method if it is fast enough for real-time processing.

4.2 Evaluation method

In real robot control, we encounter some difficulties such as measuring errors of positions or directions. Besides, it is very difficult to prepare various conditions on obstacles. We built a synthesis space to solve the above problems. We controlled the robot in the real space, and we set obstacles in a virtual space. By combining these two spaces, we can control real robots with various virtual obstacles (Fig.11).

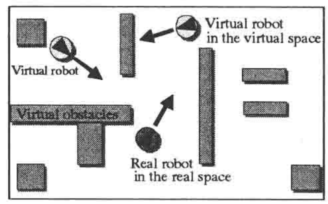


Fig.11 Synthesized space

4.3 Robot Control Method

(1) Mobile robot

We used a mobile robot (Fig.12) to evaluate our planning method. The robot is small cylinder-shaped. The robot move forward and backward, and turn to any direction. The main specifications are shown in Table 2.

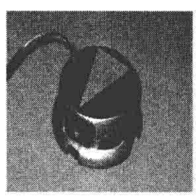


Fig.12 Mobile robot

Table 2 Robot specification

Manufacturer	Applied AI Systems, Inc.
Size	Diameter 55mm, Height 30mm
Weight	80g
Sensors	8 Ultra red sensors / light sensor
Power	Ni-MH battery
Processor	Motorola 68331,25MHz
ROM	512K
RAM	512K
Bus	K-bus(35pinI/O bus)
I/O interface	Serial port

(2) Robot control method

The robot moves in the environment where some stationary/moving obstacles exist. As shown in Fig.12, we built a synthesized space by combining the real space and the virtual one, because this synthesized space makes it easy to perform lots of control experiments under various conditions of obstacles existence. In this combined space, the stationary/moving obstacles are set in the virtual space, and a camera on the ceiling captures the position and the moving direction of the real robot.

In order to control robots in the synthesized space, the robots' position and their moving directions are necessary to be measured. Image processing is a promising method, but this is time-consuming because of its calculation computational complexity. When we apply the method to real time control systems, time lags might be caused. Therefore, there are two problems to be solved for real robots control; one is a method to measure robots' positions and their moving directions, and the other is a method to realize real time robots control.

a) Image processing algorithm to measure robots' position and their moving directions

Since virtual obstacles are made by computer, their positions and directions can be recognized accurately. The robots' positions and directions are necessary to be measured. In our experiment, we get the image of the isosceles triangle drawn on the surface. The center of gravity of the triangle shows the position, and the direction of the acute angle represents the direction. The average position error was 4.5mm, and that for direction was 4.1 degrees.

b) Real time robot control

The processing time for the above measurement was 410 ms, and the total processing time for path planning and robot controlling was 100 ms. If we perform these processing in one sequencing process, the robot control commands will be sent at intervals of 510 ms. During this interval the robot will move about 12 mm on average, and as a result the collision with obstacles is feared. We adopted a multi-process method with two processes; one is for image process, and the other is for robot control. The robot position and direction are predicted based on the control history.

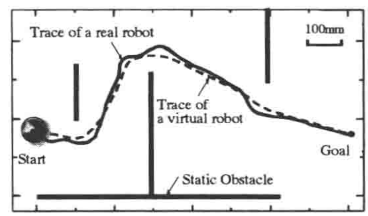


Fig.13 Trace of robot (static obstacles)

4.4 Robot control result

We evaluated the path planning method by comparing two robot traces; the trace in the virtual space and that in the synthesized space. A result example is shown in Fig.13. As you see in this figure, the real robot can avoid collisions till it reaches the final goal just like in the virtual space. The difference of the virtual robot trace distance, or the planned path distance, and the actual robot trace distance was 10.9 mm on average. We performed the similar experiment under the condition of plural stationary/moving obstacles. The robot managed to arrive at the goal with no collision (Fig.14).

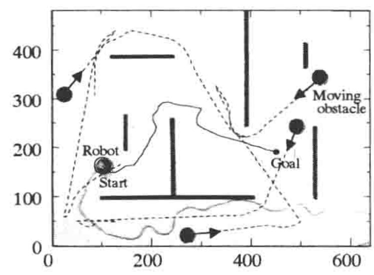


Fig.14 Trace of robot (moving obstacles)

5. Conclusions

We proposed a new path planning method for the robots to avoid collisions with stationary/moving obstacles. We divided the path plan hierarchically into two sub-plans; the global path plan and the local path plan. We evaluated the planning method by controlling a virtual robot in the virtual space. Then, a real robot was controlled to verify whether we could determine adequately the parameters values of our potential method. For this experiment, we introduced a combined space of a virtual one and the real one to perform the experiments under various conditions of stationary/moving obstacles easily. According to the experiments, the mobile robot could reach the final goal without collide with other obstacles.

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