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MOBILE ROBOT HYBRID PATH PLANNING IN AN OBSTACLE-CLUTTERED ENVIRONMENT BASED ON STEERING CONTROL AND IMPROVED DISTANCE PROPAGATING

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Abstract. *Real-time path planning serves as an essential task for mobile robots to work within a partially known and cluttered environment. According to the real-time laser scanning data, a hybrid path planner is proposed in this paper to integrate quick obstacle avoidance and global optimization effectively. For local cluttered and dynamic scenes, mobile robot can reliably avoid the unknown obstacles based on local steering angle and velocity control law. For large-scale indoor scene with prior structured information, grid point sequence can be used to represent the global workspace, and therefore a global path planner based on improved distance propagating method can generate a series of sub-goal-points to the target, which guides mobile robot's local path planning in a more optimal way. Experiment results in the cluttered indoor environments show the method's effectiveness and practicability.*

Keywords: Local steering control, Improved distance propagating, Hybrid path planning, Mobile robot

1. Introduction.

Path planning is one of the most fundamental problems that have to be solved before the mobile robot can navigate and explore autonomously in complex indoor environment. The aim of path planning is to generate a feasible path which can guarantee mobile robot's moving from the start to the target safely and optimally in complex scenarios, where dynamic obstacles and unfavorable cases may be encountered in robot's motion.

Recently, a variety of approaches have been developed for mobile robot path planning in diversiform indoor environments, and a rich body of research results has been published in the robotics literature; see for example [1-4], and the references therein. There are two forms of path planning which is local path planning and global path planning. Global path planning can provide an initial route from mobile robot's current position to the preset target position based on the prior global map or online environment perception [5]. If the initial path is not practicable for the dynamic environment any more, the path should be regenerated according to the current global environment information, so the map updating should also be integrated to path planner. The main drawbacks of global path planning reside in its slow reaction to unknown obstacles, and it will increase mobile robot's computational burden when many dynamic obstacles exist in partially known environments. Mobile robot's local path planner, without being given the prior environment information, can use exteroceptive sensors to detect the unknown obstacles and regulate the robot's velocity to avoid the obstacles in real time correspondingly. Local path planner can provide on-the-fly obstacle avoidance in known environment effectively and reliably, but it is difficult to keep the path's global optimization in practical applications and relies heavily on the accuracy of local observation [6, 7].

In our research, we present a hybrid path planning approach combining global optimization and quick obstacle avoidance, which is implemented by global path planner and local path planner in the mode of "guiding-following" cooperatively. The global path planer provides a series of sub-goal-points which can be used to guide the local path planning. The grid point sequence is a compact and efficient model to represent robot's workspace [8], and we can plan the global path by using the improved distance propagating method which takes the obstacle information into account at the same time. According to the characteristic of laser range finder, we present a local steering control approach to complete the local path planning based on the range histogram of the laser scanning, which is an effective method for local environment measuring. In order to enhance the local planner's adaptability in the cluttered environments, an additional control strategy is added into the local path planner, which is more robust and easier for the implementation of path planning in complex unknown environment. A series of experiment results for both local path planning and hybrid path planning are also given to test the effectiveness and practicability of the method.

The remainder of this paper is organized as follows. Section 2 presents the kinematic model of nonholonomic mobile robot. A local steering control altorithm is proposed to complement local path planning in unknown and cluttered scenes in Section 3. Section 4 presents a hybrid path planner combining global optimization and quick obstacle avoidance, which can not only effectively plan a global optimal path using the prior environment information, but also quickly avoid the unknown obstacles based on the laser scanning. In Section 5, experimental results using a real robot are presented in complex environments. Finally, conclusions and future work are given in Section 6.

2. Kinematic Model of Nonholonomic Mobile Robot.

A typical example of a nonholonomic mobile robot is shown in Figure 1, which is a front wheel drive mobile robot with axisymmetric and nonholonomic constraints. The robot's position in global coordinates is (x_r, y_r); the angle between X direction and X_r direction is θ_r; and the pose of nonholonomic mobile robot q can be described as $[x_r, y_r, \theta_r]^T$ (shown in Figure 1).

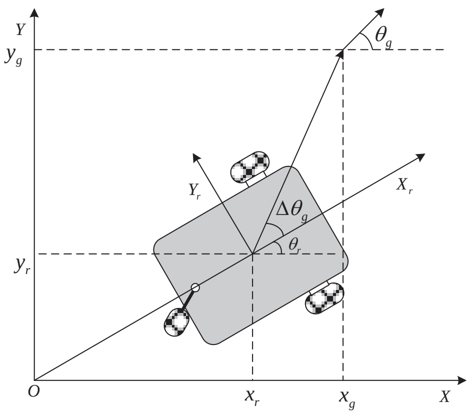


FIGURE 1. The kinematics model of nonholonomic mobile robot

The kinematics model of nonholonomic mobile robot is

$$\begin{bmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\theta}_r \end{bmatrix} = \begin{bmatrix} \cos\theta_r & 0 \\ \sin\theta_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \nu \\ \omega \end{bmatrix} \tag{1}$$

where υ is the linear velocity and ω is the angular velocity. Assuming that there is only rolling but sliding between robot's wheels and ground, the nonholonomic constraint equation is

$$\dot{x}_r \sin\theta_r - \dot{y}_r \cos\theta_r = 0. \tag{2}$$

The pose of robot's goal is $[x_g, y_g, \theta_g]$, then the steering angle of robot's motion is

$$\Delta\theta_g = \arctan\left(\frac{y_g - y_r}{x_g - x_r}\right) - \theta_r. \tag{3}$$

3. **Local Steering Control.**

In this section, a steering control approach is proposed to accomplish mobile robot path planning in unknown and cluttered environment. The laser scanning data processing is divided into three steps in this approach. Firstly, a range histogram for local environment is constructed by using laser scanning data; then a distance threshold is selected to transform the range histogram to a binary histogram; and the free areas for path planning are finally given based on the binary histogram, where the angle for local steering control is calculated. According to the steering angle and velocity control law, mobile robot can estimate the feasible velocity for obstacle avoidance accurately.

3.1. **Range histogram and binary histogram.**

In our research, LMS200 is equipped in our mobile robot. In order to reduce the computational burden, laser scanning data are selected at intervals of rotation angle $\alpha = 5°$. As shown in Figure 2, the range histogram representing the surrounding environment is constructed by arranging the reduced laser data in the sequence of $[-90°, 90°]$. Since the data errors increase as the range increases, we limit the maximum range $d = 3.5m$ to guarantee the accuracy of the laser scanning.

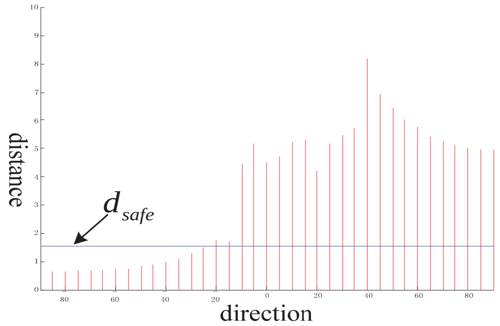


FIGURE 2. Range histogram of the laser scanning data

According to mobile robot's size and velocity, the minimum safety range d_{safe} is defined so that mobile robot can keep enough distance away from obstacles. The minimum range from the center of mobile robot to the obstacle is $d_{\min} = 45cm$. While mobile robot is running in the setting velocity, robot will still move certain distance d_{vstop} until it stops. d_{vstop} is described as

$$d_{\text{vstop}} = \frac{v_r^2}{2 \times da_{\max}}. \tag{4}$$

where v_r is robot's current linear velocity and $da_{\max}$ is robot's maximum reversed linear acceleration. d_{sample} is the distance of mobile robot's running in maximum velocity $v_{\max}$ during one sampling period T_{sample} and it can be described as

$$d_{\text{sample}} = v_{\max} \times T_{\text{sample}}. \tag{5}$$

Considering the above assurance factors, we can define the minimum safety range d_{safe} as

$$d_{\text{safe}} = d_{\min} + d_{\text{vstop}} + d_{\text{sample}}. \tag{6}$$

Comparing the laser data with d_{safe}, the binary histogram can be derived by the following criterion

$$\begin{cases} H(i) = 1 & \text{if } d(i) \geq d_{\text{safe}} \\ H(i) = 0 & \text{if } d(i) < d_{\text{safe}} \end{cases} \tag{7}$$

3.2. **Selection of steering angle.** The set of angle candidates is calculated by the method given in [6] and the one with minimum value in the evaluation function is selected as the steering angle. Our work uses a simplified evaluation function

$$G(c) = \frac{|c - k_t| \times d_{\max}}{d(c)}. \tag{8}$$

k_t is the nearest angle corresponding to $\Delta\theta_g$ and $d(c)$ is the laser scanning data corresponding to the angle candidate c. By comparing different values for the evaluation function, we can select the steering angle φ by

$$G(\varphi) = \min_{i \in \Omega}\{G(i)\} \tag{9}$$

Ω is the set of angle candidates.

In our work, the swing phenomenon will happen when mobile robot is just facing an obstacle. In this case, we take the steering angle in last step to be the current one so that mobile robot can avoid the obstacles smoothly and swiftly.

3.3. **Control of speed.** Based on the steering angle φ, mobile robot's control law of the angular velocity is designed as

$$\omega = \begin{cases} -\omega_{\max} & \varphi \leq -\dfrac{\pi}{2} \\ \omega_{\max}\dfrac{\varphi}{\pi/2} & -\dfrac{\pi}{2} < \varphi < \dfrac{\pi}{2} \\ \omega_{\max} & \varphi \geq \dfrac{\pi}{2} \end{cases} \tag{10}$$

where $\omega_{\max}$ is the maximum angular velocity.

According to the different number of the obstacles around the robot, different control laws of the linear velocity are employed in the planning, so that mobile robot will decelerate while there are many obstacles. The control law is designed as

$$v = \begin{cases} v_{\max} \times \dfrac{d_{\text{near}}}{d_{\max}} \times \left(1 - |\dfrac{\varphi}{\pi/2}|\right) & \text{if many obstacles} \\ v_{\max} \times \left(1 - \dfrac{d_{\max} - d(\varphi)}{d_{\max} - d_{\text{safe}}}\right) \times \left(1 - |\dfrac{\varphi}{\pi/2}|\right) & \text{if a few obstacles} \end{cases} \tag{11}$$

where d_{near} is the nearest distance from robot's current position to the obstacle.

In order to guarantee that the mobile robot can stop at the goal safely, robot should run in lower speed when it comes close to the goal. Due to mobile robot's kinetic characteristics, it is not feasible for robot to reach the velocity calculated by Equation (11) in the next sampling period, so the robot's practical velocity should meet the following velocity range

$$\begin{cases} \max\{-\omega_{\max}, \omega_\gamma + da_\omega T_{\text{sample}}\} \leq \omega \leq \min\{\omega_\gamma + a_\omega T_{\text{sample}}, \omega_{\max}\} \\ \max\{-v_{\max}, v_\gamma + da_{\max} T_{\text{sample}}\} \leq v \leq \min\{v_\gamma + a_{\max} T_{\text{sample}}, v_{\max}\} \end{cases} \tag{12}$$

If the velocities calculated by (10) and (11) are out of the above range, the boundaries of (12) are used as the robot's velocities.

3.4. **Additional control strategy.** We do not take robot's width into account in the velocity control, so additional control strategy has to be adopted to ensure that mobile robot can accomplish obstacle avoidance safely. We define d_{danger} and d_{pdanger} as the danger zone and the potential danger zone, respectively. The nearest distance to the left obstacle is defined as d_{left}, and the nearest distance to the right obstacle is defined as d_{right}. All these parameters are shown in Figure 3.

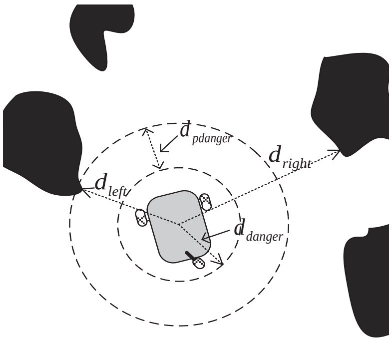


Figure 3. Additional control strategy

When d_{left} or d_{right} is in the range of d_{pdanger}, it means that the collision may happen in the side which is closer to the robot. Therefore, the angle increment ϕ should be added to mobile robot's moving direction angle φ, which is described as

$$\begin{cases} \varphi = \varphi + \phi & \text{if } d_{\text{left}} \geq d_{\text{right}} \\ \varphi = \varphi - \phi & \text{if } d_{\text{left}} < d_{\text{right}} \end{cases} \tag{13}$$

When d_{left} or d_{right} is less than d_{danger}, it means that there is a great probability of the collision between robot and obstacles. Mobile robot should stop and turn so that it can find a better moving direction. This control strategy is designed as

$$\begin{cases} v = -v_{\gamma}, \omega = 0 & \text{if} \quad d_{\text{left}} < d_{\text{danger}} \text{ and } d_{\text{right}} < d_{\text{danger}} \\ v = 0, \omega = -\beta\omega_{\max} & \text{if} \quad d_{\text{left}} < d_{\text{danger}} \\ v = 0, \omega = \beta\omega_{\max} & \text{if} \quad d_{\text{right}} < d_{\text{danger}} \end{cases} \tag{14}$$

3.5. **Simulation results and data analysis.** MobileSim is a powerful simulator for autonomous mobile robots, which is provided by MobileRobots Inc. MobileSim is suitable for the computer simulation of mobile robot's motion and laser scanning simultaneously, and it is used to test our local path planner's validity in this paper. The parameters for the simulation experiment is set as: the maximum linear velocity $v_{\max} = 0.3m/s$, the maximum angular velocity $\omega_{\max} = 1.57rad/s$, the maximum forward linear acceleration $a_{\max} = 0.3m/s^2$, the maximum reversed linear acceleration $da_{\max} = -0.3m/s^2$, the maximum forward angle acceleration $a_{\omega} = 3rad/s^2$, the maximum reversed angle acceleration $da_{\omega} = -3rad/s^2$.

In this simulation experiment, mobile robot can accomplish its local path planning in a complex unknown environment successfully. The coordinate of the start is $(0, 0, 0)$ and the target is $(12, 7, \pi/4)$. The simulation result is shown in Figure 4. It can be considered that the robot has already arrived at the target when robot's current position is in a certain range of the target, which is preset as $0.1m$ in the simulation. Since the target's direction is not considered in the mobile robot's local planning, there is a certain angular deviation while robot arrives at the target. The angular deviation can be eliminated easily as robot rotates certain angle.

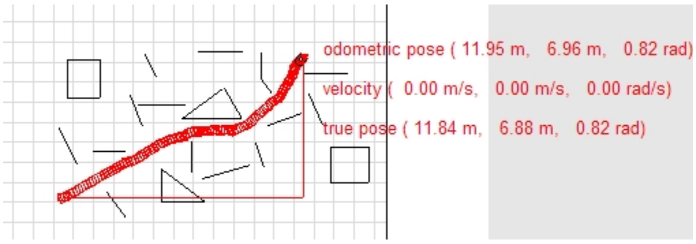


FIGURE 4. Local path planning in a complex unknown environment

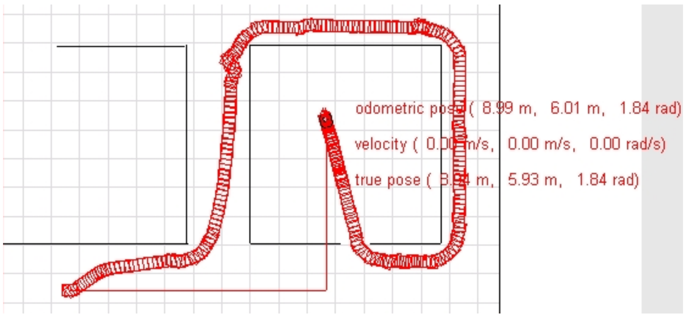


FIGURE 5. The simulation result show that local path planner is not a guarantee of global optimal path planning

In the local path planning, the steering angle is the only instruction on the selection of mobile robot's moving direction and the robot cannot acquire any global environment information, so the path obtained from the local planner is a non-global optimal one. The simulation result shown in Figure 5 is a good case to illustrate this situation. The coordinate of the target is $(9, 6, \pi/2)$ and the robot chooses the direction of motion upwardly instead of moving straightly in the local path planning, which makes the final path much longer than the global optimal one. This problem can be solved by using hybrid path planning method which is introduced in next section.

4. Hybrid Path Planning.

4.1. Global path planning based on grid point sequence. Grid is a well-known environment modelling technique which makes the environment representation practical and easy to design [9]. However, mobile robot's final path has to be represented by a series of abstract points, so the crucial step for path planning is to generate and plan these points. In our work, we adopt grid point to substitute grid for following reasons [8]. Firstly, grid point is simpler than grid and it is also convenient in practical applications. For example, the start and the target are all given by points, so we can designate the start and the target by using the grid points directly. Furthermore, the sub-goal-points in local path planning can select the grid points generated by the global path planner directly, which is easy to implement and makes the integration of local and global path planning more rationally. Another important reason to choose grid point is that additional factors such as angle information can be added in it, so that state lattices will be constructed to solve the nonholonomic constraint problem [10]. If we use grid in path planning, we have to convert these grids to points which will increase the computation burden. Comparatively, grid point sequence is easier to accomplish path planning since its path is composed by a series of points directly.

Distance propagating method introduced in [11] only takes the distance between grid point and target into account. Since the influence of obstacles is not considered, it is possible that the designed path is too close to obstacles. In order to overcome this problem, an improved method is presented to add the obstacle information into the distance propagating course.

4.2. **Improved distance propagating method.** Suppose that mobile robot's workspace can be discretized into M grid points. The neighbouring set for grid point i is defined as B_i and the number of grid points in set B_i is related to the directions of propagation. d_{ij} is the distance between any two grid points i and j.

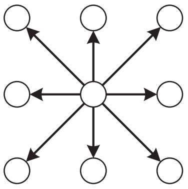


FIGURE 6. 8-directions used in distance propagating

If we use 8-directions in distance propagation which is shown in Figure 6, then d_{ij} is described as

$$d_{ij} = \begin{cases} \sqrt{2} & \text{diagonally} \\ 1 & \text{otherwise} \end{cases} \tag{15}$$

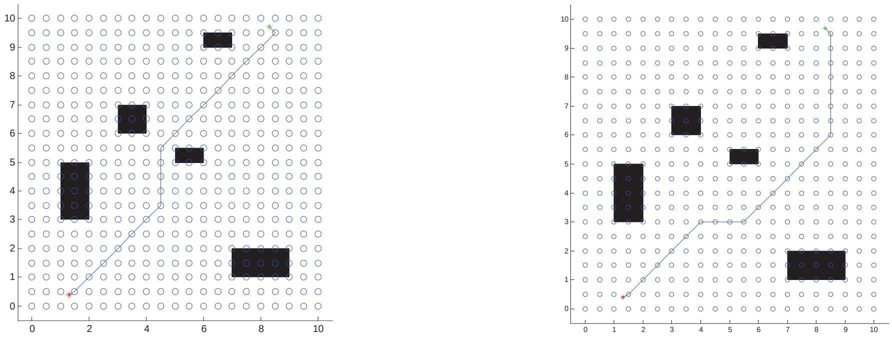
In practical application, the value of d_{ij} is set to 5 and 7. Suppose that b is the range interval between two adjacent grid points, then we can define the obstacle grid point as it is in the center of the square with side length b. If the obstacle cannot be represented by one point, the boundary of the large obstacle can be divided into several obstacle grid points. In our improved distance propagating method, we set the obstacle as the starting point and adopt 4-directions to accomplish obstacle distance propagation. After that we set the target as the starting point and adopt 8-directions to accomplish distance propagation by taking the influencing factors of obstacles into account simultaneously. We adopt back trace technique to find the entire path from the start by using the gradient descending search. In this improved method, each grid point has its own cost x_i, which represents not only the distance between this point and the target, but also the influence of obstacles. The implementation of this improved method is described by following equations.

$$x_i = \begin{cases} 0 & \text{if } i \text{ is the goal position} \\ f_i & \text{otherwise} \end{cases} \tag{16}$$

$$f_i = \min_{j \in B_i} \{x_j + d_{ij} + \alpha \times obstacle(i)\} \tag{17}$$

$$obstacle(i) = \begin{cases} (d_o - o(i))^3 & o(i) < d_o \\ 0 & o(i) \geq d_o \end{cases} \tag{18}$$

$obstacle(i)$ is the obstacle information of grid point i and α is corresponding influencing coefficient. The value of α represents the obstacle's influence on path planning. d_o is the minimum distance that obstacles can effect mobile robot's path planning and $o(i)$ is the obstacle distance propagated from the obstacle to grid point i. When $o(i)$ is greater than $d(o)$, it means that this grid point is not in the range of obstacle's influence. While $\alpha = 0$, it is similar to the path planning method proposed in [12], the planning result of which is shown in Figure 7(a). The coordinates of the start and the target are $(1.3, 0.4)$ and $(8.3, 9.7)$, respectively. While $\alpha = 0.8$, the path planning result in the same simulation data is shown in Figure 7(b). Due to the comparison of the path in Figures 7(a) and 7(b), an obvious advantage of the path in Figure 7(b) is that it passes through the region with little obstacles, but the path in Figure 7(a) passes through two adjacent obstacles and the vertical distance from the bottom obstacle to the path is less than the range interval b, which is not safe enough for robot's motion.



(a) (b)

Figure 7. Path planning results of distance propagating method (a) and improved distance propagating method (b)

4.3. **Hybrid path planner combining local steering control and global optimization.** In this paper, a hybrid path planner combining local steering control and global path planning based on grid point sequence is presented, which integrates the advantages both in local and global planner. In our work, the global optimal path is planned and generated by using the partial known environment firstly. Then we make use of this global optimal path to generate local sub-goal-points which can be used to guide the local path planning, so that we can control mobile robot's velocity effectively and accomplish the robot's real-time obstacle avoidance reliably. The layout of the hybrid path planner is shown in Figure 8.

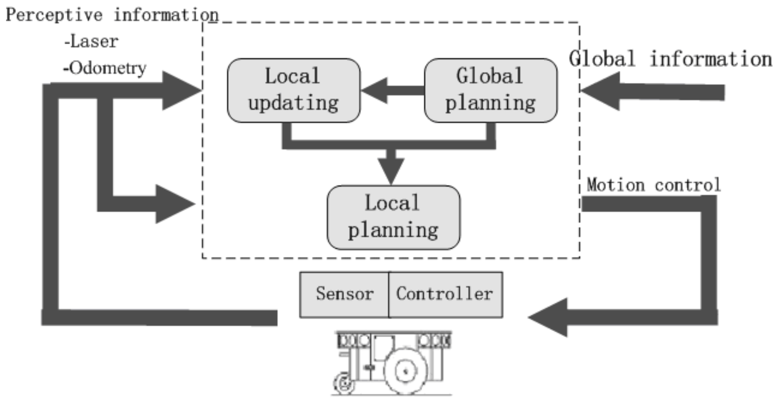
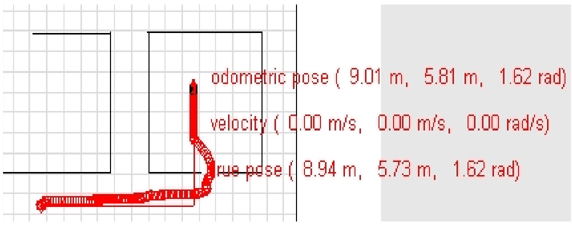


Figure 8. The layout of the hybrid path planner

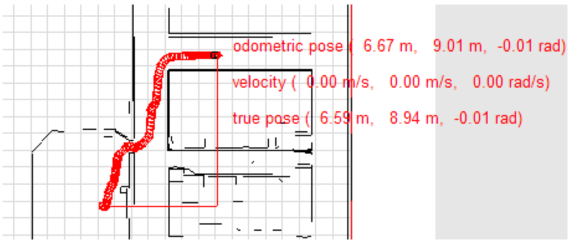
In the hybrid path planning system, the global path will guide the local path planning, whereas the local path planner is responsible for planning a practical path which could not only meet mobile robot's nonholonomic constraint but also accomplish the task of obstacle avoidance reliably. In order to guarantee the accuracy and effectiveness of global path planning, the initial global path should be updated partially when mobile robot can find obstacles using laser scanning. Mobile robot's sub-goal-points have to be selected deliberatively so that the path planned by local planner could be consistent with the global path. In our work, we choose the inflection points in the global path to be the sub-goal-points in mobile robot's local planner. This method can make full use of the advantage of local planner and reduce the number of times in changing sub-goal-point. When the robot is in the preset neighborhood of the sub-goal-point, it is considered that mobile robot has already reached the sub-goal-point and the next inflection point is chosen to be the new sub-goal-point.

4.4. **Simulation results and data analysis.** In order to test the validity of the hybrid path planner, the parameters for the simulation experiment are the same with the ones in section 3.5. $0.2m$ is the range interval between two adjacent grid points in global planning. Comparing the path in Figure 9 with the one in Figure 5, we can see that the hybrid path planning result is a global optimal one.



```
odometric pose (  9.01 m,   5.81 m,   1.62 rad)
velocity (  0.00 m/s,   0.00 m/s,   0.00 rad/s)
rue pose (  8.94 m,   5.73 m,   1.62 rad)
```

FIGURE 9. A global optimal hybrid path planning result



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odometric pose (  6.67 m,   9.01 m,  -0.01 rad)
velocity (  0.00 m/s,   0.00 m/s,   0.00 rad/s)
true pose (  6.59 m,   8.94 m,  -0.01 rad)
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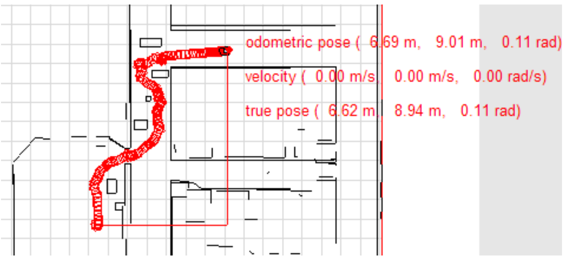
FIGURE 10. Path planning without unknown obstacles



```
odometric pose (  6.69 m,   9.01 m,   0.11 rad)
velocity (  0.00 m/s,   0.00 m/s,   0.00 rad/s)
true pose (  6.62 m,   8.94 m,   0.11 rad)
```

FIGURE 11. Path planning with unknown obstacles

In another simulation experiment, $(6.7m, 9m, 0)$ is set as the target. If the robot wants to arrive at the target successfully, it should plan its global path from the office to the corridor, then moves along the corridor and turns right at the crossing to reach the garget. The walls, the doors and the corners are given as the prior global environment information. The obstacles exist in the corridor and office randomly, and they can only be detected and estimated using laser scanning during the local path planning. If there are not any unknown obstacles along the path planned by global path planner, the effect of local path planner is only to smooth the path so that the robot's motion can be subject to nonholonomic constraints (shown in Figure 10). If there are unknown obstacles in the office and corridor, the local planner in our hybrid path planning method can guarantee both effective path planning and safe obstacle avoidance to mobile robot (shown in Figure 11).

5. **Experiment Results.** In our experiment, we use Pioneer3-DX mobile robot (shown in Figure 12) which is a mid-sized and powerful robot platform quipped with a SICK LMS200 laser range finder. In our experiment, we only use laser ranger finder to acquire enough information from indoor environment. Comparing with ultrasonic range sensors, laser range finder has not only much higher resolution, but also faster sampling rate with limited measurement noise. For wireless communications, the robot is integrated with IEEE 802.11 based wireless network adapter which allows wireless transparent TCP/IP using WaveLan. The experimental environment is in the corridor and offices of our research center. The Pioneer3-DX comes with an online supervisor console interface for displaying the experiments simultaneously. A series of experiment results for local path planning and hybrid path planning are given in following sections.

Figure 12. Pioneer3-DX mobile robot with laser range finder

5.1. **Experiment results for local path planning.** Due to the importance of local path planning in the system of hybrid path planner, a local path planning experiment without any prior environment information is given firstly to test the validity and practicability of our local path planner. Here is a list of the parameters set in the experiment: $v_{\max} = 0.3m/s$, $\omega_{\max} = 100deg/s$, $a_{\max} = 0.3m/s^2$, $da_{\max} = -1.0m/s^2$, $a_\omega = 180deg/s^2$, $da_\omega = -180deg/s^2$.

Mobile robot acquires surrounding information by exteroceptive sensors that provide a representation of the environment and obstacles. In our experiment, laser scanning is used to collect obstacles information in the unknown environment and provides the information for real-time obstacle avoidance and path planning. In the experiment environment which is shown in Figure 13, the boxes and tables are the classical obstacles for robot's path planning. The coordinate of the start is $(0, 0, 0)$ and the target is $(3.5m, 2.2m, 0)$. We set the target close to the obstacle intentionally. Four pictures shown in Figure 13 are extracted from the experiment monitoring video and four pictures shown in Figure 14 are the corresponding experiment results of local path planning displayed in online supervisor console interface simultaneously.

The online monitoring software for Pioneer3-DX is MobileEyes which can display the laser scanning data online. Taking Figure 14 for example, the blue points are the laser date in current scanning period and the grey ones are the previous data. As shown in subfigure (a) to (d) of Figures 13 and 14, mobile robot starts off from the start to the

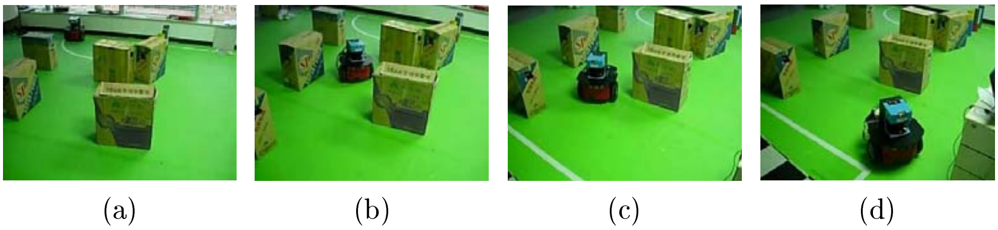


FIGURE 13. Experiment results of local path planning

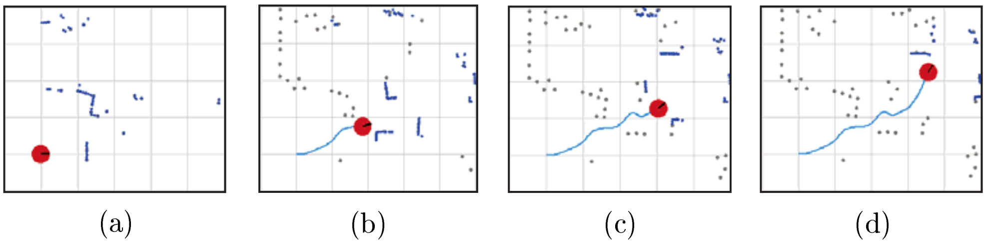


FIGURE 14. The corresponding experiment results of local path planning displayed in online supervisor console interface

target. When unknown obstacles are detected in robot's scanning range, mobile robot can accomplish path planning and obstacle avoidance effectively by using the method proposed in this paper until it arrives at the target finally. In this experiment, the target is close to the obstacle. But our method ensures that mobile robot can stop at the target directly instead of wandering around the target. According to the experiment result shown in Figure 14(d), there is an obvious error between the robot's final heading angle and the target angle because the angle information of target is not consider in the local planner. However, it is easy to eliminate the angle error when mobile robot just rotates certain angle.

The local steering control method proposed in this paper is also effective for local path planning in U type obstacle zone, which shows our local planner's applicability in complex and dynamic environment. As shown in the subfigure 15(b), a white board is rapidly put between two obstacles which makes the previous path is blocked and the mobile robot comes into a classical U type obstacle zone. As shown in the subfigures 15(c) and 15(d), mobile robot rotate certain angle and turn back to plan for a new path. The target set in this experiment is $(3.5m, 2m, 0)$. Figure 16 is the corresponding experiment results of local path planning in U type obstacle zone displayed in online supervisor console interface.

5.2. **Experiment results for hybrid path planning.** The environment for the hybrid path planning experiment is our offices and corridor. The prior environment information is only the walls and doors which are the yellow regions in Figures 18 and 20. All the other objects are considered as obstacles. The range interval between two adjacent grid points is the critical factor for computational complexity and optimization in global path planning. Due to the narrow door existing in the environment, mobile robot may not search out the global path if the range interval exceeds certain threshold value, so we set the range interval to be $10cm$. The target of global path planning is $(6m, 6m, \pi/2)$ which is shown as a green square in subfigures 18(a) to 18(e). If new obstacles are added during the course of robot's running (shown in subfigure 18(b)), mobile robot can detect the environment change in real time and update the global path in the specified local area so that mobile robot could regenerate a global path to the target (shown in subfigures 18(c)

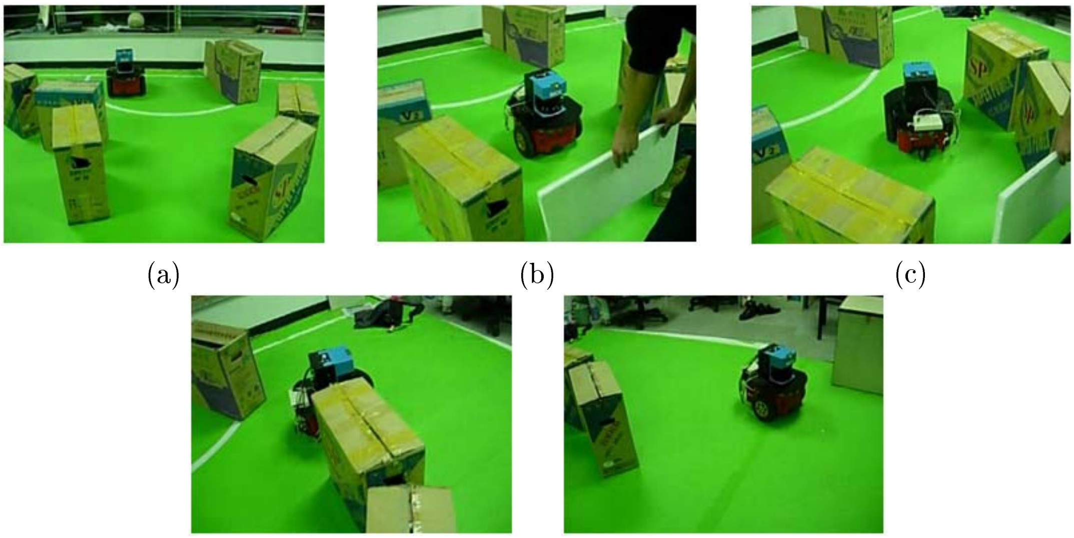

(a) (b) (c)
(d) (e)

Figure 15. Experiment results of local path planning in U type obstacle zone

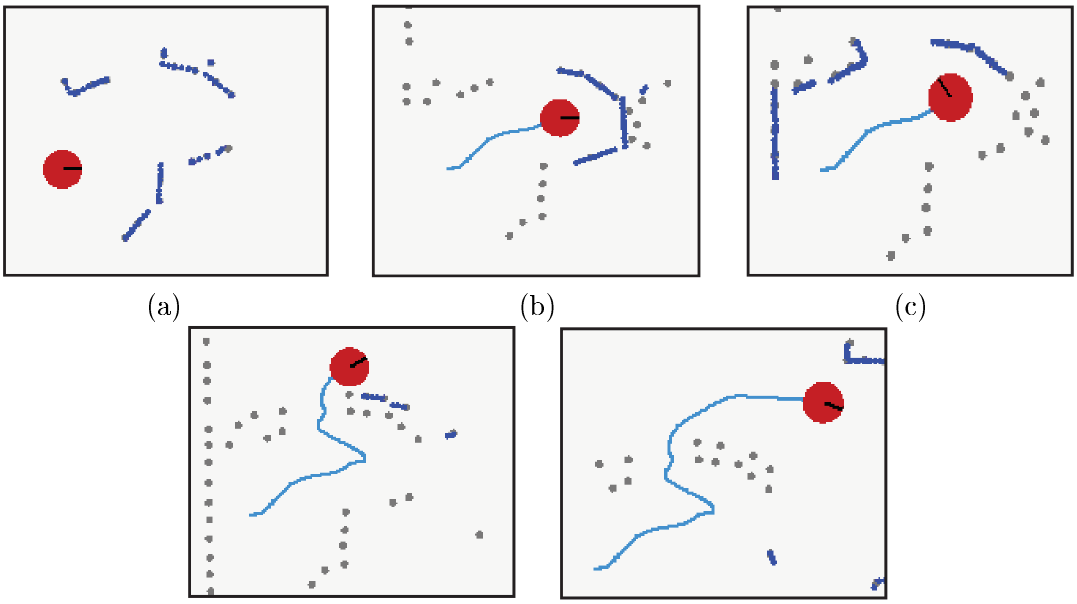
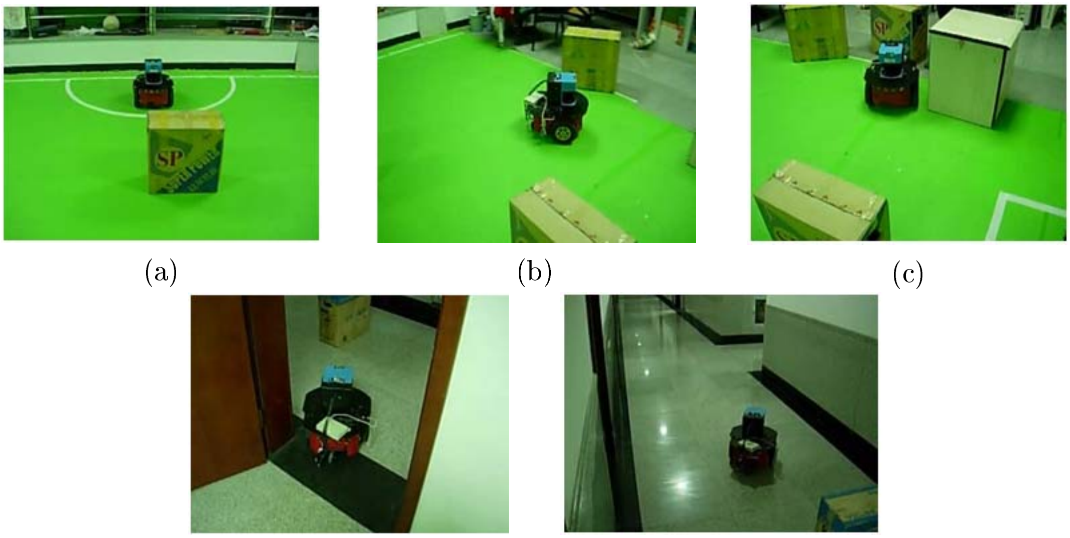

(a) (b) (c)
(d) (e)

Figure 16. The corresponding experiment results of local path planning in U type obstacle zone displayed in online supervisor console interface

and 18(d)). The real path planning result is shown in Figure 17 and the corresponding experiment results displayed in online supervisor console interface is shown in Figure 18.

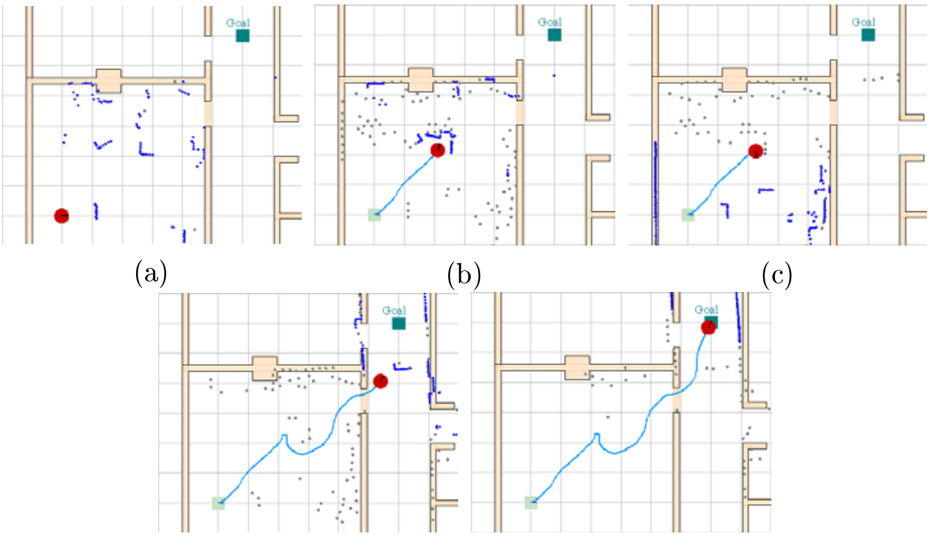
There are two doors that the robot should pass through if the global path is from one office to another. The experiment result shown in Figures 19 and 20 could demonstrate our method's validity in some complex environments. Comparing the corresponding subfigures in Figures 19 and 20, you may find out that the robot's pose and the laser scanning data shown in online supervisor console interface are not well consistent with the real situation. The hybrid path planner used in these experiments can only estimate its pose from the odometry but the localization algorithm. The errors caused by the odometry are in direct proportion to the distance of path, so the errors are much more obvious in



(a) (b) (c)

(d) (e)

Figure 17. Experiment results of hybrid path planning



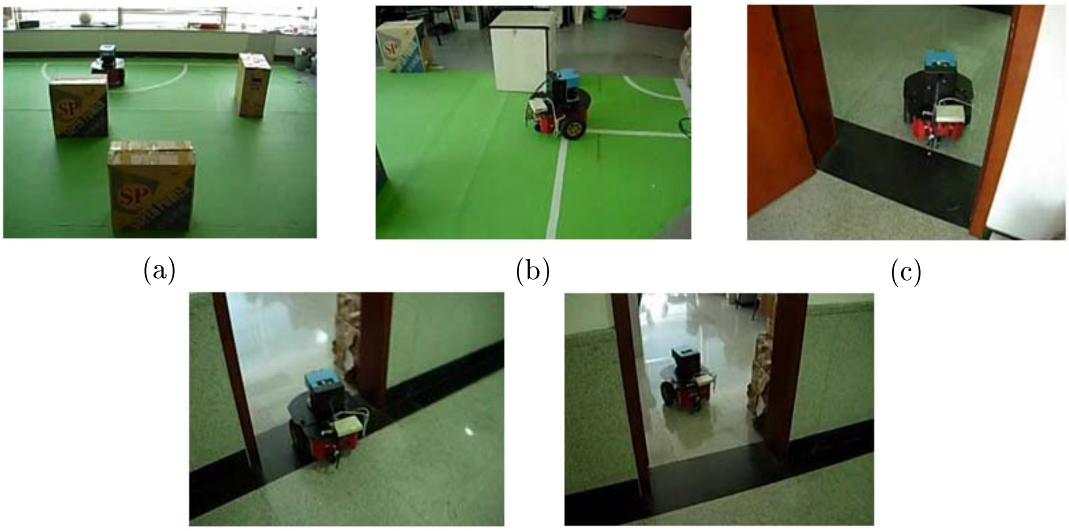
(a) (b) (c)

(d) (e)

Figure 18. The corresponding experiment results of in online supervisor console interface of Figure 17

this experiment. In our future work, the errors could be corrected by filter algorithm using observation information, which will make our hybrid path planner more robustly in practical applications.

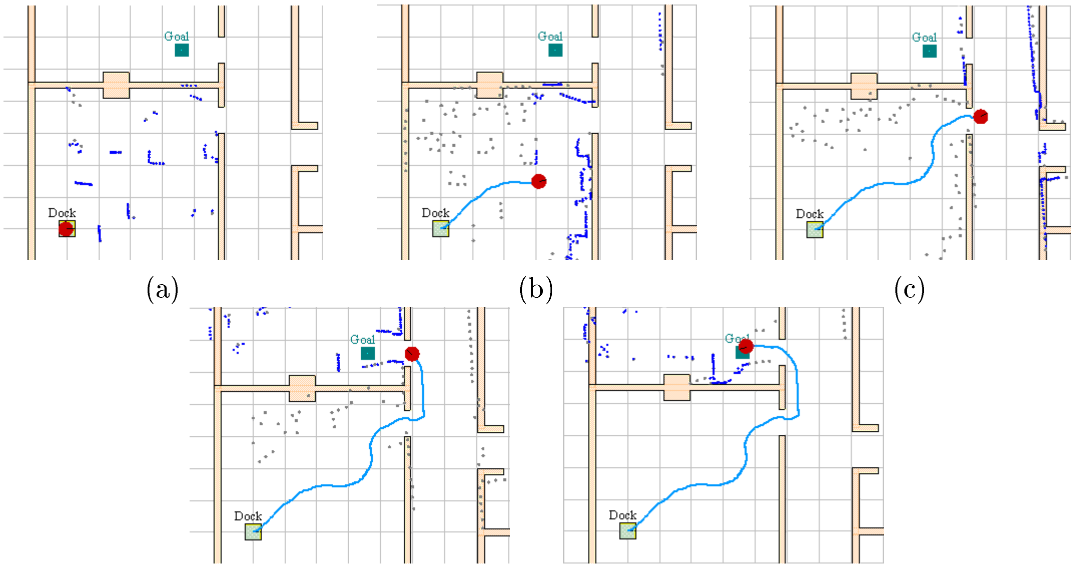
6. **Conclusions and Future Work.** Our work has mainly concentrated on how to carry out mobile robot autonomous path planning in unknown indoor environments in practical application. In order to integrate the advantages of fast obstacle avoidance in local path and the global optimization in global path, we use hybrid path planner to complete both local path planning based on local steering control and global path planning based on grid point sequence. In the hybrid path planning system, global path is used as guiding path to instruct local path planner's following. In this paper, an improved distance propagating method is proposed, which uses grid point sequence to represent the workspace. It is not only convenient for path generation, but also suitable for the seamless integration



(a) (b) (c)

(d) (e)

FIGURE 19. Experiment results of hybrid path planning from one office to another



(a) (b) (c)

(d) (e)

FIGURE 20. The corresponding experiment results in online supervisor console interface of Figure 19

of local planner and global planner. A series of experiments implemented in real mobile robot is given to tests the hybrid path planner's validity and practicability in different environment and scenarios. Further work is planned to add localization algorithm to the hybrid path planning approach, which makes the mobile robot more robustly in practical navigation, especially in the dynamic and large-scale indoor environment.

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