Optimal Reciprocal Collision Avoidance for Multiple Non-Holonomic Robots

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Abstract. In this paper an optimal method for distributed collision avoidance among multiple non-holonomic robots is presented in theory and experiments. Non-holonomic optimal reciprocal collision avoidance (NH-ORCA) builds on the concepts introduced in [2], but further guarantees smooth and collision-free motions under non-holonomic constraints. Optimal control inputs and constraints in velocity space are formally derived for the non-holonomic robots. The theoretical results are validated in several collision avoidance experiments with up to fourteen e-puck robots set on collision course. Even in scenarios with very crowded situations, NH-ORCA showed to be collision-free for all times.

1 Introduction

Multi-robot systems are designed to achieve tasks by collaboration. A key requirement for their efficient operation is good coordination and reciprocal collision avoidance. Moving a vehicle on a collision-free path is a well-studied problem in robot navigation. The work in [4], [6] and [8] presents representative examples of collision avoidance methods for single mobile robots. Basically, similar approaches as in the single robot cases can be applied in the context of collision avoidance for multiple robots. However, the increase in robot density and collaborative interaction needs methods that scale well with the number of robots. The collision avoidance approaches are extended in [11] among others for multiple robots by decoupling path planning and coordination. Other work investigated potential fields [5] and

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cooperative control laws [14] to direct a group of robots to their objectives while avoiding collisions. Decentralized control helps lowering computational cost and introduces additional robustness and flexibility to the multi-robot system.

In this paper, we develop and formally analyze a new collision avoidance strategy for a group of non-holonomic robots. Mobile robots we see being deployed nowadays in research or industry are mostly non-holonomic. Therefore installations with multiple robots in real world scenarios, such as multiple vacuum cleaners or collaborative monitoring and maintenance vehicles, require collision avoidance methods that take the non-holonomic constraints of the robots into account.

Our approach builds on Optimal Reciprocal Collision Avoidance (ORCA) [2] and extends it toward *non-holonomic* reciprocal collision avoidance. The robots are controlled to stay within a maximum tracking error $\mathscr{E}$ of an ideal holonomic trajectory. Control inputs for optimal tracking are derived from mapping holonomic onto non-holonomic velocities. We focus on differential-drive robots in the following work, even though our approach applies more generally for the class of feedback-linearizable vehicles with non-holonomic kinematics, such as car-like robots or differentially-driven robots with trailer.

Reciprocal Collision Avoidance (RVO) [3], a collaborative collision avoidance method based on velocity obstacles, was reformulated as ORCA [2] and shown to be solved efficiently through a low-dimensional linear program, which results in completeness and a speed-up of the algorithm. Each robot makes a similar collision avoidance reasoning and collision-free motion is guaranteed all time, but holonomic robots are assumed and oscillations in the form of reciprocal dances can occur. The extension in [12] combines both the concepts of basic velocity obstacles and RVO to reduce the amount of oscillations. In addition, robot kinematics and sensor uncertainty are included by enlarging the velocity cones, even though a formal proof of collision-free motion is not given. The work in [15] generalizes RVO for robots with non-holonomic constraints by testing sampled controls for their optimality. As the method requires extensive numeric computation and relies on probabilistic sampling, it may fail to find an existing feasible solution. The latest extension [13] introduces a solution for differential-drive robots by applying ORCA on the robot's virtual center. This is in contrast to our approach of extending the robot's radius, which allows to decrease its extension to zero in crowded scenarios. [13] also relies on the mapping between desired holonomic and non-holonomic velocities, but is different from ours in how it is derived; moreover it further constrains the motion of the robots. Another reactive collision avoidance method for unicycles based on velocity obstacles was presented in [9], where inputs are obtained by a weighted combination of the closest collision in normal and tangential directions.

The paper is organized as follows. We start with the problem formulation in Section 2 and review the main concepts of ORCA. Then the proposed algorithm for collision avoidance in a group of non-holonomic robots is presented in Section 3. In Section 4, we give a formal analysis of the non-holonomic controls that lead to optimal tracking of holonomic velocities and prove collision-free motion. Section 5 demonstrates the method in experiments with up to fourteen robots and shows successful collision avoidance and smooth trajectories.