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Admissible gap navigation: A new collision avoidance approach

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HIGHLIGHTS

- A new concept for collision avoidance, the Admissible Gap (AG), is introduced.
- The exact robot shape and kinematic constraints are taken into account.
- An efficient and stable methodology for extracting gaps is proposed.
- An outstanding navigation performance in unknown dense environments is achieved.
- The AG approach is evaluated and compared with three state-of-the-art methods.

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ABSTRACT

This paper proposes a new concept, the *Admissible Gap* (AG), for reactive collision avoidance. A gap is called admissible if it is possible to find a collision-free motion control that guides a robot through it, while respecting the vehicle constraints. By utilizing this concept, a new navigation approach was developed, achieving an outstanding performance in unknown dense environments. Unlike the widely used gap-based methods, our approach directly accounts for the exact shape and kinematics, rather than finding a direction solution and turning it later into a collision-free admissible motion. The key idea is to analyze the structure of obstacles and virtually locate an admissible gap, once traversed, the robot makes progress towards the goal. For this purpose, we introduce a strategy of traversing gaps that respect the kinematic constraints and provides a compromise between path length and motion safety. We also propose a new methodology for extracting gaps that eliminates useless ones, thus reducing oscillations. Experimental results along with performance evaluation demonstrate the outstanding behavior of the proposed AG approach. Furthermore, a comparison with existing state-of-the-art methods shows that the AG approach achieves the best results in terms of efficiency, robustness, safety, and smoothness.

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1. Introduction

Mobile robots have proven themselves tremendously useful in a wide variety of real-world applications, such as transportation, search and rescue, and mining. Perhaps the most interesting aspect of these robots is the ability to execute tasks that are difficult or dangerous to be performed by humans. Designing such robots requires to solve several challenges such as detection, grasping, and control. Nevertheless, whatever the task to be carried out, at some point, the robot has to move. Therefore, autonomous navigation is at the heart of any robotic system and has been thoroughly studied since the beginning of robotics.

The difficulties of autonomous navigation arise from the fact that real-world environments are often unpredictable, unstructured, and changes over time. Moreover, moving obstacles may block the robot's working area while performing tasks. Under these circumstances, it is essential to incorporate the sensory information into the control loop, bridging the gap between path planning and motion execution. By this means, the environmental changes are detected in real-time enabling robots to avoid unforeseen obstacles. These difficulties are tackled by reactive collision avoidance methods.

The majority of collision avoidance techniques present limited capability of driving robots through narrow spaces in cluttered environments. This is due the fact that these methods experience several classical problems such as being prone to local minima, failure of steering a robot among closely spaced obstacles, and the tendency to generate oscillatory motion [1]. It has been shown that using some form of high-level description of the sensory information is a successful approach to deal with these environments. The

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so-called *gap-based* methods [1–4] follow this strategy. However, these methods provide direction solutions assuming holonomic and disc-shaped robots. This is indeed a strong assumption since ignoring the actual vehicle shape may lead to collisions or failure of finding a direction solution. Additionally, ignoring the kinematic constraints may result in computing infeasible motions, relying on approximations when applied on a real vehicle. Hence, accounting for these constraints is of great importance, particularly for robots that are performing tasks in hazardous environments.

In order to deal with this limitation, some methods turn the holonomic solution into a motion control that complies with the shape and kinematic constraints. For instance, in [5] a least squares method is used to align the direction solution with the robot's heading. In [6], a similar approach is proposed by splitting the problem into subproblems (motion, shape, and kinematics). In fact, these solutions are subject to approximations and deal with each constraint separately [7]. This may arise some problems, especially in scenarios requiring high maneuverability. A more convenient solution is proposed in [7] by mapping the workspace into the so called Arc Reachable Manifold (ARM) in such away that, when the navigation method is applied in ARM, these constraints are implicitly considered. Although this approach is general and can be applied to many existing techniques, it has some shortcomings that might limit its use in dense environments: first, constructing the obstacle region in ARM is based on the assumption that the configurations are attainable by elemental circular paths only. Hence, navigable gaps may appear blocked in ARM.[1] Second, the coordinates of ARM are transformed to comply with the kinematic constraints. Searching for openings in the new coordinates is unnatural and may result in detecting incorrect or phantom gaps.

This paper introduces a new concept, the *Admissible Gap* (AG), for reactive collision avoidance. We call a gap admissible if it is possible to find a single motion control that safely guides a robot through it, while obeying the vehicle constraints. By employing the AG concept, it has been possible to develop a collision avoidance approach that successfully drives a robot in unknown dense environments. As compared with other gap-based methods, our approach directly considers the exact shape and kinematic constraints rather than finding a direction solution and then aligning the vehicle with that direction. The basic idea is to extract the set of gaps surrounding the vehicle and select the most promising one in terms of reaching the goal. A virtual *admissible* gap is then constructed in an iterative manner, such that traversing it leads to the selected gap and a compromise between path length and motion safety is achieved.

The admissible gap has appeared in part in [8]. In this paper, the concept is extended by considering all virtual gaps that are constructed in the iterative process, not only one. Consequently, the smoothness of the trajectories has been improved. Furthermore, we propose a new methodology for detecting gaps that is applicable to limited and full field of view sensor types. With this methodology, the total number of gaps is reduced by eliminating useless ones, increasing the stability of navigation and alleviating the possibility of oscillation. Additionally, this paper includes a detailed presentation of the overall method along with useful remarks which have been omitted in the conference for the sake of brevity. Finally, several experiments in dense environments are provided, where outstanding results have been achieved, outperforming existing state-of-the-art techniques in terms of efficiency, safety, robustness, and smoothness. By employing the AG approach, our team successfully competed in the 2016 World RoboCup Rescue League, where we ranked the 3rd place in our first participation in the competition.

The remainder of the paper is structured as follows. Section 2 presents the related work while Section 3 introduces some preliminary definitions. In Section 4, our methodology of extracting gaps is described, and subsequently, in Section 5 the Admissible Gap concept is presented. Section 6 shows how this concept is used to navigate a mobile robot. In Sections 7 and 8, the experimental results are discussed and the performance of the AG is evaluated. Finally, Section 9 points out some concluding remarks and presents recommendations for future work.

2. Related work

Robot motion planning has been thoroughly studied by the robotics community and has been traditionally addressed from two distinct perspectives; path planning (map-based) and collision avoidance (sensor-based). Since path planning is beyond the scope of this paper, only collision avoidance methods are covered (for those interested, refer to [9]). For brevity, the focus will be restricted to some representative approaches, including those that have proved popular across the years and those that are related to the proposed approach. For a thorough description of other methods, the reader can refer to [10].

Perhaps the majority of collision avoidance methods are based on the Artificial Potential Field (APF) concept [11–14], initially introduced by Khatib [15]. Within this concept, the robot is a particle attracted towards the goal and repelled from obstacles. The motion direction is determined based on the vector sum of the attractive and repulsive forces. APFs, although simple to implement and computationally efficient, are prone to local minima and may lead to an oscillatory motion [16]. Many research efforts were devoted towards solving the local minima problem, such as [17] by performing a random walk mechanism or [18] by using a navigation function. Bounini et al. [19] solved the problem by adding some extra repulsive potential, inspired from pouring a liquid with high pressure. Other researchers addressed the oscillation problem, such as [20] by employing a modification of Newton's method or [21,22] by utilizing a class of vector fields. A recent work has extended the APF capabilities to moving obstacles [23]. Although these methods solve the APF drawbacks, they are either subject to strict assumptions or limited to certain scenarios [24].

The family of Bug algorithms (e.g. [25–27]) are among the earliest and simplest reactive obstacle avoidance methods. The key idea of these algorithms is to drive the robot towards the target unless an obstacle is encountered, in this case the robot moves unidirectionally along the obstacle boundary until motion towards the target is once again allowable. The transition between both motion cases is controlled by a globally convergent criterion. A well-known variant, the tangent Bug [28,29], builds a graph of the robot's surroundings using a ray based sensor model. This helps in minimizing the path length as shortcuts can be made while circumnavigating obstacles. Bug algorithms allow robots to move in previously unknown environments with the guarantee that the goal is reached once it is reachable. However, they assume a point-like robot and strongly depend on the sensor accuracy. Moreover, they have only been tested in static environments which is not the case in real-world scenarios.

Other research efforts were directed towards incorporating the motion constraints into the obstacle avoidance problem, selecting an admissible velocity rather than a steering direction. The outcome of these efforts was the development of various methods [30–32], known later as *velocity space* methods. However, it was the Dynamic Window Approach DWA [33,34], initially proposed in [35], that won popularity among the scientific community. It formulates the obstacle avoidance problem as a constraint

[1] A gap is navigable in ARM only if there is a collision-free circular path that is tangent to the robot's heading and passes through both the gap and the robot's origin. In other words, only those gaps that are directly navigable from the current robot's location can be seen in ARM.

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