Robotics and Autonomous Systems 109 (2018) 125–138

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

The *Pc* metric: A performance measure for collision avoidance algorithms

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ARTICLE INFO

Article history:
Received 14 December 2017
Received in revised form 7 May 2018
Accepted 17 August 2018
Available online xxxx

Keywords:
Performance metrics
Performance evaluation
Collision avoidance algorithms
Obstacle avoidance
Mobile robots
Robot navigation
Human comfort

ABSTRACT

Despite the comprehensive development in the field of navigation algorithms for mobile robots, the research on performance metrics and evaluation procedures for making standardized quantitative comparison between different algorithms has gained attention only recently. This work attempts to contribute with such effort by introducing a performance metric for the assessment of collision avoidance algorithms for mobile robots. The proposed metric comprehensively evaluates the actions taken by the objects and their consequences, in a given scenario of any given collision avoidance algorithm, based on the concept of probability of collision. The contribution of the paper encompasses the definition of the metric, the methodology to estimate the metric, and the framework to apply the metric for any given scenario. Experiments and numerical simulations are conducted to validate and demonstrate the effectiveness of the proposed metric in performance evaluation and comparison among different collision avoidance algorithms.

1. Introduction

Navigation with collision avoidance on an autonomous mobile robot is usually carried out by planning algorithms (or planners). These planners can be classified into three categories: global, local, or hybrid (i.e., the mixed of the first two). Global planners pre-plan off-line a path for the robot to move from a starting position to a goal position using a priori information of the environment with the objective of avoiding known static obstacles [1,2]. Local planners plan reactively a path through online sensing of the unknown environment, so as to refine the path generated by the global planner to avoid collision with both static and dynamic obstacles [3–5]. Hybrid planners combine the functionalities of the other two types of planners by pre-planning and executing a path to the goal, while reactively avoiding dynamic obstacles during the path execution [6,7]. In addition, few planners have been proposed recently to enable the global, local or hybrid planners to deal with human obstacles during navigation. Such planning strategies, categorized as human-aware navigation [8], produce robot motion patterns that are not only safe and collision-free but also human-friendly (i.e., reducing discomfort to humans).

Due to the distinct objectives of the different types of planners, the performance of these algorithms is usually characterized in the specific application context for which the algorithms were originally developed. This brings in the necessity for specific measures being applied to a specific category of planners. Such performance measures (i.e., performance metrics) can be classified into two types: global and local. The global metrics consist of path length, path smoothness, deviation from pre-planned path, time taken to reach goal, success rate in reaching goal, and so on. The metrics applicable to local and hybrid planners focus on evaluating the collision avoidance behavior of the robot and they are comprised of distance to obstacles (DTO), distance to collision (DTC), time to collision (TTC), number of collisions, oscillations during avoidance, etc. [9,10]. As for the human-aware navigation, the metrics evaluate the navigation performance in terms of the comfort felt by humans. Distance metrics, i.e., the distance maintained by the robot from humans, have been widely used for this purpose [8].

The purpose of the different types of metrics listed above is not only to evaluate but also to objectively compare the planners within the specific category. Comparing different global planners using the existing global metrics becomes straightforward because it is just about the evaluation of fixed/invariable pre-planned robot paths from start to goal in a static environmental model. However, for comparing different local planners, i.e., collision avoidance algorithms based on their performance in safety, avoidance capability and also comfort felt by humans, the above mentioned local metrics alone are not sufficient. Commonly in the literature, local metrics are often complemented with global metrics for this purpose. But global metrics compare collision avoidance algorithms

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https://doi.org/10.1016/j.robot.2018.08.005
0921-8890/

only based on the path optimality with respect to goal, and not based on the avoidance behavior for a dynamic environmental setting. The reason for the existing local metrics being insufficient is that they rely on application specific assumptions and limitations for evaluating the performance in a given scenario.[1] Thus, and to the best of our knowledge, there is not any distinct and well-defined methodology to directly compare different collision avoidance algorithms and determine the "best" for a given purpose in practice [10,11].

In general, the local metrics utilize a simple and deterministic model of the objects to linearly predict their motion in time assuming a constant velocity. When the predicted motions intersect at some particular time, it refers to a potential collision event and the time and distance to that collision event are taken as a measure. This is done for every time step of the scenario, showing the proximity of the objects to the collision event. However, due to the assumption of constant velocity and linear prediction, the predicted motion of objects do not always intersect thus failing to have a measure. Hence, the limitation of not considering more complete dynamics models, along with the assumption of constant velocity, set a drawback to the usage of the existing local metrics. Furthermore, collision avoidance algorithms involve objects that are reactive to each other. The motion of one object may influence and interact with the motion of surrounding objects. The local metric that is evaluating such objects should judge the direct and indirect consequences of these motions and interactions. For example, during an avoidance between object A and object B, the collision of object A with object B is a direct consequence of the motion of object A. On the other hand, object B colliding with an object C due to the motion of object A, is an indirect consequence of the motion of object A.

To overcome these shortcomings, in this work, a single unified metric for performance evaluation and comparison of collision avoidance algorithms is proposed. The proposed metric is based on the concept of probability of collision and is referred to as the *Pc metric*. Given a scenario with objects following any collision avoidance algorithm with objects being humans, mobile robots or anything capable of navigation. The *Pc* metric evaluates the motion of each object in the scenario using the proposed evaluation approach without making any assumptions on objects' motion. At every time step, the proposed approach stochastically predicts the objects' motion until a certain time horizon and measures the probability that the predicted future motions of the objects could lead to a collision event. Unlike the classical prediction models which are estimation-measurement based or learning based, the purpose of this prediction model is to analyze every admissible future state of the objects based on the executed motion. The metric evaluates the objects not just for favorable future states but also for any worst case states that the objects' motions can possibly get to, resulting in a comprehensive evaluation technique. Further, the metric calculates the probability value collectively considering all the objects in the scenario with regards of their interactions and influences, reflecting the probability of direct and indirect collisions that the objects undergo during navigation. In contrast to existing metrics, the *Pc* metric is a normalized metric in the range of [0, 1] since it is based on probability. Such a feature, enables a direct comparison between exiting collision avoidance algorithms.

The effectiveness of the proposed metric is demonstrated and validated through various simulations, where the metric is applied to existing collision avoidance algorithms, human-aware algorithms and even to real pedestrian paths. The numerical results prove the suitability of the proposed metric in evaluating collision avoidance algorithms, optimizing algorithms' internal parameters, quantitatively comparing with other algorithms, choosing the best collision avoidance algorithm for a given environment scenario, and inferring the comfort felt by human due to the robot behavior.

The remainder of the paper is organized as follows. In Section 2, the existing performance metrics and the related work to the concept of probability of collision are discussed. In Section 3, the definition of the *Pc* metric and the methodology to estimate it are shown. In Section 4, the validation experiment and simulations are presented along with the discussion of their results. The final Section 5 shows the concluding remarks.

2. Related work

Some of the commonly used performance metrics in the literature of mobile robots, as listed in [9,10], are discussed as follows. Given a static environment model, a path/trajectory is pre-planned towards the goal and is represented as a set of way-points. This pre-planned path is evaluated by its length (i.e., sum of distance between the way-points) and its smoothness as calculated in [12,13] (i.e., instantaneous curvature of the trajectory). The robot executing this path is evaluated by the distance deviation/error of the robot from the pre-planned path, distance traveled by the robot, time taken to reach the goal, success rate in reaching the goal and precision of the robot from the goal position. All these metrics deal with path optimality and the navigation behavior of robot.

The metrics that evaluate the robot's collision avoidance behavior and the safety of the objects are total number of collisions during the navigation, robustness in narrow spaces (i.e., capability of traversing narrow spaces without collision), occurrence of oscillations, TTC, DTC and shortest DTO. The oscillations can be found using the same calculation as path smoothness, which is explained as follows. The oscillations measure is given as the mean of the instantaneous curvature of the given path, where instantaneous curvature is the ratio of the change in the tangential angle by the distance between two way-points of the path, at an instantaneous time step. The TTC and DTC can be found by the formulation explained in [14]. Given position, velocity and direction of two objects, first the point of intersection of their linearly projected paths (i.e., intersection of two straight lines) is calculated. Then the time taken by both objects to reach that point of intersection is calculated. If the difference between the time taken by the two objects is below a threshold, then a collisions happens. The time to that collision is TTC and the distance to that collision is DTC.

The DTO metric comes under the category of distance metrics. Distance metrics remain the prevalent measure for collision avoidance due to computational constraints and practical considerations [11]. Some of the distance metrics are minimum, mean and minimum means distance between the robot and the obstacles [10]. The distance between the robot and the human obstacle is taken as a common measure to approximate the discomfort felt by humans. Simulations are performed with robot and human obstacles virtually and are evaluated by the distance metrics [8].

Our proposed performance metric is based on the concept of probability of collision between moving objects. This concept has been used predominantly in the field of space objects, transportation systems, mobile robotics, and pedestrian studies. For space objects, the probability of collision is calculated to choose an avoidance maneuver that is collision free. It is derived analytically considering the uncertainty in the position of the space objects resulting from the sensor tracking error. The position uncertainties are generally represented as Gaussian and sometimes Gaussian mixtures as in [15]. During the derivation of probability of collision, the future motion of the objects are predicted linearly as in [16,17] or non-linearly as in [18–20] but with zero uncertainty.

[1] In our context, a scenario is where one or more robots execute a given collision avoidance algorithm avoiding static and dynamic (i.e., moving) obstacles. From now on, the robots and moving obstacles in the scenario will be termed as 'objects' in the scenario.