Reaching Analysis of Wheelchair Users Using Motion Planning Methods

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Abstract. For an environment to be well suited for wheelchair use not only should it be sufficiently clear of obstacles so that the wheelchair can navigate it, it should also be properly designed so that critical devices such as light switches can be reached by the hand of the wheelchair user. Given a goal location, explicitly calculating a path of the wheelchair and the person sitting in it so that they can reach the goal is not a trivial task. In this paper, we augment a Rapidly-exploring Random Tree (RRT) planner with a goal region generation stage that encourages the RRT to grow toward configurations from which the wheelchair user can reach the goal point. The approach is demonstrated on simulated 3D environments.

Keywords: Wheelchair accessibility; Reaching analysis; Motion planning.

1 Introduction

The problem of reaching analysis is key to determining if an environment is properly designed for wheelchair use and is closely related to the problem of determining the possible collision-free motion of a kinematic device. A complete solution to the motion planning problem is known to be exponential in the robot's degrees of freedom (DOFs) [1] which makes the planning problem hard for sufficiently complex devices. Given the inherent complexity a number of heuristic approaches have been developed for motion planning problems with high DOFs [2]. The Rapidly-exploring Random Tree (RRT) [3] has proven to be useful for path planning for high DOF robots with non-holonomic constraints. The RRT builds a random tree in configuration space rooted at the start state of the vehicle. New nodes are sampled randomly from configuration space and connected to the tree. This process continues until either a path to the goal is found or if some predefined resource limit is exhausted.

This paper develops a method for the reaching analysis of wheelchair users to capture the behavior of the moving wheelchair as well as the moving arm of the person sitting in the chair in a 3D indoor environment. We develop a simplified mathematical model of a wheelchair as a differential drive vehicle and the human's right arm using a spherical shoulder joint and a revolute elbow joint. This kinematic structure is used to plan motions from an initial configuration to a goal configuration implicitly specified by the position of the hand using an RRT that has been augmented to probabilistically decouple the planning project into plans requiring motion of the base and pure reaching motions of the user. The planner can be a useful tool for clinicians to assess the reaching accessibility of wheelchair users in a given environment.

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2 Related Work

Given the similarities of the underlying problem, the methodologies developed for robot motion planning have been applied to the problem of simulating and automatic testing the mobility of wheelchairs before (see [4,5] for examples). In addition, much work has been done on capturing reachable workspace properties for humans [6,7,8]. [6] describes a simplified kinematic model of human arm motion and estimates the reachable workspace by calculating all combinations of values of valid joint coordinates. Another approach presented in [7] discretizes the workspace into equally sized small cubes. Into each cube a sphere is inscribed and sample points on the sphere are examined using inverse kinematics. The methodology introduced in this paper expands upon the work that uses a Probabilistic Roadmap Method (PRM) to estimate the reachable workspace of the wheelchair user described in [9]. Instead of using a PRM, here we use a modified RRT method to search a path for its appropriateness in handling the non-holonomic constraints imposed by the wheelchair device. The main disadvantage of the basic RRT search strategy is that it slowly covers the configuration space in order to reach the goal since the tree expands in all directions in configuration space until the goal is reached. A common approach to improve the performance of an RRT-based search is to bias the tree growth towards the goal configuration (RRTGoalBias) or a region around the goal configuration (RRT-GoalZoom) [3]. In this paper we exploit this second strategy informed by the details of reaching from a wheelchair platform.

3 Motion Planning for Wheelchair User

Let $\mathcal{A}$ denote the model of the desired kinematic structure moving in a 3D static Euclidean space $\mathcal{W}$. $\mathcal{A}$ consists of a mobile wheelchair base $\mathcal{A}_{base}$ and an attached kinematic chain that models the user's arm $\mathcal{A}_{arm}$. For simplicity we only consider the right arm in this paper, but the method can easily be extended to two arms. Let p_{goal} denote the goal point in $\mathcal{W}$, where the wheelchair user's hand should be placed after following a feasible motion from an initial pose c_{init}. Any configuration of $\mathcal{A}$ uniquely determines the position of the hand in $\mathcal{W}$. The objective is to have the arm reach the goal, that is $FK(c_{goal}) = p_{goal}$. The reaching analysis of the wheelchair user involves using motion planning techniques to determine a feasible motion, which is a sequence of configurations $(c_0, c_1, ..., c_n)$ that $\mathcal{A}$ can execute such that: $c_0 = c_{init}$, $c_n = c_{goal}$ and $FK(c_{goal}) = p_{goal}$; every configuration c_i on the path is collision-free and within joint limits; every connection of c_i and c_{i+1} is free and satisfies the kinematic constraints.

Consider a person in a wheelchair attempting to reach an object in the environment. It is likely that the person will move the wheelchair to an area close to the object first and then move the arm to reach the goal. Motivated by this observation a goal reaching region $\mathcal{C}_{goal}$ is generated around the location from which the user could potentially reach the goal and then we bias the growth of the RRT towards the goal reaching region. Let $\mathcal{C}_{goal}$ be the subset of the configuration space from which the arm is potentially able to reach p_{goal}. For a given goal point $p_{goal} = (x_{goal}, y_{goal}, z_{goal})$, $\mathcal{C}_{goal}$ is bounded by by configuration volume $[x_{goal} - r, x_{goal} + r] \times [y_{goal} - r, y_{goal} + r] \times [-\pi, \pi] \times \Phi_1 \times \Phi_2 \times \Phi_3 \times \Phi_4$, where Φ_i denotes the domain of joint ϕ_i. Given the potential goal region $\mathcal{C}_{goal}$

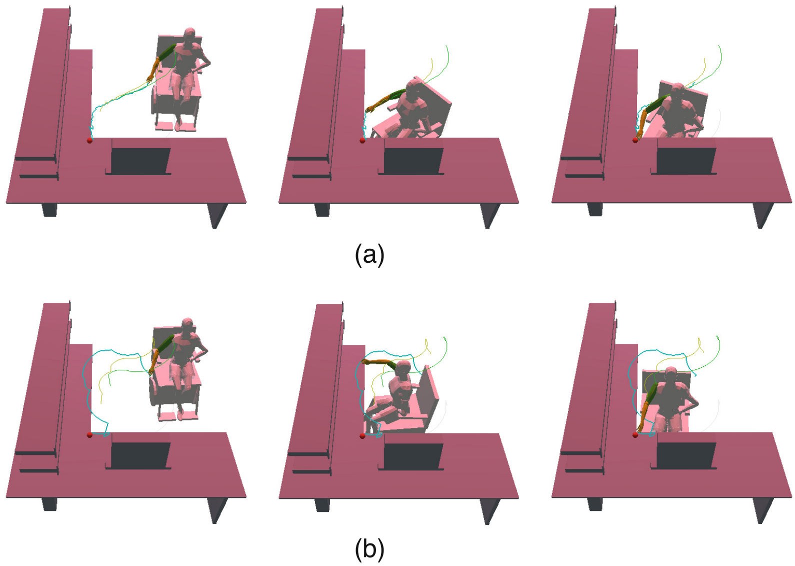

Fig. 1. Two paths found by the RRTGoalRegionBias planner. The goal location is identified by a red ball.

the goal-region biased RRT algorithm is used to find a feasible path from c_{init} to a goal configuration $c_{goal} \in \mathcal{C}_{goal}$ that satisfies its constraint $FK(c_{goal}) = p_{goal}$. The algorithm grows a single tree rooted at c_{init} to search the high-dimensional space. Here, we bias the growth of the tree toward $\mathcal{C}_{goal}$ to speed up the convergence by tossing a biased coin to determine which direction the tree should grow. Based on the coin either a random state in $\mathcal{C}_{goal}$ is chosen; otherwise, a random state in $\mathcal{C}$ is chosen. The choice of the bias can affect the efficiency of the path planner. A complex environment may require more bias towards random states in $\mathcal{C}$ to avoid local minima and to reach a good coverage of the space, and a relatively open environment may require more bias towards the potential goal region for faster convergence. Fig. 1 demonstrates two different paths found using this approach. In this example the random coin was balanced 50-50 between choosing points in $\mathcal{C}_{goal}$ or $\mathcal{C}$, so the wheelchair has equal chance to take a relatively direct path to the goal (e.g. Fig. 1(a)) or not (e.g. Fig. 1(b)).

4 Experimental Validation

The goal of the testing is to demonstrate the motion planner's ability to find paths to reach goal points in this complex environment. Table 1 shows the performance comparison of the brute force RRT and the approach described here (RRTGoalRegionBias) in six scenarios. It shows that RRTGoalRegionBias had a better success rate in finding a path than RRT. For the successful runs RRT generated larger trees than RRTGoalRegionBias. Finally the path length is recorded as the length of the trajectory the user's hand follows. RRTGoalRegionBias finds slightly shorter paths than RRT in 5 out of 6

Table 1. Performance statistics for six scenarios set in the simulated environment shown in Fig. 1 with various initial and goal specifications. Results are averaged for 100 independent runs for each scenario.

Problem		case 1	case 2	case 3	case 4	case 5	case 6
# Success	RRT	38	40	30	27	32	46
	RRTGoalRegionBias	100	100	85	91	87	80
# Nodes	RRT	10308	12267	11261	11527	10381	9941
	RRTGoalRegionBias	3556	3930	5938	7451	6708	7825
Path Length	RRT	665	860	921	739	843	837
	RRTGoalRegionBias	657	826	901	731	799	845

cases. It shows that our algorithm can find paths comparable to those found with a more exhaustive search using a naive RRT approach.

5 Conclusions

This paper describes a methodology for automatic reaching analysis of wheelchair users in an indoor environment. The methodology depends on the development of a simple model of a person sitting in a wheelchair and an efficient motion planner. The motion planner is based on RRT, which generates a potential goal region based on the point to reach first and then uses this region to bias the RRT to find a path. Experimental evaluation shows that the RRTGoalRegionBias planner is more efficient and effective than the basic RRT planner for this task. A tool has been developed to plan paths and to provide a visual display for clinicians to gain a better understanding of the wheelchair's performance in the workspace.

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