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A Real-Time Path Planning Method for Mobile Robot Avoiding Oscillation and Dead Circulation[1)]

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Abstract Robot path planning in a globally unknown environment with general obstacles is studied in this paper. Oscillation and dead circulation possibly encountered in rolling path planning are studied. And an improved planning method is proposed by storing detected environmental information. The planning method could prevent mobile robot from oscillation and dead circulation efficiently and guarantee the accessibility to the global goal. It is a fast and effective path planning method for mobile robot in an unknown obstacle environment.

Key words Robot path planning, rolling planning, local planning, subgoal, oscillation, dead circulation, accessibility

1 Introduction

Path planning is a key issue in robotics. In real applications, the environmental information for path planning is often incomplete or even unknown. The robot can only detect local environmental information. These problems cannot be solved by traditional global planning methods. Mobile robots must plan its feasible moving path by real-time detected information. These local planning methods needs less environmental information and the planning speed is high. But they can hardly guarantee the global accessibility. Borenstein[1] used VFF method to solve the collision-free problem in unknown environments. The method cannot lead the robot to the goal successfully in some situations and may even result in instability[2]. Fox uses the dynamic window approach[3] for path planning, in which the kinematic constraints of the mobile robot are taken into account. The robot can move towards the goal fast while avoiding obstacles. Although this method is applicable in many cases, the robot is still susceptible to be stuck in some local minima.

Since the local planning methods based on real-time detected information could hardly guarantee the global accessibility, a few path planning methods tried to achieve it by storing some necessary global information. Lumelsky[4] studied nonheuristical methods of path planning in unknown environments. In his method, robot should remember some special points in the workspace and the planning is always guided by a global accessibility criterion. However, the paths are not ideal in many cases because of lacking optimization. Sankaranarayanan[5] made some improvements by making the robot store more environmental information. Brock and Khatib[6] proposed a global dynamic window approach as the generalization of [7]. To collect information about the connectivity of the free space, sensory information is merged into a global map. This approach combines the dynamic window approach for reactive obstacle avoidance with the globally local minima-free navigation function, which is computed by using a wave-propagation technique starting at the goal. Oriolo[8] applied an approach based on the alternate execution of two fundamental processes: map building and navigation. In the former phase, the mobile robot collects the

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environmental information of surrounding area and integrates it into the global map. In the latter, an A* -based planner generates a local optimal path from the current robot position to the goal. The robot follows the path up to the boundary of the explored area, terminating its motion if unexpected obstacles are encountered. Although these methods fully uses the detected environmental information and the accessibility could be guaranteed, the planning region is often large, especially when the known area has been greatly expanded. Thus the information storage and the on-line computation burden would increase. Furthermore, these methods are not suitable for complex dynamic environment.

In fact, the path-planning problem of mobile robot in globally unknown environments concerns how to make full use of local detected information to plan a path that is not only feasible but also as optimal as possible. Both optimization and feedback should be considered in the planning. Using the concept of rolling optimization in predictive control for reference, an efficient path planning method was proposed in [9]. The computation burden keeps at a low level during the whole planning process and it results in a high planning speed. But when it is applied to path planning in an unknown environment with general obstacles, oscillation and dead circulation may still occur. In order to guarantee the accessibility of rolling planning, strict constraints were bounded to the obstacle environment in [9]. This restricts the real application of rolling planning. In this paper, rolling path planning in a general obstacle environment will be discussed. The rolling planning algorithm is improved by storing memorial information of the environment. The accessibility of the planning algorithm will be analyzed. It indicates a wider use of rolling path planning in an uncertain environment.

2 Rolling path planning based on local information

Consider a mobile robot (Rob) in a two-dimensional unknown workspace (*WS*) with finite size. The robot is required to move autonomously from a start point (P_i) to a goal point (P_g) successfully in a finite time.

Rob has no priori knowledge of the workspace. At any instant, *Rob* can only scan a local circular region around itself, whose radius equals to r. *WS* is arbitrarily cluttered with finite number of static obstacles ($Obs_1, Obs_2, \cdots, Obs_n$). Rob is modeled as a point by "enlarging" the obstacle-size to account for actual robot dimension and the requirement on safety. The boundaries of enlarged obstacles are safe regions that the point robot can move along. Obstacles do not intersect with each other or with the workspace boundary.

Due to lack of global environmental information, the robot can only perform the on-line path planning based on the real-time environmental information detected locally. Although it is unable to carry on global optimization in this case, optimization can also be taken into account to some extent based on the available feedback information. The key problem is how to make full use of the detected information. In [10], the basic principles of predictive control used in industrial process control is generalized to solve the problem of planning, scheduling and decision in uncertain environments. Three principles were described as making full use of known information for prediction and estimation, performing local optimization in a rolling style and updating the old knowledge with feedback information. These principles indicate the combination of optimization and feedback. Using these principles for reference, [9] proposed a rolling path planning method, as the robot has no priori global knowledge but on-line detected local information. In the following, a brief introduction to rolling path planning will be given firstly.

Set up the system Cartesian coordination in *WS*. At instant t, the position of Rob in *WS* is denoted as $P_R(t)$ and its coordinates are $(x_R(t), y_R(t))$. Let $t_1=0$ be the start instant of the planning.

Let $d(P_i, P_j)$ denote the linear distance from P_i to P_j. Assume that all the points in WS make up a closed set W and its boundary is denoted as ∂W. All the points in $Obs_i (i=1, 2, \cdots, n)$ make up a closed set O_i and its boundary is denoted as ∂O_i. To make the planning solvable, assume that P_s and P_g belong to the same connective region in WS.

To $T=[\tau_1, \tau_2]$ and $\forall P_0 \in FD$, $\forall P_f \in FD$, if a continuous mapping $FS: T \rightarrow W(X \subseteq W)$ makes $FS(\tau_1)=P_0$, $FS(\tau_2)=P_f$, $FS(t) \in FD$, $t \in (\tau_1, \tau_2)$, then FS is called a feasible path from P_0 to P_f in X. The image set $FS(T)$ is called a passage from P_0 to P_f in X and denoted as $FP(P_0 P_f)$. If there exists any feasible path from P_0 to P_f in X, then it is called that P_0 is connectible with P_f in X.

At any instant, Rob can only scan a local circular region around itself, whose radius equals to r. $Win(P_R(t_k)) = \{P \mid P \in W, d(P, P_R(t_k)) \leqslant r\}$ is called the vision scope of Rob at $P_R(t_k)$, namely its rolling window at $P_R(t_k)$, where $P_R(t_k) \in FD$ is the position of Rob at t_k (The beginning instant of the kth local planning.). The boundary of the rolling window is denoted as $\partial Win(P_R(t_k))$.

The general rolling path planning algorithm for mobile robot is presented as follows[9].

Algorithm 1. Path planning based on rolling windows.

Step 1. If the goal is reached, the planning stops.

Step 2. Update the environmental information in the current rolling window.

Step 3. Generate a local optimal subgoal $P_{sub}(t)$.

Step 4. Plan a proper local path in the current rolling window according to the subgoal and local detected environmental information.

Step 5. Move a step along the local path.

Step 6. Return to Step1.

Instead of the one-off global optimization, the rolling path planning executes local planning repeatedly and makes full use of the newest local environmental information detected. The subgoal generated in Step 3 is a mapping point of the global goal P_g in the current rolling window. It must reside in the feasible region and satisfy some optimal criterion. The determination of subgoals should not only consider the full use of the local information detected in real time, but also its consistency with the global goal. To maximize the use of the detected information, the subgoal is prone to be chosen on the boundary of the detectable region.

Let $SW(t_k) = \{i \mid O_i^{\circ} \cap Win(P_R(t_k)) \neq \Phi\}$ be the subscript set of the obstacles detected at instant t_k in the rolling window. The set of all points on $\partial Win(P_R(t_k))$ that are connectible with $P_R(t_k)$ within the rolling window $Win(P_R(t_k))$ is called the selectable set of subgoals at t_k, which is denoted as $\theta(t_k)$. Obviously,

$$\theta(t_k) \subseteq \partial Win(P_R(t_k)) \cap FD \tag{1}$$

The general subgoal determination method is described as follows:

1. If $P_g \in Win(P_R(t_k))$ and $P_R(t_k)$ is connectible with P_g in the rolling window, then $P_{sub}(t_k) = P_g$.

2. In other cases, $P_{sub}(t)$ could be determined by a heuristical function[9]. This subgoal determination method reflects the compromise of the requirement for global optimization and the limitation of finite local information. It is a natural choice of trying to pursue global optimization in the unknown environment. To reduce the computation burden, the determination of subgoal can be transformed to the following optimization problem:

$$\min J = \min_{P_{sub}(t_k)} d(P_{sub}(t_k), P_g) \tag{2}$$

$$\text{s.t.} \quad P_{sub}(t_k) \in \theta(t_k)$$

It has been proved in [9] that the above method can surely guarantee the existence of subgoals and avoid deadlocks in some strictly constrained environment during the rolling planning. If there exist more than one subgoals, Rob can choose one arbitrarily.

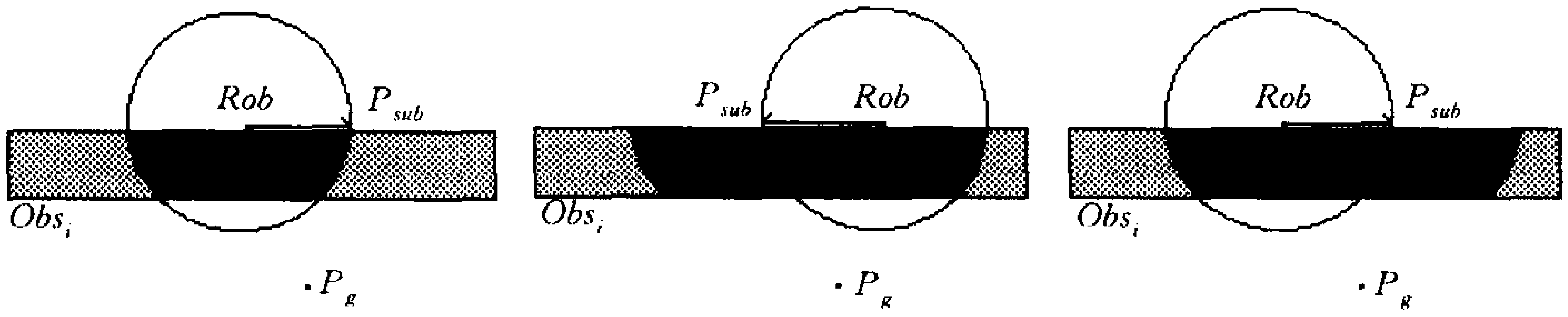
If the subgoal $P_{sub}(t)$ is determined, an optimal local path from the current position $P_R(t_k)$ to the subgoal could be planned. Rob then moves one step along the path. The step length could be constant or variable according to actual situations.

The path planning algorithm based on rolling windows depends on real-time environmental information detected locally and the on-line path planning is performed in a rolling style. At each step of rolling planning, Rob generates an optimal subgoal based on the local detected information by a heuristical method and plans a local path within the current rolling window. Then it moves a step along the local path. With the rolling window moving forward, Rob obtains newer environmental information. Thus, optimization and feedback are combined in the rolling process.

3 The avoidance of oscillations in general obstacle environment during rolling planning

The general frame of rolling path planning is given above. Path planning in an unknown obstacle environment with strict constraints can be solved and the accessibility can be also guaranteed[9]. But if there were more complicated obstacles in the workspace, the above method might probably fail (oscillation or dead circulation) and Rob cannot plan a feasible path to the goal. It is because the local detected environmental information used by Rob in its rolling planning is not enough to plan a globally feasible path in the complicated obstacle environment.

Although the general subgoal determination method described in the last section can guarantee the existence of subgoals in an obstacle environment, it might cause oscillations and Rob cannot reach the goal. For example, Rob chooses the connectible point $P_{sub}(t_{k-1})$ as its current subgoal based on the shortest distance from P_g at instant t_{k-1} (See Fig. 1(a)) and moves a step towards the subgoal. The new position is denoted as $P_R(t_k)$. At the instant t_k, the relative position of Rob and P_g has changed (See Fig. 1(b)). If Rob still determines its subgoal using (2), the new subgoal will again lead Rob to $P_R(t_{k-1})$ (See Fig. 1(c)). Thus, Rob will oscillate between $P_R(t_{k-1})$ and $P_R(t_k)$.



(a) The $(k-1)$th planning (b) The kth planning (c) The $(k+1)$th planning

Fig. 1 Oscillation caused by improper determination of subgoals

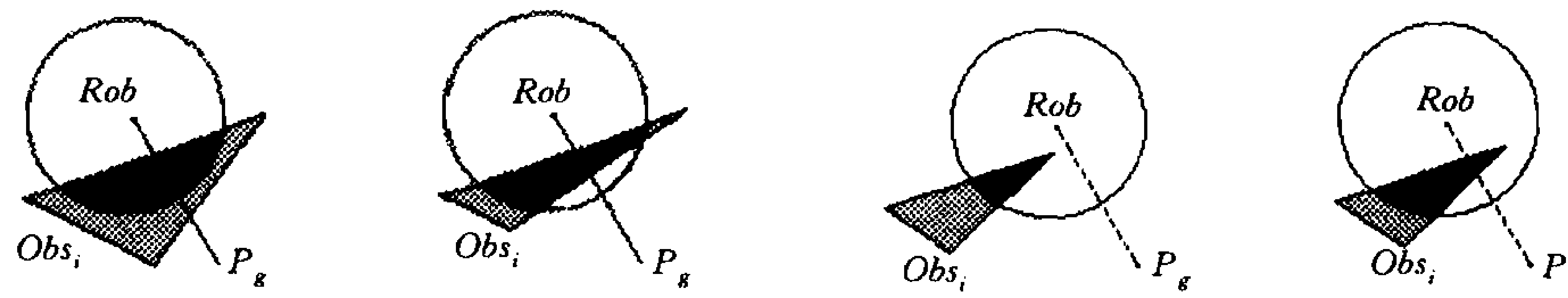
So in this case, the subgoal determination method should be modified. For further discussion, we give some related definitions first.

$\varphi(P_iP_j)$ denotes a directional beeline from P_i to P_j in WS. For simplicity, $\varphi(P_iP_j)$ also denotes the point set on that line.

If $\varphi(P_iP_j)\cap O_i^o\neq\Phi$, then $\varphi(P_iP_j)$ must intersect ∂O_i at two points successively, which are denoted as H(hitting point) and L(leaving point), respectively.

Assume Obs_i is located in $Win(P_R(t_k))$. If $\varphi(P_R(t_k)P_g)\cap O_i^o\neq\Phi$ $(i\in SW(t_k))$ and there is no leaving point L or $P_R(t_k)$ is not connectible with L in $Win(P_R(t_k))$, it is called that Rob is inescapable from Obs_i. Otherwise, it is called that Rob is escapable from Obs_i.

Fig. 2(a) and Fig. 2(b) show the two situations respectively.



(a) Rob is inescapable from Obs_i (b) Rob is escapable from Obs_i

Fig. 2 Relative positions between Rob and Obs_i

In some cases, Rob may be inescapable from several obstacles in its rolling window. In the following, we only refer the inescapable situation wrt the nearest obstacle from Rob.

At instant t_k, if Rob is inescapable from $Obs_i (i \in SW(t_k))$ and $P_R(t_{k-1}) \in \partial O_i$, $P_R(t_k) \in \partial O_i$, see Figs. 1(a) and (b), then the subgoal should be determined as follows:

$$P_{sub}(t_k) \in \theta(t_k) \cap \partial O_i \tag{3a}$$

$$\text{s. t.} \quad FP(P_R(t_k) P_{sub}(t_k)) \cap FP(P_R(t_{k-1}) P_{sub}(t_{k-1})) = \Phi, \text{ except for } P_R(t_k) \tag{3b}$$

where (3b) means that the new planned passage has no superposition with the last one.

This indicates that the subgoal of the *k*th local planning should not be chosen as Fig. 1(b), which would result in oscillation. Instead, the subgoal should be the right intersection point of the boundary of the rolling window and the boundary of the obstacle. Thus the local subgoal will move right gradually and bypass the obstacle finally.

Oscillations can be avoided by the above subgoal determination method when Rob is inescapable. Thus the mobile robot can move successfully from the start point to the goal point in an unknown environment with convex obstacles.

4 An improved rolling path planning method

By modification of the subgoal determination method, oscillations can be avoided effectively during rolling planning. But the mobile robot may still get into endless dead circulation in an unknown environment with concave obstacles. As shown in Fig. 3, although the mobile robot uses (3) to determine its subgoals and avoids oscillations, it will move around the obstacle and never reach the goal. To plan a feasible path in a general obstacle environment successfully, the mobile robot needs more environmental information. If the robot hasn't enough priori environmental information at the initial stage of planning, it should accumulate detected information gradually during its moving procedure. In the following, an improved rolling path planning method is proposed for path planning in a general obstacle environment by storing detected information and modifying the local planning algorithm.

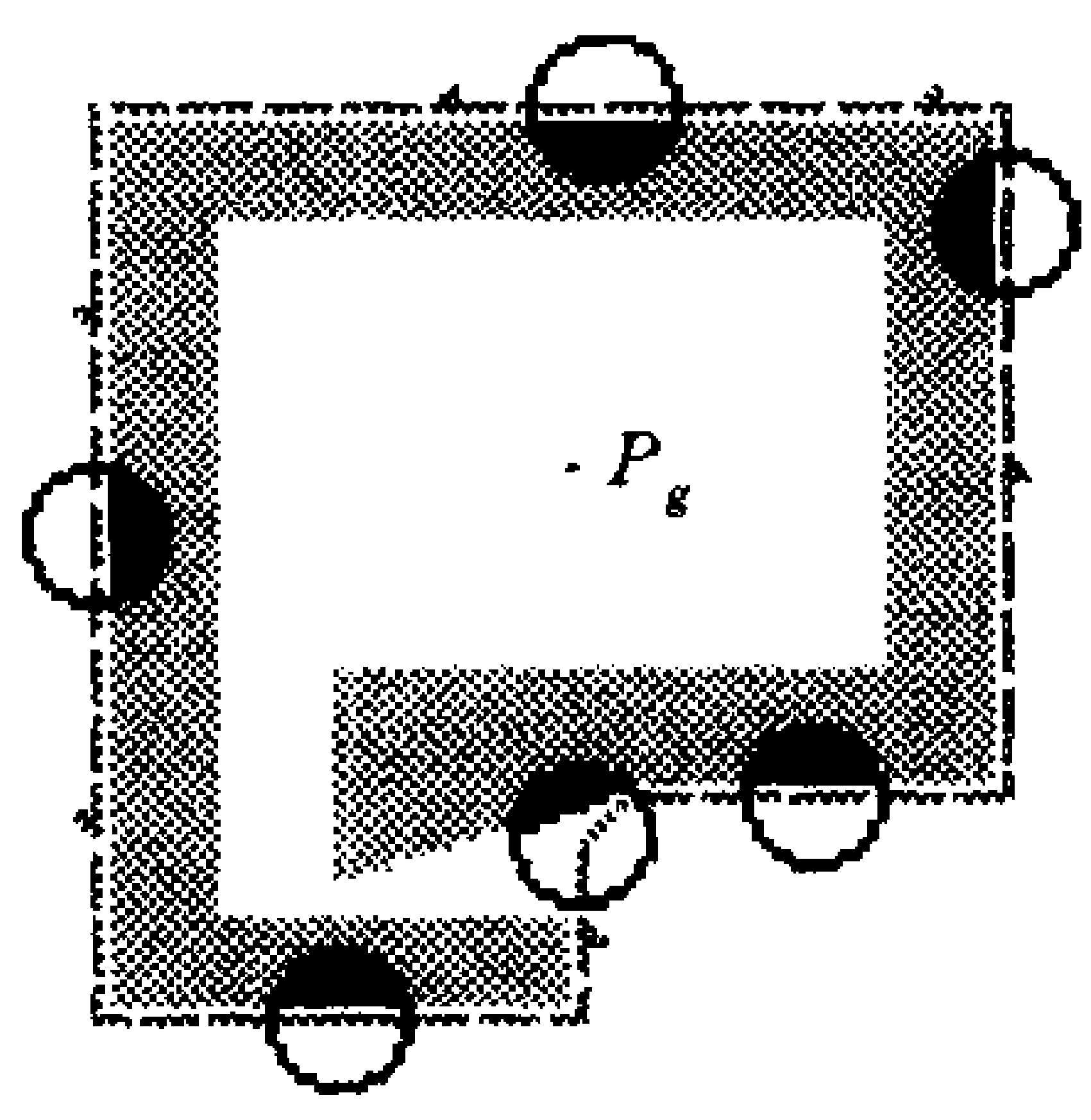


Fig. 3 Dead circulation due to lack of necessary environmental information

$WFD(P_R(t_k)) = Win(P_R(t_k)) \cap FD$ denotes the feasible region detected at t_k by Rob. $I(t_k) = \bigcup_{i=1}^{k} WFD(P_R(t_i))$ is called the detected feasible region at t_k, which denotes the accumulated environmental information stored gradually by Rob through its local detection from the start time to t_k. Its boundary is denoted as $\partial I(t_k)$.

The set of all the points on $\partial I(t_k)$, which are connectible with $P_R(t_k)$ in the detectible feasible region $I(t_k)$, is called the expanded selectable set of subgoals and denoted as

$\phi(t_k)$. Obviously, $\phi(t_k) \subseteq \partial I(t_k) \cap FD$.

Let Z be the subscript set of the detected obstacles during rolling planning.

Next, we give the subgoal determination method for Rob in a general obstacle environment without changing the frame of rolling planning.

1) If $P_g \in Win(P_R(t_k))$ and $P_R(t_k)$ is connectible with P_g in the rolling window, then $P_{sub}(t_k) = P_g$.

2) In other cases:

Case I. If Rob is inescapable from $Obs_i (i \in SW(t_k))$ and $P_R(t_{k-1}) \in \partial O_i$, $P_R(t_k) \in \partial O_i$, see Figs. 1 (a) and (b), then the subgoal is determined by (3):

$$P_{sub}(t_k) \in \theta(t_k) \cap \partial O_i,$$
$$\text{s.t.}\quad FP(P_R(t_k)P_{sub}(t_k)) \cap FP(P_R(t_{k-1})P_{sub}(t_{k-1})) = \Phi,\ \text{except for } P_R(t_k).$$

If the situation is not like Case I, then go to Case II.

Case II. If $P_R(t_k) \in FS(\tau)$ $(0 < \tau < t_k)$, that is, Rob returns to its original passage, then local path planning should be performed in $I(t_k)$ and the subgoal should be determined as follows:

$$\min J = \min_{P_{sub}(t_k)} d(P_{sub}(t_k), P_g)$$
$$\text{s.t.}\quad P_{sub}(t_k) \in \partial\phi(t_k),\quad P_{sub}(t_k) \notin \partial O_i,\quad i \in Z \tag{4}$$

The last constraint above is given for avoiding dead circulation.

Case III. Otherwise, the subgoal is determined by (2):

$$\min J = \min_{P_{sub}(t_k)} d(P_{sub}(t_k), P_g),$$
$$\text{s.t.}\quad P_{sub}(t_k) \in \theta(t_k).$$

In Case II, Rob uses the accumulated environmental information detected before and performs local path planning beyond its current rolling window. It is called expanded local path planning. When the subgoal is determined, Rob plans an optimal path in the detected feasible region and moves a step along it and reaches the subgoal. In other cases, Rob still plans a path in its rolling window and moves along it.

When Rob scans the local rolling window, it not only plans its current local path, but also stores the environmental information it detects. This action continues through the rolling process. Note that this information storing action is basically different from environment exploration aimed at map building by wandering. It is an accessory accompanying Rob's rolling path planning towards the goal. Though it may be even useless in some simple situations, the accumulation of environmental information guarantees the global accessibility in the unknown environment. Timely execution of expanded local planning could make full use of finite environmental information detected and plan an optimal path leading robot away from complicated obstacle region. Thus oscillation or dead circulation could be efficiently avoided. And at the same time, rolling planning provides the possibility of low calculation burden during the whole planning process.

5 Analysis of accessibility

Using the above improved rolling path planning method, the global accessibility in a generally unknown obstacle environment can be guaranteed. In the following, we will prove that Rob can surely reach the global goal in a finite time

Theorem 1. The subgoal $P_{sub}(t_k)$ determined by the above method always exists during rolling planning.

Proof. In Case I, Rob will determine its subgoal by (3). If it fails to find a subgoal, Case II or Case III will be considered. In Case II, the subgoal is determined by (4). Since

Rob moves always in the feasible region, its current position and the goal belong to the same connective region. Thus there must exist a feasible path from $P_R(t_k)$ to P_g with its corresponding passage denoted as $FP^*(P_R(t_k)P_g)$. Therefore, it is true that $FP^*(P_R(t_k)P_g) \cap \partial\phi(t_k) \neq \Phi$. Due to the environmental constraints, the obstacles do not intersect with each other or with the workspace boundary. Then there must exist non-obstacle part on $\partial\phi(t_k)$. Let $P \in FP^*(P_R(t_k)P_g) \cap \partial\phi(t_k)$. If $P \in \partial O_i (i \in Z)$, then a point Q can be found in the neighboring region of P, which satisfies $Q \in \partial\phi(t_k)$ and $Q \notin \partial O_i (i \in Z)$. So in Case II, the subgoal $P_{sub}(t_k)$ can be surely determined. Otherwise, it is easily proved that the subgoal always exists in Case III by using (2)[9]. □

Corollary 1. Deadlock will not occur during rolling planning.

Since the subgoal for each local planning always exists, Rob won't get stuck during the rolling planning process.

Corollary 2. *Dead circulation will not occur during rolling planning.*

Proof. If Rob arrives at a point which is on its original passage, its subgoal will be determined by (4). Then its subgoal is on the boundary of the detected feasible region, which Rob hasn't been to. After the local planning, Rob will move towards and then reach the subgoal along its local optimal path. So dead circulation will not occur during rolling planning. □

Theorem 2. Rob can surely reach the global goal safely in a finite time by rolling planning.

Proof. If the global goal is inaccessible, then the detected feasible region of the robot will gradually expand with the rolling process going on and cover the whole feasible region of the workspace in the end. That is, $I(t_K) = FD$, where K is a sufficiently large integer. Then the original problem is transformed to path planning in a globally known environment. Since P_s and P_g belong to the same connective region, the planning problem can be surely solved. So it is guaranteed that Rob can reach the global goal in a finite time by rolling planning. □

In fact, Rob doesn't need to detect all the environmental information for reaching the goal in most cases. Since the local subgoal generated by heuristic method aims at approaching to the goal, the environment detection action accompanying rolling path planning is not blindfold. In common cases, just part of the accumulated environmental information is required. Only in very few cases, Rob needs to detect all the environmental information before it can plan a feasible path to the final goal.

6 Simulation results

Fig. 4 shows the simulation process of the mobile robot path planning in a general obstacle environment. In the unknown environment, Rob uses real-time information detected locally and performs rolling planning. With the rolling process going on, the detected feasible region of the robot expands gradually and more environmental information is acquired. When local path could not be planned by the detected information in the current rolling window, Rob uses all the environmental information stored to perform expanded local planning. It plans an optimal path within the detected feasible region and moves along the path. In the figure, we can find that Rob changes its path when it detects an obstacle encumbering in its way to the goal. This method efficiently avoids the occurrences of oscillation and dead circulation. Since in most time of the rolling planning, Rob plans its local paths only in its small rolling window, the calculation burden of the whole planning process is low and the planning speed is high. Fig. 4 shows clearly that Rob moves from the start point (S) to the goal point (G) successful by rolling planning.

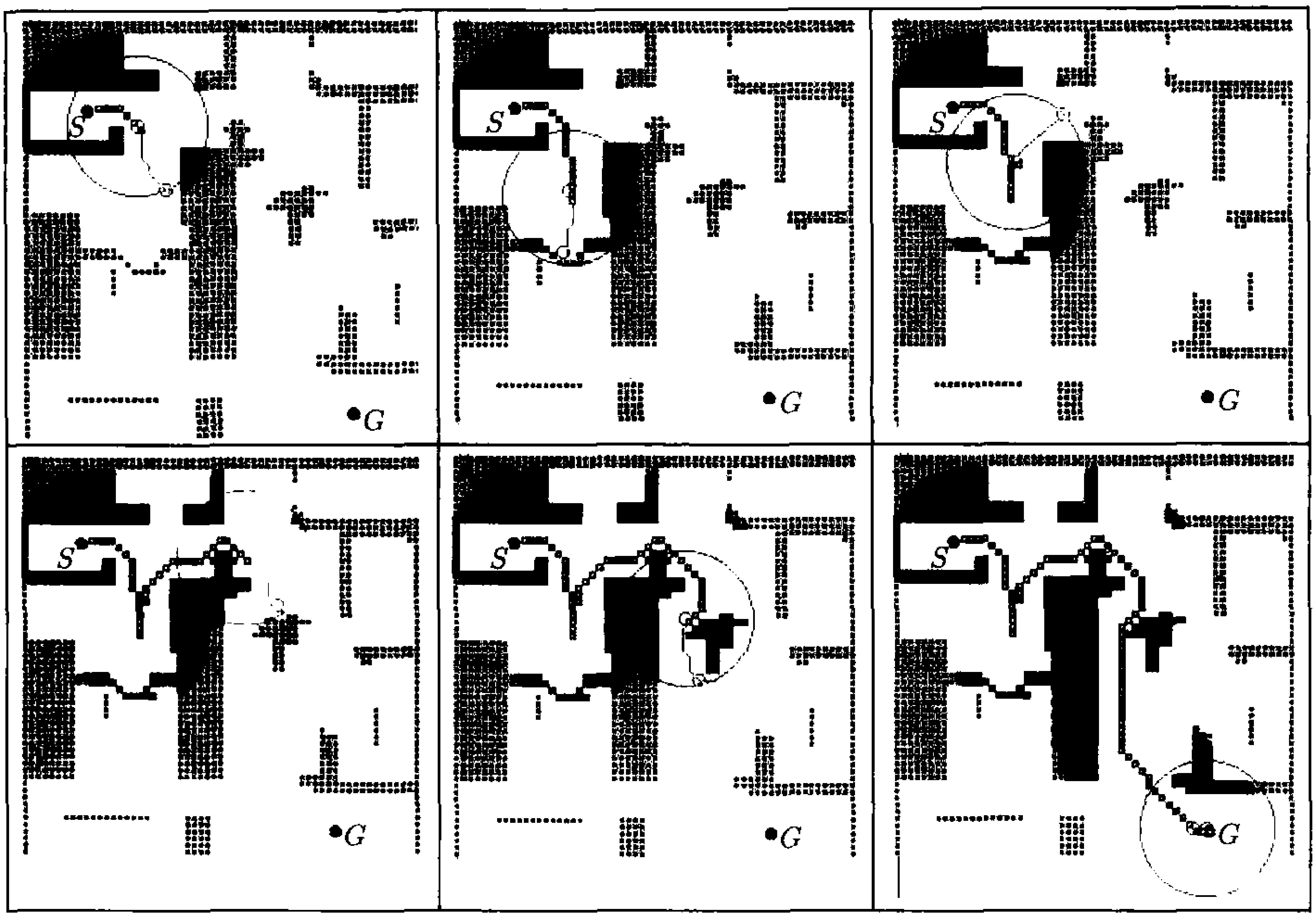


Fig. 4 Mobile robot rolling path planning in general obstacle environment

7 Conclusions

The problem of mobile robot path planning in the unknown environment is a key issue in robotics. The off-line global planning methods are prone to fail due to lack of priori environmental information. Furthermore, the robots are always constrained by finite sensorial scope in real applications. Only local detected information can be used for planning. Using the idea of rolling planning, robot path planning in a general obstacle environment is studied in this paper. By storing detected environmental information during the planning process, an improved rolling path planning method is proposed. Oscillation and dead circulation can be avoided effectively. Besides, the accessibility of the planning algorithm is also guaranteed. From the view of methodology, the rolling path planning is much alike the behavior of human being in an unknown environment. It is an apery planning method with intelligence, which is not only suitable to the path planning problems in a static environment discussed in this paper, but also has significant meanings to the ones in a dynamic unknown environment[11, 12].

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一种克服振荡与死循环的机器人实时路径规划方法

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摘　要　本文研究了一般障碍环境下全局信息未知的机器人路径规划问题，分析了基于实时探测信息的滚动路径规划算法可能遇到的振荡和死循环现象，提出了增加适量记忆的改进滚动路径规划算法，不仅有效地克服了振荡和死循环的发生，而且保证了机器人对全局目标的可达性，为移动机器人在一般未知障碍环境下的路径规划提供了快速、有效的方法.

关键词　机器人路径规划，滚动规划，局部规划，子目标，振荡，死循环，可达性

中图分类号　TP24