On-line Navigation of Mobile Robot Among Moving Obstacles Using Ultrasonic Sensors

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Abstract. This paper proposes a realistic on-line navigation method of the mobile robot in dynamical environment where multiple obstacles are always changing their velocities. Considering characteristics of actual sensor system, a method to estimate the velocity of moving obstacles is presented. The estimated velocity and measured distance from the nearest obstacle are used to plan a velocity of mobile robot based on a new idea of Collision Possibility Cone(CPC). Then an on-line navigation method is proposed by using CPC and feasible velocity space of mobile robot. Simulational examples show an effectiveness of the new navigation.

1 Introduction

Navigation of mobile robot to travel for given destination autonomously in various environment is considered as one of the most important capability, thus many researchers have studied about the navigation problem. Particularly, the study on on-line sensor based motion planning or control is recently active, and some algorithms are proposed[1][2]. Most of these studies treat the case of multiple static obstacles, and mainly focus theoretical global convergence of the proposed algorithms. For more applications to real world, the mobile robots are expected to surely reach desired point even in the dynamical environment where many obstacles are moving. This problem is considered as an on-line sensor-based navigation problem among multiple moving obstacles.

Considering such dynamical environment, some on-line motion planners are presented. Tsoularis[3] gives a path from start point to goal point neglecting moving obstacle's paths, then plans velocity pattern of the robot along the given path to avoid moving obstacle by changing the velocity. Another important approach for moving obstacles is the idea of time-state space which adds time axis to normal configuration space[4].

These methods, however, take much time for planning, thus are not appropriate for on-line use. Fiorini et al. propose an on-line method based on the idea of Velocity Obstacle[5]. Moving obstacles are mapped into a two-dimensional

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"velocity space". Then velocity of mobile robot is directly planned using Velocity Obstacle in velocity space. Most of studies of on-line motion planning for multiple moving obstacles assume that the velocity and position of each moving obstacle can be measured using robot's sensor systems. In the situation of multiple obstacles moving crowdedly, it is, however, very difficult to distinguish each obstacle using sonar sensor or laser range finder, because the sensor systems have only limited space resolution. Furthermore, most on-line navigation methods assume that velocity of moving obstacle is constant during sensor cycle. It is not appropriate for the dynamical environment such as multiple moving obstacles where the obstacles may change their velocities at any time.

In this paper, a realistic on-line navigation problem is discussed, where multiple obstacles are moving around and their paths, velocities and sizes are not given in advance. The paper also deals with the problem of velocity changes during the sensor cycle. The available information is assumed to be only distance information to obstacles at every sensor cycle considering the use of sonar sensor. Our navigation method basically selects the best velocity of mobile robot considering the worst case in the view point of danger for collision with moving obstacles at every sensor cycle.

2 On-line Collision Avoidance for Moving Obstacles

This section describes assumptions on mobile robot and moving obstacles. Then, an estimation method of relative approaching velocity of obstacle is presented.

2.1 Assumptions

- Mobile robot is an omni-directional vehicle.
- The mobile robot and moving obstacles move on a flat floor.
- The mobile robot does not communicate with moving obstacles.
- The mobile robot and moving obstacles are assumed to be approximated by cylinders.
- The mobile robot has n_r ultrasonic sensors. Each sensor detects distance from the robot to moving obstacle every sensor cycle if the obstacles are in the detectable area. The maximum range of the area is denoted by L_s.
- Moving obstacles possibly change their velocities v_o and accelerations a_o at anytime within maximum values of $\pm v_{o\,\max}$ and $\pm a_{o\,\max}$.
- Maximum values $v_{o\,\max}$ and $a_{o\,\max}$ of moving obstacles are smaller than mobile robot's maximum velocity $v_{r\,\max}$ and acceleration $a_{r\,\max}$.

2.2 Estimation of Approaching Velocity for Obstacle

The ultrasonic sensor basically detects only distance d_k from mobile robot to a nearest moving obstacle inside the sensor detectable area (sector-k) every sensor cycle(See Fig.1). When the distance data changes from $d_k(i)$ to $d_k(i+1)$ during

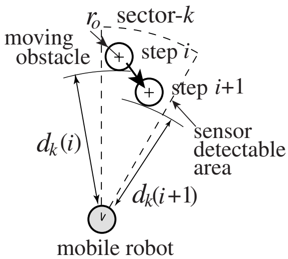

Fig. 1. Sensor detectable area (sector-k)

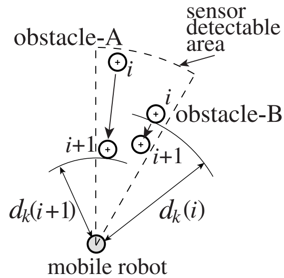

Fig. 2. Multiple moving obstacles in the same area

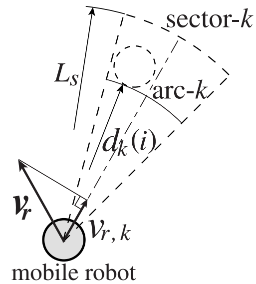

Fig. 3. Velocity $v_{r,k}$ to the direction of sector-k

sensor cycle T_s, the relative approaching velocity of moving obstacle in the direction of sector-k may be written $v_{ap,k}(i+1) = (d_k(i+1) - d_k(i))/T_s$ (where i is the step number of sensor cycle). This is, however, incorrect for the case that multiple moving obstacles are in a same sensor area, because the sonar sensor can not distinguish the individual obstacles as shown in Fig.2. In the figure, two distances $d_k(i)$ and $d_k(i+1)$ are the result of two different obstacles.

To cope with the problem, we modified the estimation of approaching velocity of obstacles by

$$v_{ap,k}(i) = v_{r,k} + v_{o\ \max} \qquad (\text{if} \quad d_k(i) < L_s) \tag{1}$$

where $v_{r,k}$ denotes projection of velocity $\boldsymbol{v}_r$ to the direction of sector-k as shown in Fig.3. This estimation basically assumes most dangerous case of velocity and moving direction of moving obstacles for the mobile robot.

3 Collision Possibility Cone

An idea of Collision Possibility Cone(CPC) is introduced to guarantee of collision free with moving obstacles using distance information and estimated approaching velocity from sonar sensor. In this section, the robot (r) and the obstacles (o) are described by circle (see STEP 0 in Fig.4). The mobile robot's radius and velocity are denoted with r_r, v_r. On the other hand, a smallest radius of the moving obstacles is denoted by $r_{o\ \min}$(if radius is unknown, it is defined with zero). The procedure to construct CPC is described as follows.

STEP 0 Detect distance $d_k(i)$ from mobile robot to moving obstacle if a moving obstacle enters into sensor detectable area.
STEP 1 Calculate the possible existing area of the moving obstacle using the detected distance as in STEP 1 of Fig.4.
STEP 2 Enlarge the area with r_r, then denote the extended area $\bar{O}$. The mobile robot is then represented by point robot $\bar{R}$.

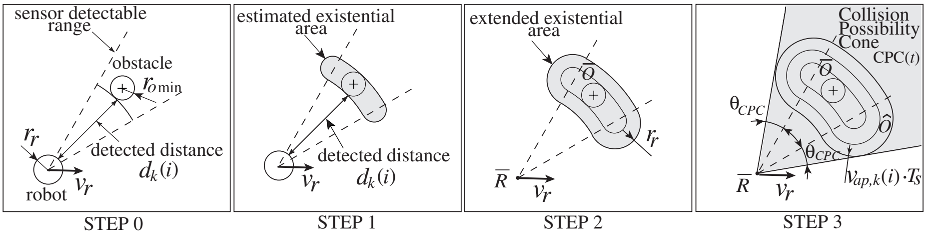

Fig. 4. Collision Possibility Cone (CPC)

STEP 3 Enlarge $\bar{O}$ with $v_{ap,k}(i) \cdot T_s$, then denote the extended area $\hat{O}$. Where T_s is sensor cycle of robot. Make two tangential lines to the extended area $\hat{O}$ from the point robot $\bar{R}$. The resultant cone region surrounded by the two lines is CPC. Where θ_{CPC} is an extended angle from the original sensor detectable area.

CPC indicates admissible collision free velocity of mobile robot. If the end point of the velocity vector located out the region of CPC, the mobile robot will never collide with moving obstacle. Note that collision free is guaranteed at least until next sensor step.

4 On-line Motion Planning Problem

This section formulates an on-line motion planning problem. Then, a navigation strategy based on the idea of CPC is proposed.

4.1 Formulation of On-line Motion Planning

The dynamics of the mobile robot is generally described by the following equation

$$\ddot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}, \dot{\boldsymbol{x}}, \boldsymbol{u}) \tag{2}$$

$$\boldsymbol{u} \in U, \quad |\dot{\boldsymbol{x}}| < v_{r\,\max} \tag{3}$$

where $\boldsymbol{x}$ is position vector, $\boldsymbol{u}$ is actuator input vector, U is admissible input set, and $v_{r\,\max}$ is maximum velocity of mobile robot. The on-line motion planning problem is to generate velocity for minimizing traveling time from an initial point to goal point avoiding moving obstacles. Where the moving obstacles change their velocities. The dynamics of moving obstacle is assumed to be unknown considering general application. However, we assume the velocity and acceleration of moving obstacles are limited as described in section 2.1.

4.2 On-line Velocity Planning

When the mobile robot moves with velocity $\boldsymbol{v}_r(t)$, the possible velocity at $t + \Delta t$ is described with

$$\boldsymbol{v}_r(t + \Delta t) = \boldsymbol{v}_r(t) + \ddot{\boldsymbol{x}}(t)\Delta t \tag{4}$$

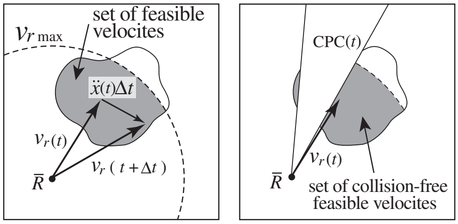

Fig. 5. Sets of feasible velocities and collision-free feasible velocities

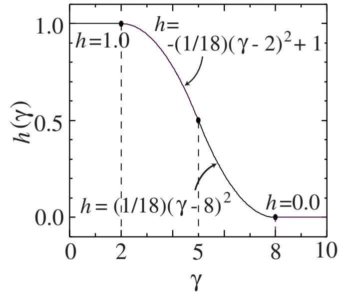

Fig. 6. Weighting function $h(\gamma)$

by dynamics of mobile robot and input constraints of mobile robot. Where $\ddot{\boldsymbol{x}}(t)$ is an element in the set of feasible velocity (gray region in Fig.5(left)) which is satisfied with equation (2) and admissible input (3). By removing the region of CPC(t) from the feasible velocity set, we get collision-free feasible velocity set as shown in Fig.5(right). We plan the mobile robot's motion by selecting velocity which minimizes the traveling time in the collision-free feasible velocity set.

4.3 Collision Distance Index

If the mobile robot current position is far from moving obstacle, the selected velocity by CPC is no danger of collision with obstacle by considering maximum velocities of moving obstacles. To prevent the conservative property, we introduce the following "collision distance index". It is defined by the detected distance $d_k(i)$ and the relative approaching velocity of obstacle $v_{ap,k}(i)$ by (1). The index is used for changing the extended angle θ_{CPC} of CPC which means danger of collision in the meaning of velocity. We define the collision distance index by

$$\gamma = \frac{d_k(i)}{v_{ap,k}(i)T_s} \tag{5}$$

Then using the index, the extended angle θ_{CPC} of CPC is modified by

$$\tilde{\theta}_{CPC} = h(\gamma)\theta_{CPC} \tag{6}$$

where a function $h(\gamma)$ is shown in Fig.6 as an example. The function $h(\gamma)$ is selected such that the value of the function is 1 when γ is small, and becomes asymptotically 0 in accordance with increasing γ.

5 Simulation of On-line Navigation

This section shows some simulational examples to confirm the effectiveness of the idea of CPC and collision distance index. In the simulations, the constraints

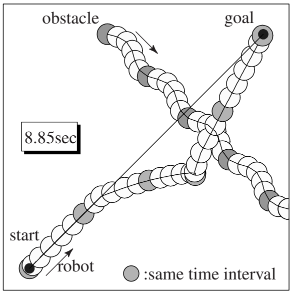

Fig. 7. Path 1 for changing velocity of moving obstacle without considering collision distance index γ

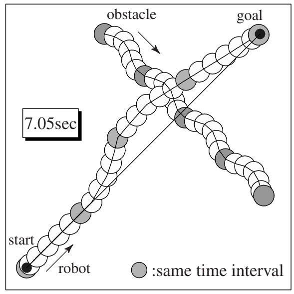

Fig. 8. Path 2 for changing velocity of moving obstacle considering collision distance index γ

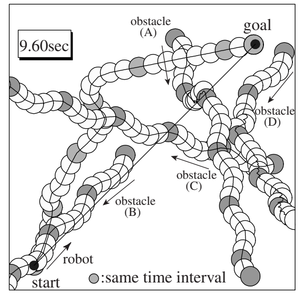

Fig. 9. Path 3 for the effectiveness of proposed navigation method in the dynamical environment

on mobile robot and moving obstacles are $v_{r\,\max} = 2.0$m/s, $v_{o\,\max} = 1.5$m/s, $L_s = 6.0$m, and $T_s = 0.3$sec. Then, the size of test field is 12m × 12m, and the radius of robot and obstacles are $r_r = 0.4$m and $r_o = 0.4$m. The mobile robot has 12 ultrasonic sensors with ring shape. In the following example, the robot does not know the velocities and paths of obstacles in advance, but only knows the distance from the nearest obstacle by its sensor system every sensor cycle.

Simulation results with one moving obstacle are shown in Fig.7 and Fig.8. Circles in the figures represent positions of robot and obstacle at same time interval. Each traveling time to goal point is shown in shaded box. In Path 1 (Fig.7), the velocity of moving obstacle is always changing, and the path of obstacle is a meandering one. By estimating the maximum velocity of obstacle in the idea of CPC, the mobile robot could arrive at goal point without collision, even for the case that the velocity of obstacle changes between sensor cycle. In Path 2 (Fig.8), the collision distance index γ is considered, whereas it is not considered in the simulation of Path 1. We find that the consideration of the collision distance index γ results in more efficient path by this example.

To confirm the effectiveness of the proposed navigation method for more complicated case, we simulate an example of four moving obstacles in Fig.9. All moving obstacles always change their velocities. Also for this example, the mobile robot successfully reaches its destination without collision.

6 Conclusions

In this paper, a realistic on-line navigation problem in dynamical environment with multiple moving obstacles is discussed. By considering the characteristics of actual ultrasonic sensors, an estimation method of velocity for moving obstacles is presented. For the on-line collision avoidance of moving obstacles, the idea of CPC is presented. New on-line motion planner is proposed by using the idea of

CPC. The method is based on a selection of admissible velocities in the restricted two dimensional velocity space. For an over conservative property of the proposed navigation method, the collision distance index is introduced. An effectiveness of the proposed method is shown by simulational examples.

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