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Velocity-Change-Space-based dynamic motion planning for mobile robots navigation

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ABSTRACT

This paper deals with the problem of dynamic motion planning in an unknown environment, where the workspace is cluttered with moving obstacles and robots. First, we give the principle of hybrid velocity obstacles, the definition of the preferred velocity and the collision-avoidance behavior. Second, we give new rules for the size regulation of obstacles and the kinematic and dynamic constraints of wheeled robot. Then, we establish a new Velocity Change Space (VCS) using the changes of the speed and direction of the robot's velocity as coordinate axis, and map the goal, velocity obstacles and dynamics constraints in this space. Finally, we explore the dynamic motion planning problem in the VCS. Mobile robot making motion planning in its velocity change window is achieved in multiple sensing-acting time steps, and directly gets the new velocity using point search and multi-objective optimization. We apply VCS-based motion planning methods to mobile robots, and simulation is used to illustrate the collision-free, interactive, un-conservative, foresighted and multi-objective optimized navigation of mobile robots.

1. Introduction

Mobile robots are expected to carry out various tasks in all kinds of application fields, and their work environments are usually uncertain and dynamic [1,2]. Therefore, after the allocation of a task, each robot faces a dynamic motion planning problem during navigation in unknown environments, and the collision avoidance with moving obstacles is a basic problem [3]. Many classical approaches designed for static environments are extended to dynamic environments [4–7]; these methods perform well in static environments, but do not automatically imply good performance in the dynamic environments. Then, the moving obstacles are regarded as static in a period of time in [8], and the grid method is used to plan the optimal path for dynamic obstacle avoidance. The multilayer fuzzy control method [9], the artificial potential field method [10], the reactive collision avoidance [11], and the rolling window method [12] are also used in dynamic environment. These motion planning methods based on Position Space (PS) could not effectively represent and directly use the velocity information, and have difficulty in collision detection.

Other heuristic and probabilistic methods have been developed. The path-velocity decomposition is used to navigate in dynamic environments [13–15]. In this method, the motion-planning problem is decomposed into two sub-problems: path planning and velocity planning. A feasible path among the static obstacles is first computed, and then the velocity along the path is chosen to avoid the moving obstacles. The main drawback of this method is when an object stops on the planned path. The configuration-time space-based methods are also used [16,17]. In this formulation, the time dimension is included in the space configuration, which may result in additional algorithmic complexity. A method without computing the C-space obstacles is proposed in [18].

A particularly successful concept for mobile robot real-time navigation is the collision cone [19,20], especially in the form of a velocity obstacle. The velocity obstacles method is proposed in [21,22], which defines the velocity obstacles according to relative velocity information in the Velocity Space (VS). Then the concept of nonlinear velocity obstacle is proposed in [23,24], but the dynamic obstacle should give a general known trajectory. Furthermore, [1,25] view collision avoidance behavior as the interactive dynamic process between the robot and moving obstacles, translate the collision avoidance problem into a control problem or optimization problem in robot's Acceleration Space (AS). The concept of virtual plane is introduced in [26], which belongs to the family of methods that use relative velocity (similar to the velocity obstacles). The suggested method solves the problem of path planning in dynamic environments by reducing moving objects to stationary objects, and achieves simple deviation using parameter-dependent linear navigation laws.

Velocity obstacles have been used for applications, such as navigating a robotic wheelchair through a crowded station [27], high-speed autonomous navigation [28], determining forbidden steering

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directions for a passenger car in urban environments [29], and safe maritime navigation for unmanned surface vehicles [30]. Several variations of velocity obstacles have been proposed for multi-robot systems [31–34]; these have attempted to incorporate the reactive behavior of the other robots in the environment. Formulations such as reciprocal velocity obstacles [32–35] use various means to handle reciprocity between robots for oscillation-free navigation.

The velocity obstacles methods are well done in collision detection, but they do not specify where and when the collision will happen. The robot, which does not take into account the impact of distance and time before collision, falls into "conservative" strategy, i.e., begins to avoid obstacle as soon as the obstacle is perceived, which results in long detour to the final goal, especially when the obstacles are moving along arbitrary trajectories [36]. Moreover, these methods either select velocity outside velocity obstacles without considering the dynamic constraints or incorporate acceleration constraints within a time step of the sensing-acting cycle. However, the available velocities in one time step or a constant time horizon [37] are small, which does not fully represent the set of achievable velocities before collision, so the robot has no foresight, resulting it to be "shortsighted". Besides, the optimal selection of new velocity is another problem [38,39]. Usually, the intersections of velocity obstacles or the points on the edges of velocity obstacles that is the closest to the preferred velocity are selected [1,32–35,39]. However, the intersections and edges are hard to compute and the optimal velocity may lie in other positions when multi-objective optimization is considered.

In this paper, we present some new velocity obstacle methods to solve the problems of conservative, shortsighted navigation and the optimal selection of new velocity. We translate the motion planning into a problem of acceleration selection in a new Velocity Change Space (VCS). First, the goal, velocity obstacles and dynamics constraints are mapped in VCS, and then we explore the dynamic motion planning problem in this space for mobile robots navigation.

The rest of this paper is organized as follows. We begin by introducing some definitions in Section 2 and formally define the problem of mobile robots navigation in Section 3, including velocity obstacle, preferred velocity, and collision-avoidance behavior. In Section 4, we introduce our formulation of dynamic motion planning in VCS. Section 5 verifies the effectiveness of the proposed method by various simulation experiments. Finally, Section 6 concludes this paper, and points out topics to be further studied.

2. Notations and problem definition

In this paper, black bold symbol denotes a vector, e.g., the velocity vector $\boldsymbol{v}$, set v be its speed norm $\|\boldsymbol{v}\|_2$, set θ be its direction angle, and let $\boldsymbol{v}=[v,\ \theta]^{\mathrm{T}}$ or $\boldsymbol{v}=[v_x,\ v_y]^{\mathrm{T}}$, where v_x and v_y are the corresponding components on x-axis and y-axis, respectively. A point $\boldsymbol{p}$ in a plane is written as $\boldsymbol{p}=[p_x,\ p_y]^{\mathrm{T}}$, where p_x and p_y are the corresponding components on each axis. Let $\angle(\boldsymbol{v})$ denote the angle between vector $\boldsymbol{v}$ and x-axis, $\angle(\boldsymbol{p}_{\mathrm{A}}-\boldsymbol{p}_{\mathrm{B}})$ denote the angle between vector $\boldsymbol{p}_{\mathrm{A}}-\boldsymbol{p}_{\mathrm{B}}$ and x-axis, $\angle(\boldsymbol{v}_{\mathrm{A}},\ \boldsymbol{p}_{\mathrm{A}}-\boldsymbol{p}_{\mathrm{B}})$ denote the angle between vector $\boldsymbol{v}_{\mathrm{A}}$ and $\boldsymbol{p}_{\mathrm{A}}-\boldsymbol{p}_{\mathrm{B}}$.

This paper mainly addresses the dynamic motion planning problem in real-time navigation of distributed mobile robots. The robots are modeled by circular shapes and moving on a plane. Each robot could measure the sizes, positions and velocities of obstacles and other robots online by sensors, or directly gets the other robot's position and velocity with limited local communication; however, there is no central coordination, every robot uses the same independent navigation strategy. The robot's coverage area of sensing or communication is radius r_{ca}, and the robots have kinematic and dynamic constraints.

3. Mobile robot navigation

In this section, we review the concepts of velocity obstacles, discuss the formulation of interactive velocity obstacles that we use for navigation of multiple mobile robots, and then introduce our definitions of the preferred velocity and the collision-avoidance behavior.

3.1. Velocity obstacle

As shown in Fig. 1(a), let R be a robot and its current position is $\boldsymbol{p}_{\mathrm{R}}$, current velocity is $\boldsymbol{v}_{\mathrm{R}}$; let O be a dynamic obstacle and its current position is $\boldsymbol{p}_{\mathrm{O}}$, current velocity is $\boldsymbol{v}_{\mathrm{O}}$. Let r_{R} and r_{O} be the radius of R and O, respectively, and let d_{RO} be the distance between $\boldsymbol{p}_{\mathrm{R}}$ and $\boldsymbol{p}_{\mathrm{O}}$. In VS, as shown in Fig. 1(b), the obstacle O is enlarged to PO (position obstacle) with radius $r_{\mathrm{OR}}=r_{\mathrm{O}}+r_{\mathrm{R}}$. Let l_{MO} and l_{NO} be the left tangency ray and right tangency ray of PO starting from $\boldsymbol{p}_{\mathrm{R}}$, respectively, and let l_{RO} be the ray starting at $\boldsymbol{p}_{\mathrm{R}}$ with direction of $\boldsymbol{v}_{\mathrm{RO}}$.

1) *Collision cone*: The relative velocity of R with respect to O is $\boldsymbol{v}_{\mathrm{RO}}=\boldsymbol{v}_{\mathrm{R}}-\boldsymbol{v}_{\mathrm{O}}$, then O could be seen as a static obstacle, the velocity of R is seen as $\boldsymbol{v}_{\mathrm{RO}}$. The collision avoidance between

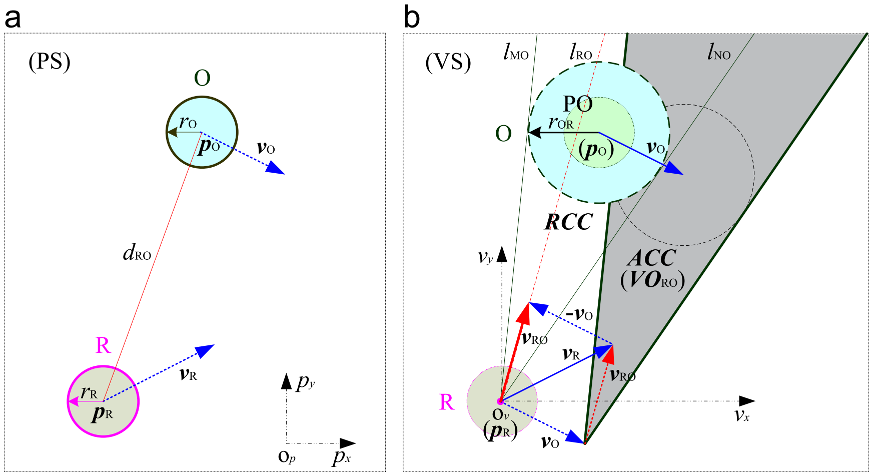

Fig. 1. Construction of the velocity obstacle. (a) Mobile robot R and dynamic obstacle O moving in a plane (i.e. PS). (b) Velocity obstacle $\boldsymbol{VO}_{\mathrm{RO}}$ for robot R induced by dynamic obstacle O.