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Safe and high speed navigation of a patrol robot in occluded dynamic obstacles

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Abstract: It is difficult to detect all dynamic obstacles around a robot due to the limitation of field of view. Visibility information is necessary in order to avoid collisions. In previous research, we proposed a path planning and speed control scheme that could be applied to a robot to avoid occluded dynamic obstacles. In this paper experimental verifications of the proposed scheme for various environments are presented. The path planning scheme is improved by considering the robot's moving direction. Experimental results show that the proposed high speed navigation of a patrol robot can be achieved together with safety.

1. INTRODUCTION

A considerable number of studies have been carried out on the autonomous navigation of a mobile robot. In order to improve efficiency of a service robot, high speed navigation is desirable without sacrificing safety. It is important to improve the speed of patrol robots to cope with emergency. However, there are many difficult problems to achieve high speed navigation.

Unexpected collision and visibility problems have been investigated extensively in numerous studies. Sadou *et. al*. focused on the occlusion of obstacles. This study focuses on one significant consideration in dealing with unexpected obstacles. However, the scope of unexpected obstacles is limited to the occluded obstacles on the path, and the path is always fixed. Another approach is to utilize navigation experiences (Bennezitz *et. al,* 2005). It was shown that the robot can provide appropriate mobile services by monitoring and utilizing the moving patterns of people. This approach allows the robot to deal with the change of environments. However, the navigation experience provides only stochastic information. In order to solve the safety issue, a deterministic approach is required. Krishna *et. al*. computed the safe velocity profile of a robot along a path and modified the path near the invisible region. They showed one example of speed control for safety. However, a more general approach combining path planning and velocity control should be considered to solve practical problems. Another example of a speed control problem can be found (Mandow *et. al*., 1997). Well-defined speed constraints are addressed with respect to vehicle features and operational conditions. However, there is no scheme combining path modification. The major advantage of this paper is the general usefulness and a structural scheme to deal with risks of navigation.

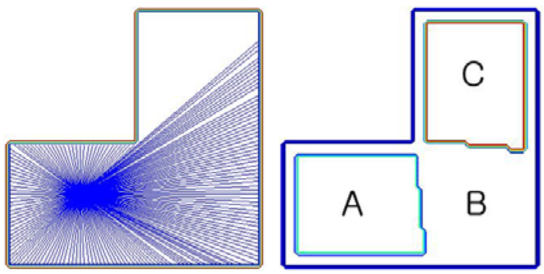
Our previous research focused on unexpected environmental changes (Kim *et. al*., 2007). Path planning and speed control schemes were developed and applied to robots. Under these schemes, the robots were able to avoided possible collision with dynamic obstacles from occluded regions. Although the basic concepts and analysis were presented, previous research did not clearly present the usefulness of the algorithm. Furthermore, the algorithm carried out computations of the regions with limited field of view without considering the robot's moving direction.

In this paper, we propose a path planning scheme considering the visibility information and moving direction. According to the heading direction, the existence of occluded area is determined when moving from one sector to another. This paper shows that safe and faster navigation is possible by considering the robot's moving direction.

This paper is organized as follows. Section 2 presents the definition of the visibility sector. A path planning scheme is proposed by using the visibility information and moving direction. In section 3, the usefulness of the proposed algorithm will be shown through experiments for various real environments. Concluding remarks are given in section 4.

2. A PATH PLANNIG SCHEME USING VISIBILITY INFORMATION AND MOVING DIRECTION

2.1 Visibility Sector



(a) (b)

Fig. 1. Ray Tracing (a), Visibility Sector (b)

Range sensor data from one point of a known environmental map is shown in Fig. 1(a). At a convex edge, range sensor data would be changed suddenly. Therefore, the convex edge presents a limited field of view. All possible points of environment with same discontinuous points can bind one sector (O'Rourke, 1987). As a result, an area is divided by an extension of the convex edge as shown in Fig. 1(b). This area is defined as the 'Visibility sector' (Lee at al., 2000). When a robot moves to C from A through B, the risk of incident obstacles which could appear from C must be considered. On the other hand, when a robot moves left from A, this risk should be excluded.

2.2 Collision risk area and Maximum safe speed

Collision risk distance can be easily calculated by the method proposed by Kim *et. al*.

$$d_{delay} = t_{delay} \times (v_r + v_{obs}) \tag{1}$$

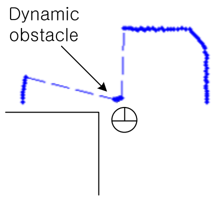
$$d_{break} = v_r^{\ 2} / (2 \times a_{robot}) \tag{2}$$

$$d_{obs} = v_{obs} \times v_r / a_{robot} \tag{3}$$

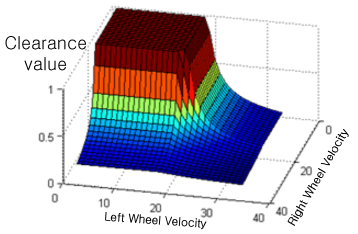
$$d_{collision} = d_{delay} + d_{break} + d_{obs} \tag{4}$$

$d_{collision}$, d_{delay}, d_{break}, and d_{obs} are collision risk distance, robot and obstacle moving distance in time delay, moving distance while decelerating for a stop, and moving distance while stopping respectively. v_r, v_{obs}, and a_{robot} are the speed of the robot, speed of the obstacle and acceleration of the robot respectively. Using the difference between the robot's reachable region and visible area, this method can determine the existence of the occluded area. The occluded area is calculated mostly around the convex edge. Collision risk distance ($d_{collison}$) relies on the robot's and obstacle's speed.

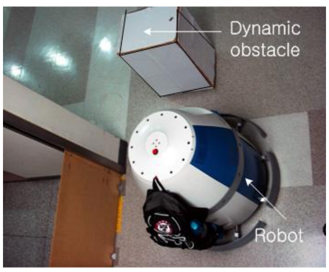
2.3 Danger Index



(a)



(b)



(c)

Fig. 2. Range Sensor Image (a), Clearance Object (b), Environmental picture (c)

Danger index is defined to represent the collision risk, quantitatively. It is defined as the ratio of collision free speed area and collision speed area in a controllable speed area (Dynamic window) during the sampling frequency (Fox et al., 1997). Within the dynamic window speed range, the danger index becomes close to 1 when the collision area increases. On the other hand, the danger index is 0 when the robot is collision free. Fig. 2(a) shows the sensor data when a dynamic obstacle exists in front of a robot. The clearance object in the dynamic window is shown in Fig. 2(b). The collision time is calculated by considering the speed of the robot when obstacles are detected by the range sensor. The speed range of possible collision has 0 values. We will prove the motion safety from calculating the danger index.

2.4 Collision Risk Area considering Moving Direction

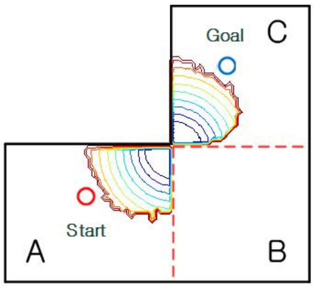
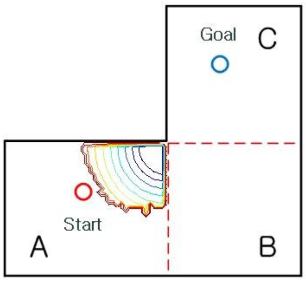
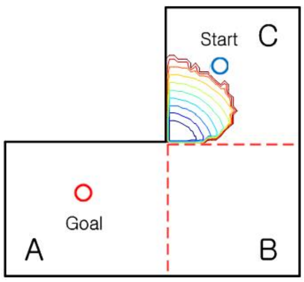


Fig. 3. Collision Risk Area

Fig. 3 shows the computed collision risk area without considering the robot's moving direction. However, it is not appropriate because we assume that collisions occur in front of the robot's heading. It does not consider collisions with obstacles behind the robot. Therefore, the collision risk area should be reset by considering the moving direction and visibility information in path planning.



(a)



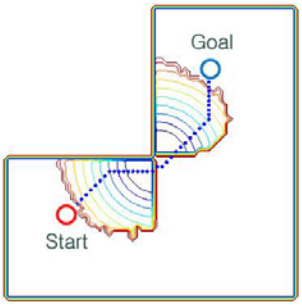
(b)

Fig. 4. Fixed Collision Risk Area

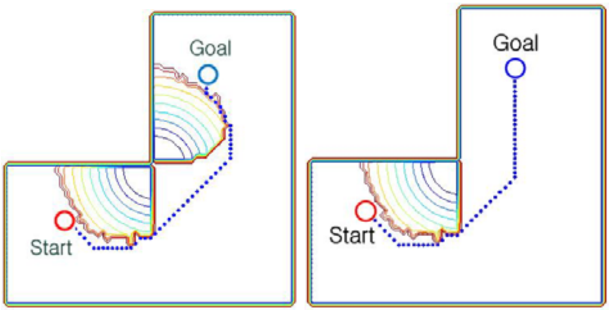
Fig. 4 shows the result of collision risk area reset with consideration of the occluded area and the moving direction. Fig. 4(a) shows the robot moving from A to C passing through B. Collision risk can be eliminated by determining the robot's moving direction. In Fig. 4(a), collision risk exists with respect to the dynamic obstacle of C when the robot is moving from A to B. Therefore, the collision risk area in C is valid. When the robot is moving from B to C, the collision risk area in C is not valid because there is no occluded area. Fig. 4(b) shows that the robot is moving from C to A passing through B. Collision risk exists with respect to the dynamic obstacles from A when the robot is moving from C to B. As a result, collision risk area in C is valid. In case of moving from B to A, collision risk area in A is invalid because there is no occluded area.

2.5 Path Planning Using Visibility Sector

This paper uses the gradient path planning method (Konolige, 2000). The motion control and the path planning are performed by a hybrid approach (Brock; Khatib, 1999). Real time collision avoidance algorithm is based on the dynamic window approach (Fox *at. al*., 1997). Adjacency cost in the gradient method is the reciprocal of the maximum speed of the robot position. Then, the adjacency cost implies the travelling time (Kim *et. al*. 2007). In the collision risk area, the adjacency cost is large due to the speed limitation of the robot.



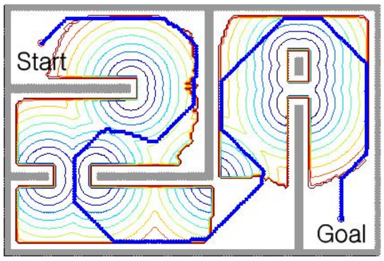
(a)



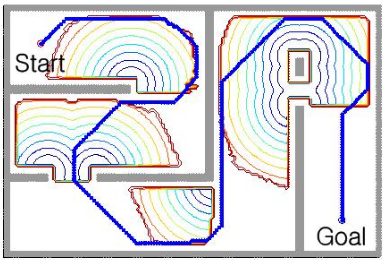
(b) (c)

Fig. 5. Gradient Path (a), Kim's Path (b), Proposed Path (c)

Fig. 5(a) shows the path obtained by using gradient method. Fig. 5(b) shows the path obtained by using Kim's method. Fig. 5(c) shows the path obtained by using the proposed method. Travel times were 9.4sec, 12.4sec and 11.6sec for the three methods, respectively, in the 6m x 6m environment. Fig. 5(a) shows the shortest path. However, collision risk due to dynamic obstacles is high. In Fig. 5(b), the path is safe because collision risk of the occluded area was considered. However, the path makes a detour around the corner in spite of guaranteed visibility in the moving direction. In Fig. 5(c), the path is generated with consideration of the moving direction. A detour path is generated in the occluded area and the shortest path is generated visibility to the moving direction is ensured. In this case, a safe and shorter path is generated. Compared with the previous method, travel time is shortened about 0.8sec while the safety of motion is maintained. Therefore, it is a desirable path planning scheme. The following figure shows the simulation result for the large environment and faster obstacle speed.



(a)



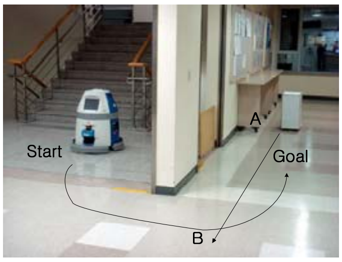
(b)

Fig. 6. Kim's Path (a), Proposed Path (b) (Wide Area)

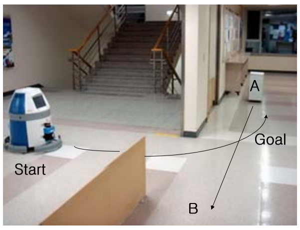
Fig. 6(a) is the result of path planning obtained by using Kim's method. Fig. 6(b) shows a path is generated by the proposed method. In each case, the robot and the obstacle speed are set to 1m/s and 4m/s, respectively. The computed travel times are 77.8sec and 61.9sec, respectively. A safe and faster path was generated by excluding unnecessary collision risk area considering moving direction.

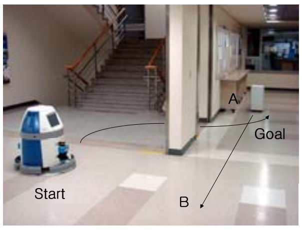
3. EXPERIMENTS

Experiments were carried out in an office building (20m x 80m). The maximum speed of safety was calculated in the environmental grid map. The maximum speed of the robot was 0.5m/s. The maximum acceleration of the robot was 0.8m/s^2. The sampling time of the laser range finder was 0.2 second. The speed of the dynamic obstacle was 5m/s. The experimental environment was classified into three cases: hair pin navigation, doorway navigation, and pillar passing. In addition, the experimental environment was divided into multiple sectors based on visibility information. Each experiment was performed in three different methods: One by the conventional gradient method, the second by the Kim's method, and the third by the proposed path planning scheme.



(a)





(b) (c)

Fig. 7. Hair-pin (a), Doorway (b), Pillar Passing (c)

For motion safety and effectiveness, experimental performances were evaluated by the danger index and travel time. Fig. 7 shows the experimental environments. Dynamic obstacles moved from A to B at 3.0m/s.

3.1 Hair Pin Navigation

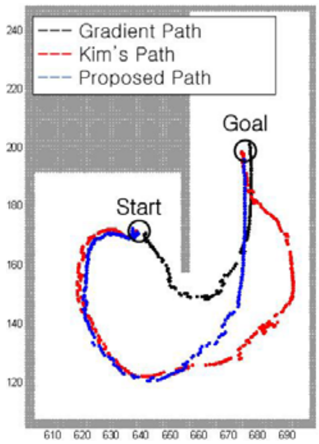
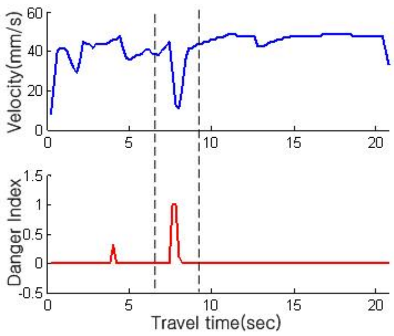


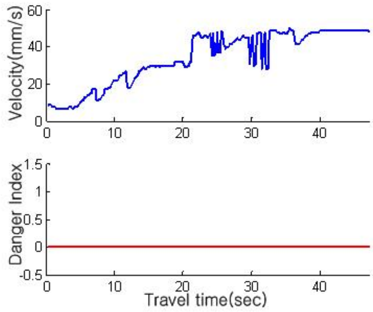
Fig. 8. Gradient Path, Kim's Path, Proposed path

Fig. 8 shows the resultant paths. The path generated by the gradient method is shortest. The path length by the Kim's method was longest. Travel times were 20.8sec, 61.4sec and 47.2sec, respectively.

Fig. 9 shows the speed of the robot and the danger index. In Fig. 9(a), the travel time using gradient method is fastest as 20.8sec. However, the danger index increases and speed decreases suddenly when the robot meets the dynamic obstacle around 8 sec. This is a dangerous situation. Fig. 9(b) presents the speed of the robot and the danger index during navigation by the proposed method. The danger index maintains 0 because of the detour around the collision risk area having the dynamic obstacles. Also, the speed of robot does not change suddenly. Moreover, navigation time was shortened by 14.2sec from the Kim's method.



(a)



(b)

Fig. 9. Gradient method (a), Proposed Method (b)

3.2 Doorway Navigation

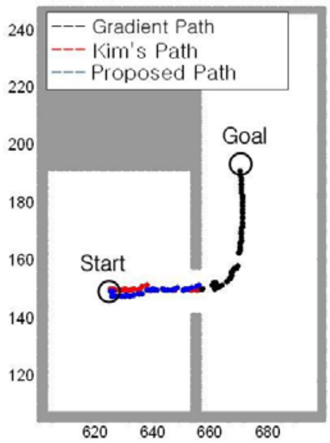
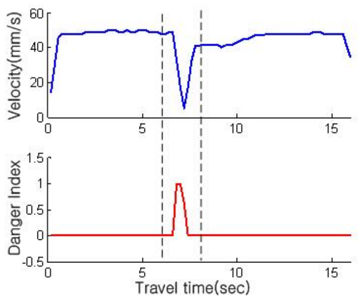
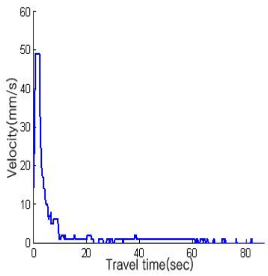


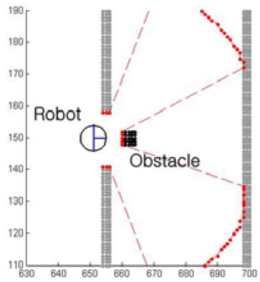
Fig. 10. Gradient Path, Kim's Path, Proposed Path

Fig. 10 shows the resultant paths. In the cases of the Kim's method and proposed method, the robot stopped before entering the door where the computed maximum speed was 0 due to the limitation of the field of view which the limit of maximum speed is 0.



(a)





(b) (c)

Fig. 11. Gradient Method (a), Proposed Method (b), Speed 0 Situation (c)

Fig. 11(a) presents the velocity of the robot and the danger index obtained by using the gradient method. The danger index increases and the speed decreases suddenly when the robot meets the dynamic obstacle at about 7 sec. Fig. 11(b) presents the velocity profile generated by the proposed method. A robot could not pass through the doorway because its speed decreased when it approaches the door. Finally, the robot stopped because the speed of robot became to 0. This zero speed means that the collision free speed is 0 when the robot proceeds along the present path as shown in Fig. 11(c). This fact coincides with our daily experiences. If a car is parked at the narrow parking lot, a driver cannot proceed to a roadway without other person's help. The danger index maintains 0, for the Kim's method and the proposed method.

3.3 Pillar Passing Navigation

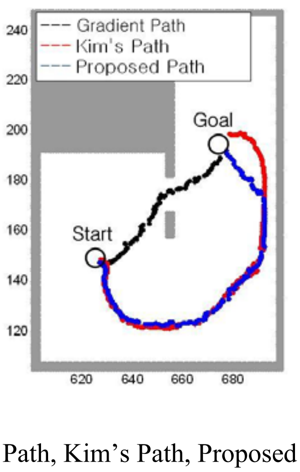


Fig. 12. Gradient Path, Kim's Path, Proposed Path

Fig. 12 shows the resultant paths. Travel times are 15.8sec, 40.0sec and 34.6sec respectively. The shortest path is generated through a narrow region surrounded by a pillar and wall by the gradient method. Detoured paths are obtained when we adopt the Kim's or the proposed method. If the robot tries to go through a narrow region, the robot reduces its speed greatly to avoid possible collision. Therefore, the shortest path requires much travel time. As a result, detour paths are obtained.

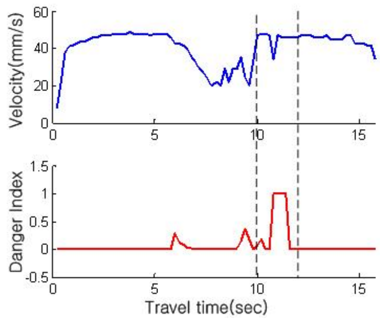


Fig. 13. Velocity and Danger Index

Fig. 13 presents the velocity of the robot and the danger index obtained by using gradient method. The danger index increases suddenly when the robot meets a dynamic obstacle at about 11 sec.

4. CONCLUSIONS

This paper presented a path planning scheme by considering the visibility information and the moving direction of the robot for safe and fast navigation. Based on the visibility information, the whole area is divided into several visibility sectors with the same occluded area. Considering the moving direction, the existence of occluded area is decided when a robot moves between one sector to another. If the occluded area exists, path and speed control is carried out. If the occluded area does not exist toward moving direction, the fastest path is generated. The proposed method maintains safety shown in Kim's research. Furthermore, the travel time is saved by considering moving direction. The advantage of the proposed method is verified through simulations and several experiments in real environments.

ACKNOWLEDGMENT

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