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Safe navigation of a mobile robot using the visibility information

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Abstract— **In this paper, we present one approach to achieve safe navigation in indoor dynamic environment. So far, there have been various useful collision avoidance algorithms and path planning schemes. However, those algorithms have a fundamental limitation that the robot can avoid only "visible" obstacles. In real environment, it is not possible to detect all the dynamic obstacles around the robot. There exist a lot of "invisible" regions due to the limitation of field of view. In order to avoid possible collisions, it is desirable to consider visibility information. Then a robot can reduce the speed or modify a path.**

This paper proposes a safe navigation scheme to reduce the risk of collision due to unexpected dynamic obstacles. The robot's motion is controlled according to a hybrid control scheme. The possibility of collision is dually reflected to a path planning and a speed control. The proposed scheme clearly indicates the structural procedure how to model and to exploit the risk of navigation. The proposed scheme is experimentally tested in a real office building. The presented result shows that the robot moves along the safe path to obtain sufficient field of view, while appropriate speed control is carried out.

I. Introduction

FROM the viewpoint of autonomous navigation, safe navigation in human co-existing environment is essential problem to be solved. On the other hand, high speed navigation is preferable in order to increase service efficiency. There are fundamental difficulties when we want to increase the speed of a mobile robot. Such problems can be classified into three categories as follows.

1) Dynamic and mechanical limitations.
2) Control and computational limitations.
3) Unexpected dynamic change of environment.

The first problem implies that there might take place wheel slippage, or rollover of a robot when the speed is excessive when the robot makes a sharp cornering or an emergency stop. In practical applications, the first problem is rarely considered, because other problems provide more strict limitation on the maximum speed of the mobile robot.

The second problem can be interpreted as a real time obstacle avoidance problem. Navigation speed is limited by sensor capability, sensing speed, computational cost and motion control response. There have been a lot of research activities for dynamic obstacle avoidance as in [2]. A mobile robot can navigate without collision by adopting some useful developed technologies.

Our major scope in this paper is to solve the third problem addressed above. In order to solve the third problem, an appropriate scheme to utilize environment information is significant. While a person drives along a narrow road without traffic signals, he might reduce speed when he approaches a junction. It is natural to assume that there might be dynamic obstacles in invisible regions. Sometimes a driver chooses a path to minimize the invisible region. These kinds of people's behavior are also observed in indoor environment motion while passing through a junction, a pillar, and a door. Our key idea of this paper is that visibility and safe maximum speed information should be taken into account for safe navigation.

There have been some works to deal with unexpected collision and visibility problems. Sadou *et. al.* [4] focused on occlusion of obstacles. This study points out one significant consideration of 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 in [8]. It was shown that the robot can provide appropriate mobile services by monitoring and utilizing patterns of people. This can be one approach to deal with change of environments. However, the experience provides only stochastic information. In order to solve safety, a deterministic approach is required. Krishna *et. al.* [6] computes the safe velocity profile along the path and modified the path near the invisible region. This result showed one example of speed control for safety. However, more general approach to combine the path planning and the velocity control should be considered to solve practical problems. Another example

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of speed control problem can be found in [9]. Well-defined speed constraints are addressed with respect to vehicle features and operational conditions in [9]. However, there is no scheme of combining path modification. The major advantage of this paper is the generality and a structural scheme to deal with risk of navigation.

We proposed the detection algorithm of unexpected obstacle in [10]. In this paper, we establish the safe navigation scheme from two aspects. One is path planning under the consideration of visibility. The collision possibility is modeled in the form of the intrinsic cost of the gradient method in [1]. Then, the risk of collision is reflected into the speed control through the dynamic window approach in [2]. Under the assumption that we have a map of environment, we compute the invisible region where the field of view is obstructed.

This paper is organized as follows. Section 2 describes how to compute invisible regions and how to determine the risk of unexpected collision. In section 3, the proposed scheme of motion control is presented. Experimental verifications are made in section 4. Some concluding remarks are given in section 5.

II. NAVIGATION RISK MODELING USING VISIBILITY

A. Risky area due to visibility

Under the assumption that we have an environmental map, the region where the field of view is geometrically obstructed can be computed. For computation, it is required to consider the invisible region which is sufficiently close enough to a robot, because our interest is on abrupt collision. Considering robot's dynamic capability and dynamic obstacle's speed, the risky neighborhood of a robot can be computed using following equations:

$$d_{col} = d_{delay} + d_{break} + d_{obs} \tag{1}$$

$$d_{delay} = t_{delay} \times (v_r + v_{obs}) \tag{2}$$

$$d_{break} = v_r^{\,2} / (2 \times acc) \tag{3}$$

$$d_{obs} = v_{obs} \times \frac{v_r}{acc} \tag{4}$$

The collision distance d_{col} implies the minimum clearance which should be guaranteed to avoid collision with a dynamic obstacle. d_{delay} is caused by time delay of sensors and controllers. d_{break} is a breaking distance and d_{obs} is the moving distance of the obstacle.

The maximum speed and the acceleration of the robot were 0.5m/s and 0.8m/s^2 respectively. The robot is two wheel differential driven, and the control cycle time is 0.2 second. The speed of a dynamic obstacle is around to be 2m/s. based on these conditions, the computed d_{col} is about 2m.

The invisible region around the robot's position can be computed by a following equation:

$$Invisible\,area(s_t) = search(s_t) - scan(s_t) \tag{5}$$

where s_t is a robot's position. The $search(s_t)$ is the robot's neighborhood by considering d_{col}. The $scan(s_t)$ is computed visible region around the robot using the ray tracing method.

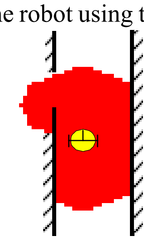


Fig. 1. Computing the reachable region by the wavefront propagation

When computing the neighborhood, the reachable region should be considered, instead of simple euclidian distance. Fig. 1 shows one example of reachable region, which is different from a circular shape. Since the exact computation of nonholonomic robot's reachable region is computationally expensive, we adopt the wavefront propagation algorithm in [1]. Invisible regions are iteratively computed for all possible robot locations. This step corresponds to a pre-processing step to model the risk of navigation.

Fig. 2. Experimental environment (top) and invisible region (bottom)

The top of the fig.2 shows the real environment. The bottom of fig. 2 shows the computed invisible region using (5). It is clear that the invisible regions are located around the corner or a pillar. Computational result well matches our daily experience on the risky area, where unexpected collision might takes place.

B. Computation of safe speed

When a robot has full field of view, navigation speed is limited only by dynamic obstacles. However, when a robot moves in the obstructed visibility region the robot should slow down in order to avoid unexpected obstacles.

In the obstructed visibility region, there are some particular points which limit the visibility. Most of these points are placed on convex edges. With the grid map that represents environment exactly, these edges can be easily found out.

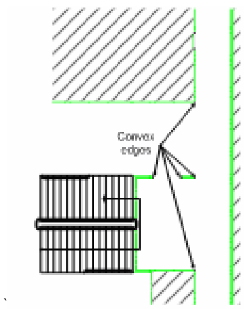


Fig. 3. Convex edges

Fig. 3 presents the convex edges at the environment. These convex edges are utilized for designing collision avoidance speed around the obstructed region.

One of the most dangerous cases is that the dynamic obstacle moves from the invisible area to a robot. To represent these cases, we draw a circle centered at convex edge as shown in fig. 4. A similar motion model of obstacles can be found in [6]. In [6], under the assumption that collision takes place at intersection of the circle and the path, the safety speed is derived.

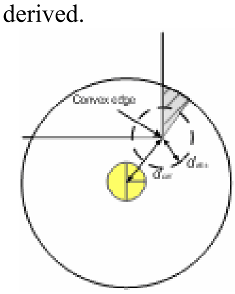


Fig. 4. Computation minimum clearance to prevent collision

In this paper, considering more conservative case, the distance from a robot to a convex edge is taken into account to define safe speed.

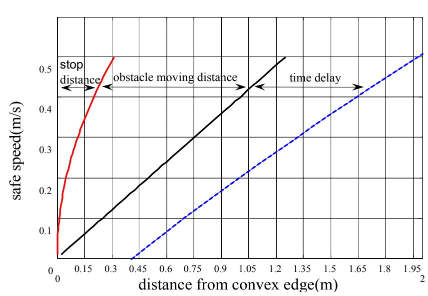


Fig. 5. d_{col} versus maximum safe speed of a robot

Fig. 5 shows the relationship between the clearance to the convex edges and the robot's maximum speed. The convex edge is considered to be the starting position of an unexpected obstacle. The sampling rate of a control loop is about 0.2 second. Since we assumed that the obstacle speed is 2m/sec, d_{delay} is about 0.4m when the robot speed is 0. This result can be seen in fig. 5. When we want to maintain the robot's speed as 0.3m/sec in minimum, we can conclude that the clearance should be always greater than 1.35m from fig. 5. Therefore, d_{col} can be understood as the distance margin before collision.

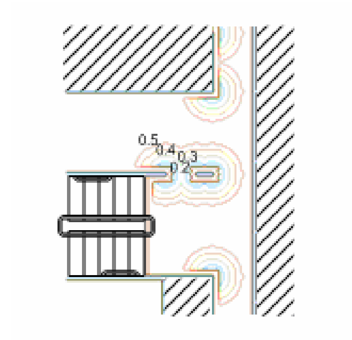


Fig. 6. Computed maximum speed for safety speed (m/s)

The computational result of safe speed from all the convex edges is shown in fig. 6. The result shows that a robot should move slowly near the convex edge.

C. *Visibility & safe speed*

The result of visibility and safe speed looks similar. However, there is some difference. In fig. 6, safe speed cannot reflect the visibility exactly. Safe speed at obstructed visibility region can be derived by comparing visibility information and safe speed information addressed above.

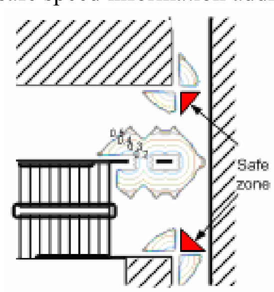


Fig. 7. Safe speed at visibility obstructed region

The result of association of visibility and safe speed information is shown in fig. 7. There are some safe zones around the convex edge, by adding visibility information. Furthermore, the level of collision risk can be quantitatively modeled as shown in fig. 7.

III. PATH PLANNING AND MOTION CONTROL

There are some possible alternatives to reflect environmental risks. First, visibility can be taken into account path planning. Second, the distance margin can be reflected in motion control as a maximum speed limitation.

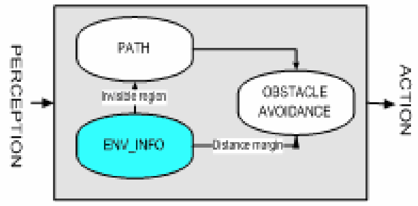


Fig. 8. The structure of safe navigation

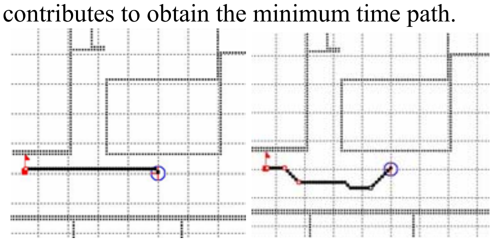
Our navigation strategy is a hybrid approach to combine path planning and reactive control, as in [3]. The path planner is designed based on the gradient method in [1] and the dynamic window approach in [2], which is adopted as a reactive motion controller. More details on our navigation strategy are introduced in [5].

The gradient method path planning [1] generates a minimum distance path without local minima. The concept of optimality is derived by assigning costs to a path, based on its length and the distance to obstacles, as well as any other criteria that may be chosen. In this method the path cost is computed as the sum of an intrinsic cost and an adjacency cost as a following equation:

$$F(P) = \sum_i I(P_i) + \sum_i A(P_i, P_{i+1}) \tag{6}$$

where P_i indicates unoccupied free space. Intrinsic cost at P_i, $I(P_i)$ can be assigned high near an obstacle or unknown region, slippery region, and so on. Adjacency cost $A(P_i, P_{i+1})$ is proportional to moving distance.

Our approach is to use the distance margin and the visibility information in the gradient method. The gradient method provides a general framework to model risks in the form of the intrinsic cost. Therefore, the distance margin is mapped into the intrinsic cost. The computed maximum speeds can be reflected in the form of the adjacency cost, which contributes to obtain the minimum time path.



(a) (b)

Fig. 9. Path passing through the junction ((a) conventional path (b) proposed path)

Fig. 9 shows the results of the path planning passing through a junction. The left path of the fig. 9 is obtained by a conventional method. The optimality is computed with respected to the minimum distance. However, the right path in fig. 9 is optimal with respect to both the distance and the safety. Under the consideration of safety, it is evident that the right path is safer than the left path.

Our collision-free navigation scheme is designed based on global Dynamic Window Approach (DWA) in [3]. In DWA, the performance measure function is composed of three criteria. One of the criteria is the speed object, which encourages fast movement of the robot. It is quite simple to reflect the risk due to the visibility, because the distance margin can be mapped into the speed object in the form of the maximum speed.

IV. EXPERIMENT

The proposed approach has been implemented and tested in a real office building of 25m x 80m. We built a grid map, and then carried out a pre-processing to compute visibility and distance margins.

A. Danger index

It is necessary to define the danger index to evaluate the safety during navigation. We define the danger index as a following equation.

$$I_{danger} = \frac{A_{collision}}{A_{collision} + A_{safe}} \tag{7}$$

All areas are defined in the dynamic window where $A_{collision}$ and A_{safe} respectively indicate the area of collision which cause collision and the area of admissible velocity. Danger index can be changed from 0 to 1. The danger index close to 1 implies that most of velocities in the dynamic window cause collision.

B. Entering a corner experiment

We measured the danger index and navigation time, for each experiment which is performed by the different navigation scheme. At each experiment, a person started to walk from position A to B as shown in fig. 10. This experiment aims at evaluating the collision safety and the efficiency with respect to two measures, i.e., the safety and the travel time.

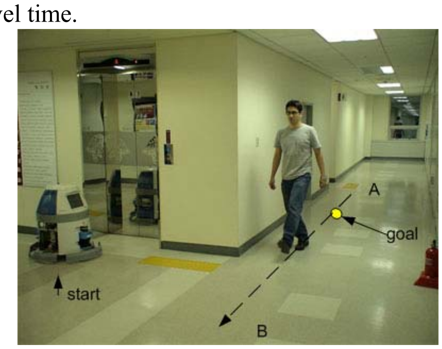
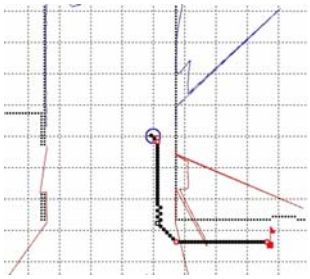


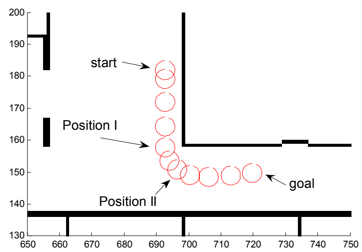
Fig. 10. Experimental environment

1) Conventional global dynamic window approach in [3]

A path is generated by the conventional gradient method and the speed control is not restricted by the visibility information. The robot can reactively avoid dynamic obstacle purely using sensor information.



(a) Experimental path



(b) Robot's motion

Fig. 11. Experimental path and the robot's motion with conventional approach (experiment 1) (Experiment 1. travel time 10.2s)

Fig. 11 shows the experimental path and robot's motion. The path is very close to the convex edge because it is a minimum distance path. From fig. 11 (b), it is easily found that the robot rapidly reduced speed at the moment when a dynamic obstacle appeared from the invisible region.

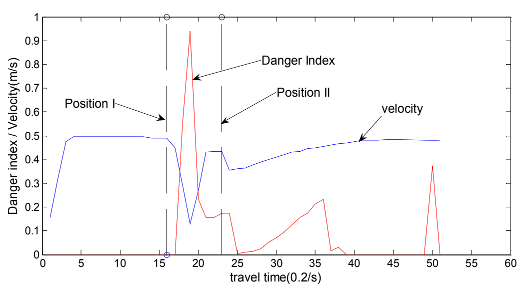
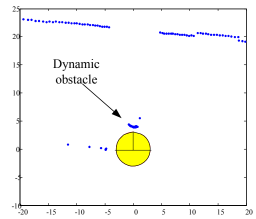
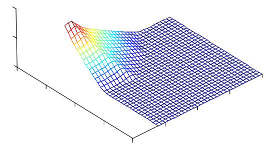


Fig. 12. Danger index and speed change (experiment 1)

Fig. 12 represents the change of danger index and speed during navigation. Since the robot approached to corner with high speed, the robot abruptly reduced speed when the robot encountered the unexpected obstacle and the danger index became high in a moment at position I. After the obstacle disappeared at position II, the robot recovered its speed to the goal.



(a) Laser data



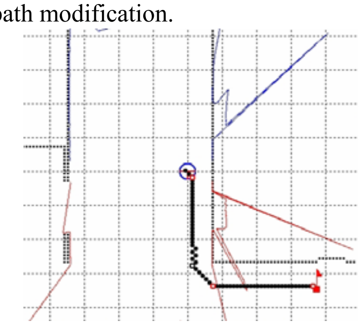
(b) Clearance object dynamic window

Fig. 13. Appearance of dynamic obstacle and the computed area of collision/collision-free velocities in dynamic window
(left wheel velocity: 0.24m/s, right wheel velocity 0.34m/s)

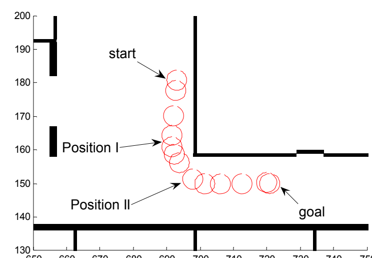
Fig. 13 shows the image of the laser range finder and the dynamic window clearance values indicate the collision and collision-free velocity. Since the velocities having 0 clearance value cause collision, the velocity should be carefully selected from the collision-free velocities. It is clear that this situation is quite dangerous.

2) Experiment by the proposed speed control

At the second experiment, visibility information is only reflected in reactive motion control as a speed constraint, without a path modification.



(a) Experimental path



(b) Robot's motion

Fig. 14. Experimental path and robot's motion with the proposed speed control (experiment 2) (Experiment 2. travel time 12.4s)

In fig. 14, a path was same with the first experiment. However, the robot reduced speed while approaching the corner. It can be seen that the maximum speed is successfully limited by the appropriate change of the speed object in DWA.

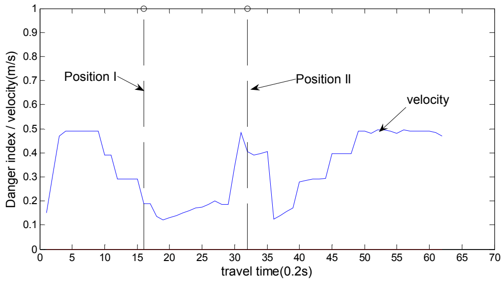
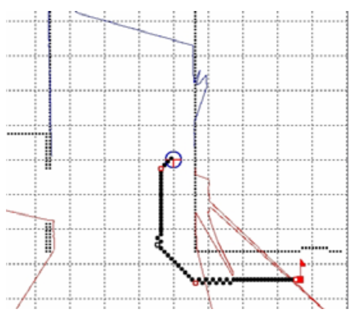


Fig. 15. Danger index and speed change (experiment 2)

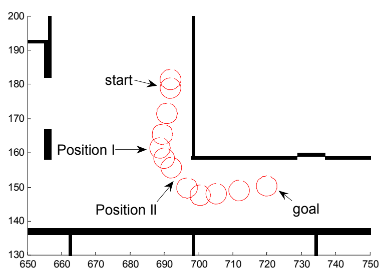
From fig. 15, it is clear that the speed is reduced when the robot enters a dangerous area around the position I. After leaving the dangerous area, the robot recovers its speed at position II. Owing to the speed control, the danger index was 0 all the time, which implies that the movement was safe.

3) Experiment by the proposed path planning and the speed control

At last experiment, visibility information is reflected to both the path planning and the motion control.



(a) Experimental path



(b) Robot's motion

Fig. 16. Experimental path and robot's motion with proposed path and speed control algorithm (experiment 3)
(Experiment 3. travel time 11.8s)

The result of path planning and robot's motion is shown in fig. 16. The planned path detour the region nearby the convex edge and the robot moved slowly while entering the corner. However, the robot moved faster than second experiment near the corner, because the passing region is far from the dangerous region.

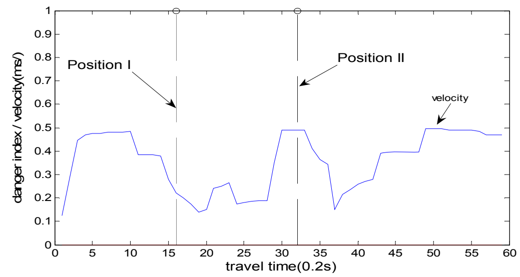


Fig. 17. Danger index and speed change (experiment 3)

Even under the unexpected appearance of a dynamic obstacle, there was no dangerous situation. The danger index was 0 during the navigation. It is remarkable that although the travel distance of the path is longer than the distance of experiment 2, the total navigation time is shorter than the time of experiment 2

V. CONCLUSION

In this paper, it is shown how to develop a safe and efficient navigation scheme, based on the visibility information. The environmental risks were quantitatively derived to deal with unexpected collision with dynamic obstacles. Those risks were exploited both for path planning and the speed control in a structured way. The presented experimental results clearly demonstrated that the efficient and safe navigation control was successfully achieved.

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