ARTICLE IN PRESS

Robotics and Autonomous Systems ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Seeking a path through the crowd: Robot navigation in unknown dynamic environments with moving obstacles based on an integrated environment representation

Andrey V. Savkin, Chao Wang *

School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney 2052, Australia

HIGHLIGHTS

- We present a novel algorithm for collision free navigation of a non-holonomic robot.
- Our approach is based on an integrated representation of the information about the environment.
- We provide mathematically rigorous analysis to the proposed approach.
- The performance is demonstrated via experiments with a real robot and computer simulations.

ARTICLE INFO

Article history:
Received 23 November 2013
Received in revised form
8 April 2014
Accepted 9 May 2014
Available online xxxx

Keywords:
Moving obstacles
Collision avoidance
Obstacle avoidance
Wheeled mobile robots
Non-holonomic robots
Robot navigation
Unknown dynamic environments
Multiple obstacles
Integrated environment representation

ABSTRACT

We present a novel algorithm for collision free navigation of a non-holonomic robot in unknown complex dynamic environments with moving obstacles. Our approach is based on an integrated representation of the information about the environment which does not require to separate obstacles and approximate their shapes by discs or polygons and is very easy to obtain in practice. Moreover, the proposed algorithm does not require any information on the obstacles' velocities. Under our navigation algorithm, the robot efficiently seeks a short path through the crowd of moving or steady obstacles. A mathematically rigorous analysis of the proposed approach is provided. The performance of the algorithm is demonstrated via experiments with a real robot and extensive computer simulations.

1. Introduction

Avoidance of collisions with obstacles is a key component of safe navigation. Therefore collision free navigation of a mobile robot in cluttered environments is a fundamental problem of robotics. This problem has been the subject of extensive research.

Existing navigation approaches can be generally classified as global or local (reactive) [1]. Global path planning algorithms use a priori information to build a complete model of the environment and then try to find the best possible solution [2–8]. In this approach, the environment is assumed to be known a priori. On the other hand, local or reactive navigation algorithms use on board sensors to locally observe small fragments of an unknown environment at each time [1,9]. However, one problem is that these strategies are often heuristic and they are not based on mathematical models such as kinematic equations of the vehicles and their non-holonomic constraints. Many of the proposed obstacle avoidance techniques, such as the dynamic window [10,11], the curvature velocity [12], the lane curvature [13] the boundary following [14,15] and the tangent graph based navigation [8] approaches consider the case of stationary obstacles. The problem of avoiding collisions with moving obstacles is much harder. For this problem, a number of approaches like velocity obstacles [16,17], collision cones [18], or inevitable collision states [19,20] have been proposed. These approaches assume a deterministic knowledge about the obstacle velocity and a moderate rate of its change. Furthermore, these methods tend to be computationally expensive. Moreover, these

* Corresponding author. Tel.: +61 02404409208.
E-mail addresses: a.savkin@unsw.edu.au (A.V. Savkin), wc42888@hotmail.com, z3184703@student.unsw.edu.au (C. Wang).

http://dx.doi.org/10.1016/j.robot.2014.05.006
0921-8890/

and many other papers on this topic (see e.g. [2–5]) do not take into account non-holonomic constraints on robot's motion which is a severe limitation in practice. Up to now, fully actuated robots were mostly studied in this area. Furthermore, the obstacles were interpreted as rigid bodies of the simplest shapes (e.g., discs [21–23] or polygons [24,25]), the sensory data were assumed to be enough to determine the location of obstacle characteristic points concerned with its global geometry (e.g., the disc centre [21,22] or angularly most distant polygon vertex [25]) and to provide access to its full velocity [21,25,22]. Furthermore, mathematically rigorous performance justification of the proposed algorithms is rarely given.

A local range-only based navigation algorithm for non-holonomic robots was proposed in [26]. In [26], obstacles are not assumed to be rigid or even solid. They have arbitrary and time-varying shapes that may rotate, twist, wring, skew, wriggle, or be deformed in any other way. However, the main results of [26] require quite restrictive assumptions on velocities of the moving obstacles. New algorithms for navigation in dynamic environments were proposed in [27,28]. However, the algorithms of [27,28] do not take into account non-holonomic constraints. Moreover, the papers [27,28] do not give any mathematically rigorous analysis of the proposed navigation algorithms.

A typical obstacle avoidance algorithm in a complex environment with many obstacles consists of selecting the "closest" or the "most dangerous" obstacle and avoiding collision with it and then moving in a desired direction until there is another "dangerous" obstacle. However, this approach raises many difficult issues, such as how to determine the "most dangerous" obstacle, how to separate several obstacles, how to handle obstacles which are hidden or outside the sensing field, how to deal with situations with two or more "dangerous" obstacles at the same time.

In this paper, we propose instead a novel reactive navigation approach based on an integrated environment representation which overcomes the above problems. This approach is partially inspired by the paradigm shift from binary interaction models to an integrated treatment of multiple interactions which are typical for social interactions in human crowds or animal swarms suggested in [29] for analysis of pedestrian behaviour in crowds. Our approach is based on an integrated representation of the information about the environment in which the combined effect of close multiple stationary and moving obstacles is implicitly included in the representation of a sensing field of the robot. An advantage of our approach is that we do not have to separate obstacles and approximate their shapes by discs or polygons. Moreover, our algorithm does not require any information on the obstacles' velocities or any other derivatives of measurements. The proposed approach results in a very efficient and intelligent robot's behaviour. Instead of being repelled by a crowd of obstacles, as it happens for many other navigation algorithms, the robot seeks a path through this crowd.

In this paper, we assume that the mobile robot is a Dubins car like vehicle described by the standard non-holonomic model with a hard constraint on its angular velocity. It is well-known, that the motion of many wheeled robots, missiles, unmanned aerial and underwater vehicles can be described by this model; see e.g. [30,31] and references therein. Unlike many other papers on this area of robotics which present heuristic navigation strategies, we give a mathematically rigorous analysis of our navigation algorithm with a complete proof of the stated theorem. Moreover, the proposed algorithm is quite simple and computationally efficient.

We confirm the performance of our real-time navigation strategy with extensive computer simulations and experiments with a Pioneer P3-DX mobile wheeled robot. In particular, the performance of the proposed method has been compared with that of the velocity obstacle approach [16,17] which is very popular in the area.

The remainder of the paper is organized as follows. Section 2 presents the system description and the problem statement. In Section 3, our navigation algorithm is introduced. Computer simulations for the proposed navigation algorithm are given in Section 4, whereas Section 5 presents experiments with a Pioneer P3-DX mobile non-holonomic robot. Mathematical analysis of the algorithm is given in Section 6. Finally, Section 7 presents brief conclusions.

2. Problem description

We consider a planar vehicle or wheeled mobile robot modelled as a Dubins car. The control input is the angular velocity limited by a given constant. The mathematical model of the vehicle is as follows

$$\begin{aligned} \dot{x} &= V\cos\theta, \\ \dot{y} &= V\sin\theta, \\ \dot{\theta} &= u \end{aligned} \tag{1}$$

where

$$u \in [-U_{\max}, U_{\max}]. \tag{2}$$

Here $[x(t), y(t)]$ is the vector of the vehicle's Cartesian coordinates, $\theta(t)$ gives its heading, $V > 0$ and $u(t)$ are the speed and angular velocity, respectively. The angle $\theta(t) \in (-\pi, \pi]$ is measured in the counter-clockwise direction from the x-axis. The maximum angular velocity $U_{\max}$ is given. Under this model, the vehicle is moving with the constant speed V and the minimum turning radius R_m where

$$R_m = \frac{V}{U_{\max}}.$$

Let $\delta > 0$ be the sampling period. The robot updates its angular velocity $u(t)$ at discrete times $0, \delta, 2\delta, 3\delta, \ldots$. Also, let

$$c_R(t) := [x(t), y(t)] \tag{3}$$

be the vector of the robot's coordinates, and

$$v_R(t) := \dot{c}_R(t) \tag{4}$$

be the robot's velocity vector.

We consider a quite general problem of vehicle navigation with collision avoidance. We assume that there exists a dynamic environment that is unknown to the robot. This environment consists of any number of moving or stationary components which can be deformable. In other words, the environment is described by a time-varying planar subset $\mathcal{E}(t)$ which is not known to the robot. The current distance $d(t)$ from the robot to the environment $\mathcal{E}(t)$ is defined as

$$d(t) := \min_{r \in \mathcal{E}(t)} \|r - c_R(t)\|.$$

Here $\|\cdot\|$ denotes the standard Euclidean vector norm.

We also consider a stationary target $\mathcal{T}$ modelled as a small circle of radius R_T. Let $\theta_0(t) \in (-\frac{\pi}{2}, \frac{\pi}{2})$ be the direction from the robot to the centre of the target $\mathcal{T}$, and $\theta_0(t)$ is assumed be known to the robot. Furthermore, let $d_{\text{safe}} > 0$ be a given distance. Our goal is to navigate the robot towards the target $\mathcal{T}$ while satisfying the safety constraint $d(t) \geq d_{\text{safe}}$ for all t.

Definition 2.1. A robot navigation strategy is said to be *safe collision free* if $d(t) > d_{\text{safe}}$. Furthermore, a robot navigation strategy is said to be *target reaching* if $c_R(t_f)$ belongs to the target circle $\mathcal{T}$ for some finite time $t_f \geq 0$.

Please cite this article in press as: A.V. Savkin, C. Wang, Seeking a path through the crowd: Robot navigation in unknown dynamic environments with moving obstacles based on an integrated environment representation, Robotics and Autonomous Systems (2014), http://dx.doi.org/10.1016/j.robot.2014.05.006