International Journal of Smart Home
Vol. 2, No. 3, July, 2008

Accessibility Assessment Via Workspace Estimation

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Abstract

The process of evaluating a built environment for accessibility is known as "accessibility assessment." Determining accessibility is closely related to the problem of determining possible motions of a specific kinematic structure – given an environment and a mobile device, how much of the environment is accessible? Given these similarities, here the accessibility assessment process is reformulated as a motion planning problem. Rather than treating each of the degrees of freedom 'equally' while planning, we explore a hierarchical characteristic of all of the degrees of freedom when constructing the roadmap. The approach is demonstrated on simulated environments as well as on a student residence at York University.

1. Introduction

The term "accessibility" is used to refer to the degree to which portions of a built environment are reachable by people with limits to their mobility. Accessibility is an important factor for people with disabilities in order for them to live and work independently and to minimize the cost of personal care services. For an environment to be well suited for wheelchair use not only must the ground plane be flat and approximately horizontal, it must also be the case that the space be sufficiently clear of obstacles so that the wheelchair can navigate the environment. In order to fulfill accessibility requirements an analysis of built houses and recommendation for home modifications to enhance accessibility are required. This process is known as "accessibility assessment." Accessibility assessment is typically performed manually, resulting in an error-prone and time consuming task that must be accomplished by trained assessors. Although manual assessment can be successful, the shortage of trained assessors can introduce significant delays in assessing specific environments. Even when assessors are available, the lack of advanced tools can introduce delays in the process of assessment, and at the very least introduces a level of subjectivity in the process that is undesirable.

The problem of determining accessibility is closely related to the problem of determining the possible collision-free motion of a specific kinematic device. Given these similarities, by reformulating the accessibility assessment process in terms of this kinematic planning problem it is possible to leverage results from the robotic path planning literature to assist in accessibility assessment.

This paper develops an accessibility assessment method that is designed to automatically evaluate the accessibility of physical environments of wheelchair users or others with limited mobility. We investigate the problem by first formally defining accessibility assessment in terms of robot workspace estimation. We use the estimated reachable workspace, points reachable by the user, to evaluate a wheelchair user's accessibility within the environment. Based on the probabilistic roadmap (PRM) planner [12] a hierarchical PRM method for efficient reachable workspace estimation is developed. Enhancements are developed to the basic PRM planner to enable efficient computation of reachability. The resulting planner can be a useful tool for clinicians to assess accessibility.

The paper is organized as follows. Section 2 reviews existing approaches and technology for accessibility assessment. In Section 3, the problem of accessibility assessment is formalized in terms of robot workspace estimation and path planning, followed by the development of a general solution to the accessibility assessment problem using a variant of the PRM (Section 4). Section 5 evaluates the algorithm on the robotic wheelchair "PlayBot" in a real environment. Finally Section 6 summarizes the work and provides possible directions for future research.

2. Traditional accessibility assessment and existing tools

The lack of basic accessibility to public buildings is understood all over the world. National laws enforce accessibility in various countries. For example, in the United States, under the Americans with Disabilities Act (ADA) [18], new public and private business construction must be accessible. Existing private businesses are required to increase the accessibility of their facilities when making other renovations in proportion to the cost of the other renovations. Similar legal requirements exist in Australia [17], the UK [21], and South Africa [20]. In Ontario, the Ontarians with Disabilities Act [19] requires that the Government of Ontario develop barrier-free design guidelines to promote accessibility for persons with disabilities to government buildings, structures and premises. More specifically, the level of accessibility for persons with disabilities should be equal to or exceed the level of accessibility required by the Building Code Act, 1992 and the regulations made under it. The analysis of built structures and the development of recommendations for modifications to enhance accessibility is known as "accessibility assessment."

The normal practice for assessing accessibility is via a manual prescriptive code-based approach [7]. The evaluation of a specific environmental design follows parameters specified in relevant official guidelines. For example, the Americans with Disability Act Accessibility Guidelines [4] contain "prescriptive" specifications for clear doorway width, lavatory clearance, and the like. Trained clinicians assess a building by checking these specifications. This approach can be successful and is very straightforward but it has a number of limitations. First, it requires professional accessibility assessors to visit the structures that need to be assessed. Providing services in rural or remote areas can require extended travel time. This can lead to unaffordable expenses on the part of individuals who need the service. Second, the prescriptive assessment document cannot address all possible building design configurations or wheelchair use patterns. The gross structure of different wheelchairs may be similar, but the details, including their motor constraints and kinematic structures, can vary considerably. Providing a standard guideline for all kinds of wheelchairs and buildings is almost impossible. Third, even for a wheelchair whose structure is known, its performance against an environment is hard to predict exactly especially when we consider a person sitting in the wheelchair. A design configuration that is code-compliant does not necessarily imply real usability, and a design that does not satisfy the prescriptive accessibility requirement might actually be accessible by wheelchair users [7].

Advanced tools to support and extend the traditional accessibility assessment are being developed. 3D acquisition and modeling has been intensively studied in the past few decades and can be used to assist the assessment. For example, the Virtual Reality Telerehabilitation System (VRTS) [13] relies on the Photomodeler Pro (by Eos System Inc.) to construct 3D virtual models from a collection of 2D photographs of an interior environment and customized algorithms to analyze the 3D models for wheelchair accessibility. Laser and stereo-based scanners are an alternative to the image-based approach. Hand-held devices such as the instant Scene Modeler (iSM) [23] and the AQUASensor [9] automatically deal with issues related to depth acquisition, view registration and model construction. The user directs the sensor at a scene of interest to record images and the system creates a photo-realistic 3D calibrated model automatically.

Once a 3D environmental model has been constructed it can be used to model the accessibility/usability of the environment through either simulation of the entire population or the motion of a single individual. Many computer-aided systems for environmental design and assessment have been developed based on these approaches (e.g. [7], [8], and [25]). By producing visible results of users' behavior the simulation can assist evaluation and the comparison of design alternatives, and this can help designers gain a better understanding of the interrelationship between the environment and the users.

Users seated in wheelchairs and capable of reaching from the chair can be modeled as high degree-of-freedom (DOF) kinematic structures connected to a wheeled mobile base. Accessibility assessment can be framed as the task of estimating portions of the environment that can be reached by such a device – a task that is equivalent to workspace estimation in the robotics literature. Robot workspace estimation has been applied in areas such as assembly planning [15] and the mechanical design of robots [26]. Although a range of techniques exist for workspace estimation (e.g., [1] and [11]) most existing approaches consider the problem for robotic manipulators and do not consider arbitrary obstacles in the environment. Robotic manipulators are fixed at one end and this provides certain efficiencies in terms of workspace estimation. For example, one straightforward method for workspace estimation is to take plane sections of the workspace defined by the joint angles that make up the kinematic structure and determine the contour of the section in the plane. Rotating and translating this plane based on other joints in the chain yields the three-dimensional workspace [16].

Estimating the workspace for a mobile robot can be expressed in terms of the ability of the device to plan motions within its environment. The motion planning problem is typically broken down into two basic steps: (i) Define a graph to represent a geometric structure of the environment, and (ii) Search the resulting graph to find a connected path between nodes corresponding to the start and the goal. Most traditional methods are based on one of the three approaches: roadmap, cell decomposition, or potential field. These planners are resolution-complete, i.e. they always find a path if there exists one. In practice, they can solve complex path planning problems for up to 3 DOFs but none of these planners extends well to systems with more than 4 or 5 DOFs [14, 22].

A complete solution to the motion planning problem is known to be exponential in the robot's DOF and a historical account of the computational analysis is given in [5]. A number of heuristic techniques have been proposed for high-dimensional planning. It is not guaranteed that these planners will find a path even though one exists, but if they do find a path it will take the device from the start to the goal. The Probabilistic Roadmap Method (PRM) [12] was developed for multiple-query motion planning in high DOF environments and continues to be used and developed (see [2, 3, 6, 10, 22]). The main difference between the PRM and traditional complete approaches to motion planning is that the PRM does not attempt to construct an exact representation of the shape of the configuration space so that the roadmap can be constructed in reasonable time. The idea is to create a very simplified roadmap that approximately "covers" the free space. Given the specifics of the accessibility assessment problem here we examine the use of PRM methods to solve the accessibility assessment problem.

3. Formal statement of the problem

The problem of accessibility assessment involves assessing the reachable portion of the environment, given (i) a fixed and known environment, (ii) a set of kinematic constraints introduced by the wheelchair and the user (here modeled as a generic 'arm'), and (iii) an initial configuration of the kinematic model in the environment. We begin by defining each of these properties in terms of motion planning notation.

Following [14], let $\mathcal{A}$ be a kinematic device defined in an n-dimensional configuration space $\mathcal{C}$, and operating on a plane in a three-dimensional Euclidean space $\mathcal{W}$. $\mathcal{A}$ consists of a mobile base $\mathcal{A}_{base}$ and an attached kinematic chain $\mathcal{A}_{\mathrm{arm}}$. $\mathcal{W}$ consists of obstacles and is static. Each obstacle has exactly one pose in $\mathcal{W}$.

Reachable workspace

Given an initial configuration $c_{init} \in \mathcal{C}_{free}$, the reachable workspace $\mathcal{W}_{reach}$ of $\mathcal{A}$ is the set of points in $\mathcal{W}$ reachable by the end-effector of $\mathcal{A}$'s manipulator starting from c_{init}. Here, for $w \in \mathcal{W}_{reach}$, w is "reachable" iff it satisfies the following two criteria:

1. There exists at least one configuration $c \in C_{free}$ such that the end-effector is positioned at w;
2. There exists at least one path from c_{init} to c that $\mathcal{A}$ can execute (subject to both kinematic and obstacle constraints).

Given the formalism, accessibility assessment can be reformulated as the task of finding $\mathcal{W}_{reach}$ for a given environment. The motion planner takes the environmental model, the user's kinematic model and initial configuration as inputs, and constructs a roadmap in $\mathcal{C}_{free}$, which can be mapped to the workspace to estimate $\mathcal{W}_{reach}$.

4. Hierarchical probabilistic roadmap method

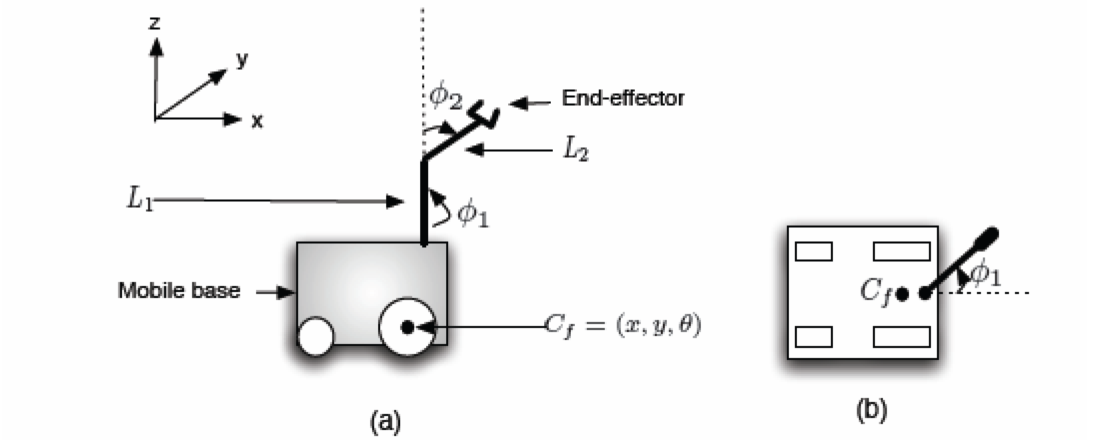

Figure 1: $\mathcal{A}$ consists of $\mathcal{A}_{base}$ and $\mathcal{A}_{arm}$ that has two links L_1 and L_2 connected by revolute joints. The configuration of $\mathcal{A}$ is written as $c = (x, y, \theta, \varphi_1, \varphi_2)$.

Given an initial configuration c_{init} and a goal configuration c_{goal} of $\mathcal{A}$, the motion planner generates a free path between c_{init} and c_{goal} if there exists one, and reports failure otherwise. The basic PRM proceeds in two main phases: a preprocessing phase and a query phase.

In the preprocessing phase configurations are sampled by picking a random configuration of $\mathcal{A}$. Sampled configurations are tested for collision with obstacles and self-collision in workspace and only collision-free configurations are retained in $\mathcal{R}$. Given some metric defined on $\mathcal{C}$, for each node x, all the other nodes are ordered according to increasing distance from x and a simple local planner tries to connect x to each of the K (a predefined parameter) closest nodes. In the query phase, a query (c_{init}, c_{goal}) is processed by first connecting c_{init} and c_{goal} to $\mathcal{R}$, and then performing a graph search on $\mathcal{R}$ for a global path that starts at c_{init} followed by a concatenation of local paths and ends at c_{goal}.

Traditionally PRM assumes that all the joint angles are equivalent but in the accessibility assessment domain (and likely in many other domains) not all DOFs are 'equal.' Consider a person in a wheelchair who attempts to reach an object in the environment. It is more likely that the person will move the wheelchair to an area close to the object first and then move his arm than to first move the arm and then the wheelchair. Clearly in this task the movement of the arm is 'secondary' to that of the wheelchair in terms of the wheelchair user's reachability. PRM is also typically used to find only a single path in the environment. Here we wish to find all reachable locations in the environment. Motivated by these observations we explore a hierarchical structure of the DOFs of the kinematic device to improve the efficiency of the search process.

4.1. Hierarchical probabilistic roadmaps

Considering the problem of accessibility assessment, we can exploit specific properties of the domain. Specifically we order the DOFs of the kinematic structure and apply a hierarchical approach to the planning task. We begin by extending the definition of the traditional roadmap given an 'ordered importance' of the configuration space.

Normally a configuration c of $\mathcal{A}$ is written as a vector of length n, say $c = (j_1 \ldots j_n)$. Instead we seek a representation within which certain joint angles are 'free' and can assume arbitrary values within some previously defined domain. Order the joints such that more important joints have a lower index. Let the domain of j_i be D_i, $c^r = (j_1, j_2, \ldots j_r)$ is a subset of $D_1 \times D_2 \times \ldots D_n$, given by $\{\forall x_{r+1} \in D_{r+1}, x_{r+2} \in D_{r+2}, \ldots, x_n \in D_n \mid (J_1, J_2, \ldots, J_r, x_{r+1}, x_{r+2}, \ldots, x_n)\}$. That is c^r is the set of possible configurations with joints $1 \ldots r$ having specific values but joints $r+1 \ldots n$ are free. This hierarchical concept applies to general kinematic structures in the domain of motion planning. To establish the general representation of c^r, we first order the n DOFs, then fix the first r DOFs and take all possible values of the remaining DOFs to construct the hierarchical body. This definition implies the hierarchy: joint i is "more important" than joint i+1. For a general kinematic structure it may be very difficult to define a strict hierarchy. However, as the purpose of the hierarchy is only to direct the search process this ordering of joints need not be exact.

A configuration c is said to be valid if the robot in configuration c is in the free space of $\mathcal{W}$. Similarly c^r is said to be valid if every element of c^r is in the free space of $\mathcal{W}$. Let $V(c^r)$ denote the function that returns true if c^r is valid. The reachable area of a configuration c is the points in $\mathcal{W}$ where the end-effector can reach. The reachable area $RA_c(c^r)$ of c^r is therefore the union of the reachable points of every element in c^r. In addition, the region of the world that the robot can occupy is also of interest and let $OA_c(c^r)$ be the union of the occupied volume of every element in c^r. Nodes with lower r occupy and reach larger workspaces than those with higher r. To be precise, we have these three lemmas:

Lemma 1: $\forall i, j \in [0..n], i < j \wedge V(c^i) \Rightarrow V(c^j)$. For some configuration of $\mathcal{A}$, that its lower hierarchical representation is free implies the higher hierarchical representation is free, too.

Lemma 2: $\forall i, j \in [0..n], i < j \Rightarrow RA_c(c^i) \supseteq RA_c(c^j)$. For some configuration of $\mathcal{A}$, the reachable workspace of the lower hierarchy is the superset of that of the higher hierarchy.

Lemma 3: $\forall i, j \in [0..n], i < j \Rightarrow OA_c(c^i) \supseteq OA_c(c^j)$. For some configuration of $\mathcal{A}$, the occupied workspace of the lower hierarchy is the superset of that of the higher hierarchy.

The basics of the notation is illustrated in Figure 1 which shows a mobile manipulator $\mathcal{A}$ that consists of a mobile base $\mathcal{A}_{base}$ and a two link manipulator $\mathcal{A}_{arm}$. (This model is a simplified version of the kinematic structure in the problem of accessibility assessment of a user on a wheelchair with a single useful arm.) Based on the observation of the different effects of $\mathcal{A}_{base}$ and $\mathcal{A}_{arm}$, we order the DOFs of $\mathcal{A}$ from its base to its end-effector such that its configuration is written as an ordered array $c = (x, y, \theta, \varphi_1, \varphi_2)$. Also, suppose $D_1 = [x_{\min}, x_{\max}], D_2 = [y_{\min}, y_{\max}], D_3 = [-\pi, \pi), D_4 = [-\pi, \pi), D_5 = [-\pi, \pi)$. Figure 2 shows the hierarchy of occupancy, and Figure 3 shows the hierarchy of reachability. c^0 is not illustrated but can be easily imagined, it is the entire workspace of $\mathcal{A}$. Note the relationship between Figure 2 and Figure 3. If the test for occupancy for Figure 2 (a-d) passes then the corresponding Figure 3 (a-d) is reachable.

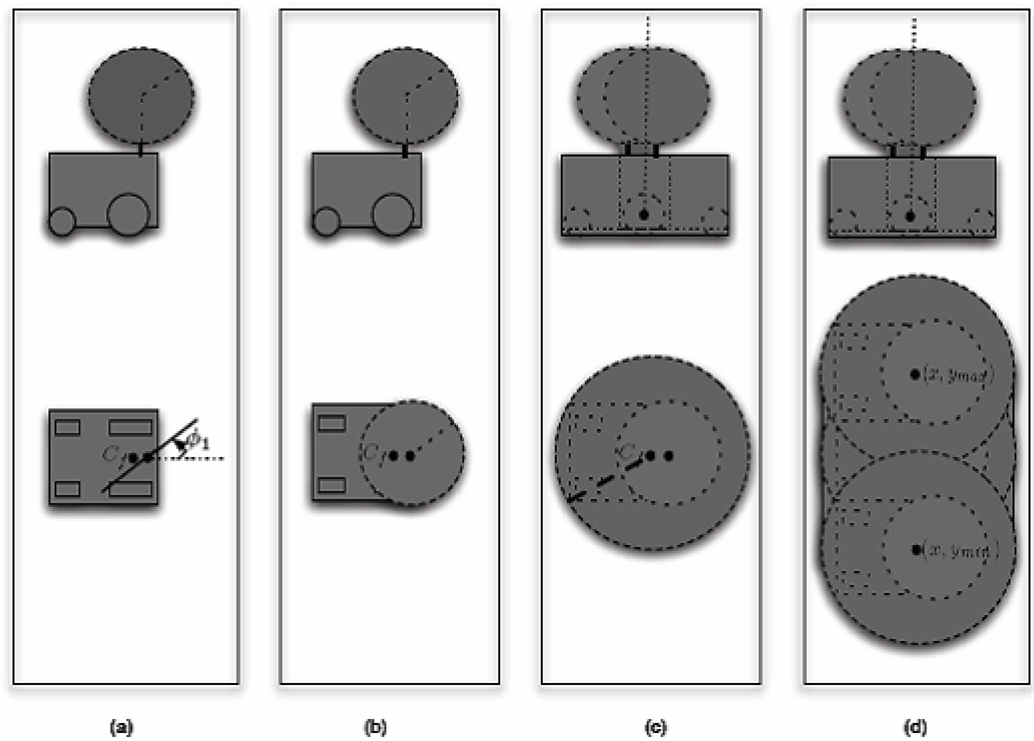

Figure 2: Representations of hierarchical occupancy. (a) $OA_c(c^4)$; (b) $OA_c(c^3)$; (c) $OA_c(c^2)$; (d) $OA_c(c^1)$.

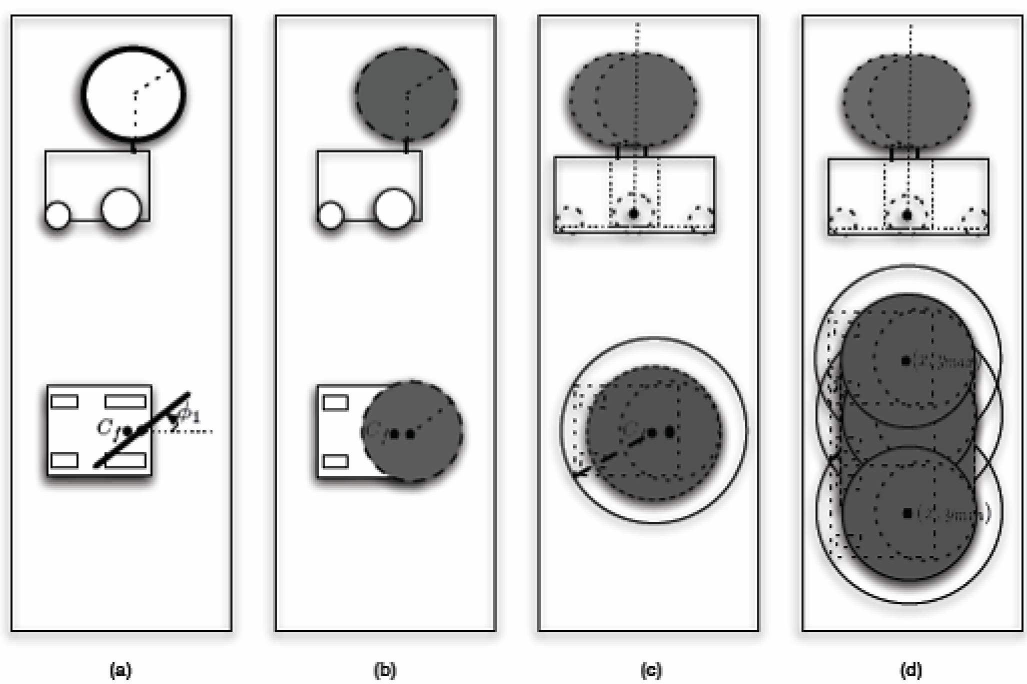

Figure 3: Representations of hierarchical reachability. (a) $RA_c(c^4)$; (b) $RA_c(c^3)$; (c) $RA_c(c^2)$; (d) $RA_c(c^1)$.

Hierarchical representations can be very complex shapes. In practice the computation of the exact hierarchical representations is time consuming and unnecessary. For occupancy estimation conservative representations of these complex shapes can provide significant computational savings. Note that the hierarchical representations of the combined robot bodies can be computed prior to the execution of the motion planner. This needs to be done only once for each DOF of the robot, independent of the robot's configuration. It is not repeated for each new planning problem. Moreover, in the domain of accessibility assessment, models of the kinematic structures are often available long before they are used for motion planning leaving opportunities for pre-computation.

The hierarchy is applicable not only to the kinematic configurations (nodes of the roadmap), and also can be applied to the paths connecting configurations. The motivation here is the different effects of $\mathcal{A}_{base}$ and $\mathcal{A}_{arm}$ discussed in the previous section. To generalize the local path to incorporate the hierarchy of states, we define a label e^r, meaning that each configuration c along edge e is associated with the same or smaller r.

4.3. Construction of the hierarchical probabilistic roadmap

We now describe the main steps of the construction of the hierarchical roadmap introduced in the previous section. Nodes with large reachable areas are preferred in the domain of accessibility assessment (they establish more of the environment as being reachable for each calculation). So for each configuration c, we look for minimum values r_{min} such that $V(c^{r_{\min}})$ is true, and we call r_{min} the rank of c. The procedure described in the pseudocode below tries to find a new random configuration and establish its most general representation in the hierarchy.

Algorithm 1 Node selection

1: $nodeFound \leftarrow false$
2: **while** $!nodeFound$ **do**
3:     $c \leftarrow$ a randomly chosen configuration in $\mathcal{C}$
4:     **for** $k \leftarrow 1$ to n **do**
5:         **if** $V(c^k)$ **then**
6:             $nodeFound \leftarrow true$
7:             break
8:         **end if**
9:     **end for**
10: **end while**
11: $N \leftarrow N \cup \{c^k\}$

In the for loop from Line 4 to Line 9, the algorithm computes the rank of the node by checking collisions of the hierarchical representations. Once the minimal valid hierarchical representation is established the minimal configuration together with the computed rank is added to the set of nodes N (Line 11).

Whenever a new hierarchical node is found, we select a number of candidate nodes from the current set N and try to connect the new node to each of them. In addition to the connection computation performed by the traditional local planner, we need to establish the rank (i.e. the minimal hierarchy) of the edge. For an edge e we look for the minimum dimension r_{min} such that $V(e^{r_{\min}})$ is true.

The hierarchical node interconnection is built upon an existing local path locator and a hierarchy establisher. The local path locator returns an edge candidate, i.e. a local path that $\mathcal{A}$ can follow from one configuration to another. Then the hierarchy establisher checks if the edge candidate is collision free and meanwhile establishes the edge's most general representation in the hierarchy. The process of establishing the hierarchical node interconnection is outlined in Algorithm 2.

Algorithm 2 Connect(a^{r_1}, b^{r_2})

1: $\tau \leftarrow$ the edge candidate returned by the local path locator
2: Discretize τ into a list of configurations $\tau' = (c_1, c_2, \ldots, c_m)$
3: $r_{current} \leftarrow MAX(r_1, r_2)$
4: **for all** $c_i \in \tau'$ **do**
5:     **for** $k \leftarrow r_{current}$ **to** n **do**
6:         **if** $V(c_i^k)$ **then**
7:             $r_{current} \leftarrow k$
8:             break
9:         **else**
10:             exit and report failure
11:         **end if**
12:     **end for**
13: **end for**
14: $E \leftarrow E \cup \{(a,b)^{r_{current}}\}$

In line 3, the hierarchy r is initialized to be the maximal value of the two ends. There is an obvious lemma according to the definition of the hierarchical edge connecting two nodes a^{r_1} and b^{r_2}:

Lemma 4: $V(e^r) = true \Rightarrow r \geq r_1 \wedge r \geq r_2$, i.e. the rank of an edge is not less than the rank of either end node of the edge.

Further details of the process of roadmap construction and workspace estimation and can be found in [27].

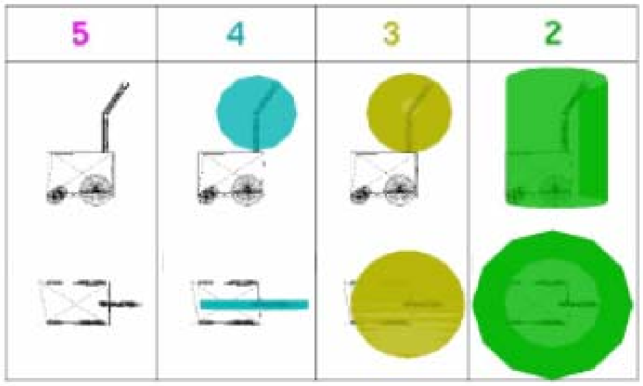

Figure 4: Representations of the hierarchical occupancy of $\mathcal{A}$ are shown in different colors. The body of the robot itself also has occupancy constraints but these are not shown.

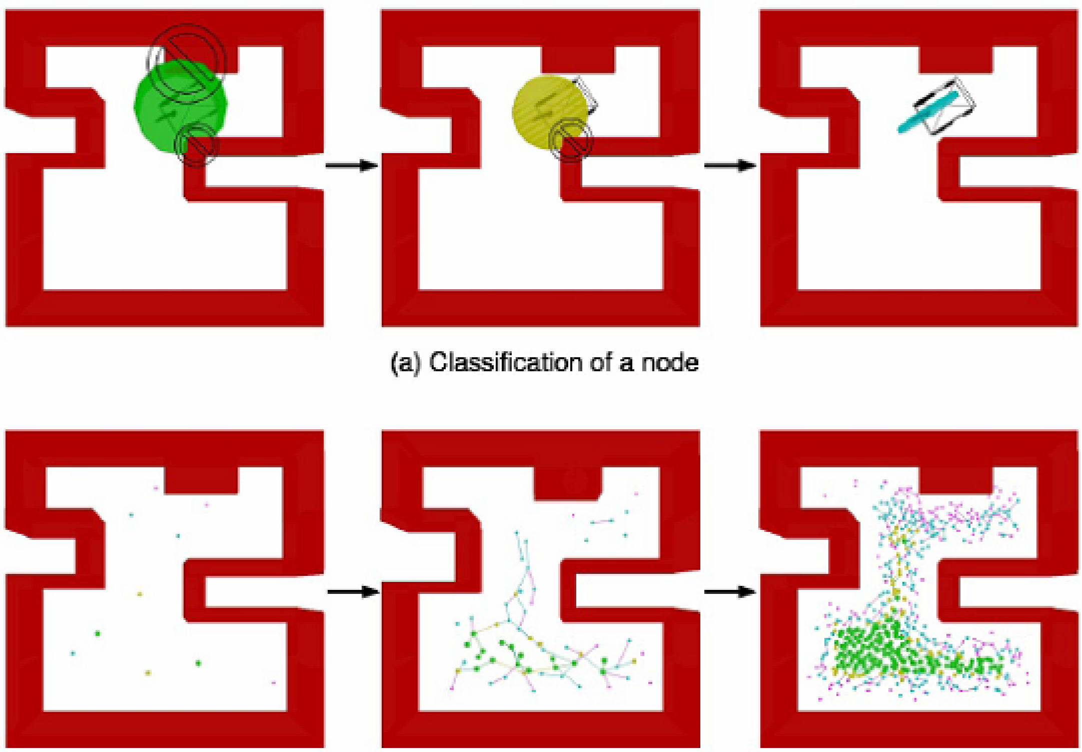

Figure 5: Construction of the hierarchical roadmap $\mathcal{R}$. The upper row shows the generation and classification of one node. The rank of a node c^r is calculated by checking the hierarchical occupancy representation of $\mathcal{A}$. Since c^2 and c^3 both introduced collision but c^4 does not, the rank of the node is set to be 4. The lower row shows the hierarchical PRM in operation. The coverage and connectivity of $\mathcal{R}$ increases as more nodes are added. Nodes in $\mathcal{R}$ are shown in different colors matching the rank of the corresponding nodes.

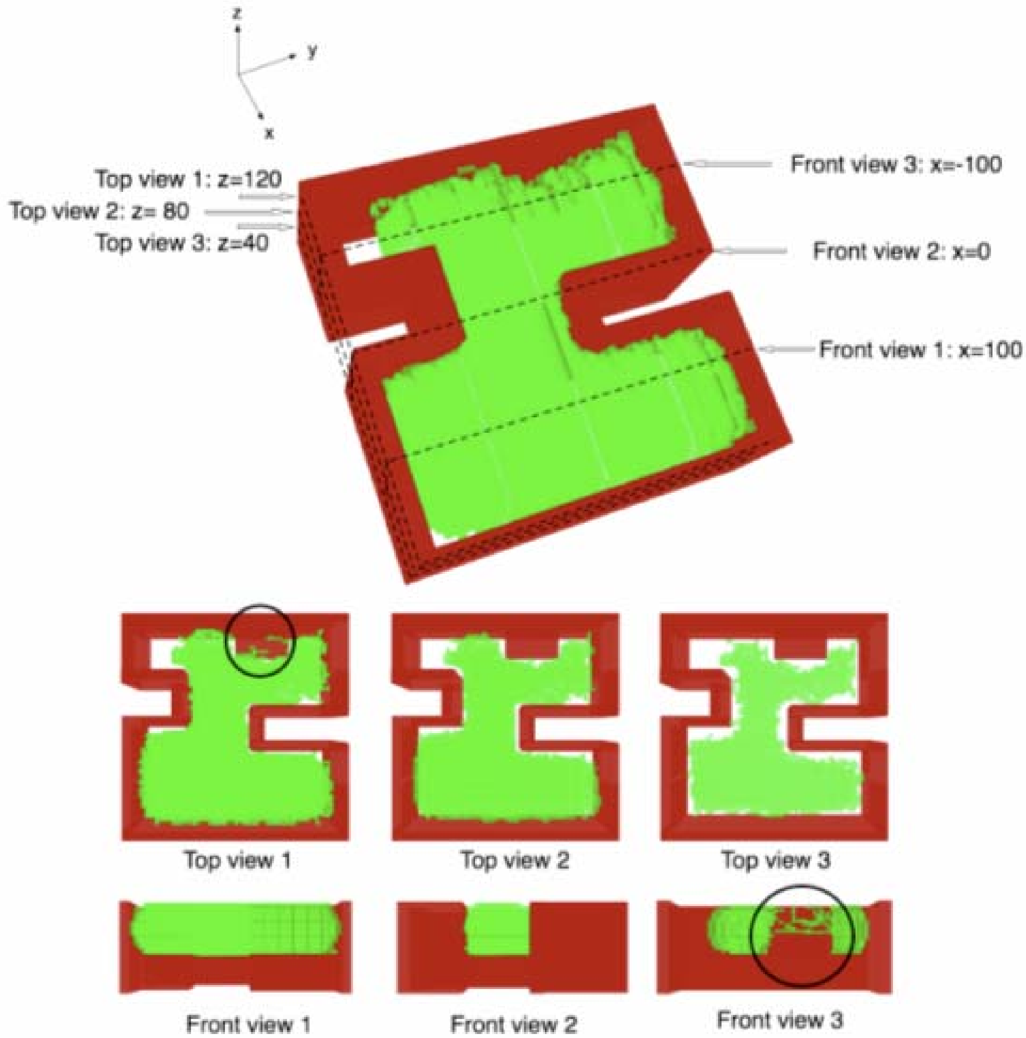

Figure 6: The estimation of the 3D reachable workspace (green area) is shown in different layers of top and front views.

4.5. An example

This section provides an example that illustrates the hierarchical strategy described in the previous section. The environment is in 3D (discretized into 64 × 64 × 25 cells) and the kinematic structure is a mobile manipulator $\mathcal{A}$. Figure 4 shows the hierarchical representation of $\mathcal{A}$, indicated by color.

Figure 5 provides details of the execution of the hierarchical PRM on this example. Initially the roadmap contains only one node that represents the initial configuration of $\mathcal{A}$. The rank of each randomly generated node is determined by looking for the most general occupancy representation of $\mathcal{A}$ that does not collide with any obstacles. Similarly the rank of each edge is determined by looking for the most general occupancy representation of $\mathcal{A}$ along the edge that does not collide with any obstacles. The top row shows tests for a randomly generated node. c^2 and c^3 generate collisions while c^4 did not, so this specific node is classified as c^4. The construction of the roadmap is incremental. The lower row shows incremental changes in the roadmap. As more nodes are added both coverage and connectivity of the roadmap increases.

Figure 6 shows the reachable workspace $\mathcal{W}_{reach}$ mapped from the constructed hierarchical roadmap. $\mathcal{W}_{reach}$ can be viewed in different layers in 3D. Some free regions are not included in $\mathcal{W}_{reach}$ but the roadmap can be enhanced to discover such regions. The user seeds a potentially unreachable region and the HPRM attempts to link these seeds to the connected graph. It is possible that the regions that are actually reachable by $\mathcal{A}$ may not be included in $\mathcal{W}_{reach}$ even after the enhancement. But such an enhancement still provides insight into the reachability analysis. In the domain of accessibility assessment, such regions can be considered as "difficult" or "unreachable" since they are difficult or impossible to reach.

This process of enhancement is illustrated in Figure 7. Before enhancement the HPRM identified the region in the upper right (marked with a "?") as unreachable. The user seeds this region and the algorithm in this case was able to link these seeds to the reachable environment thus increasing its volume.

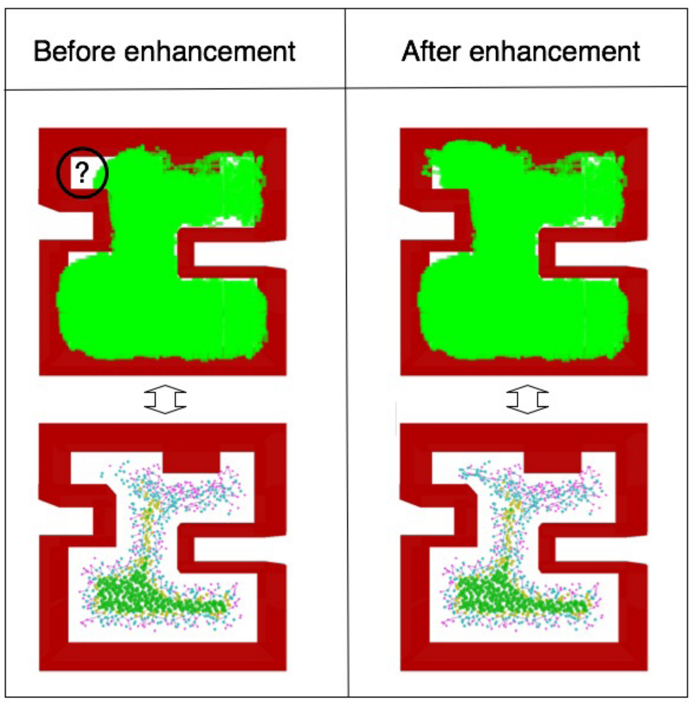

Figure 7: The enhancement phase. See text for details.

(a) (b)

Figure 8: The Pond Road Residence at York University. (a) shows an external view of the residence. (b) shows a floor plan of a student suite.

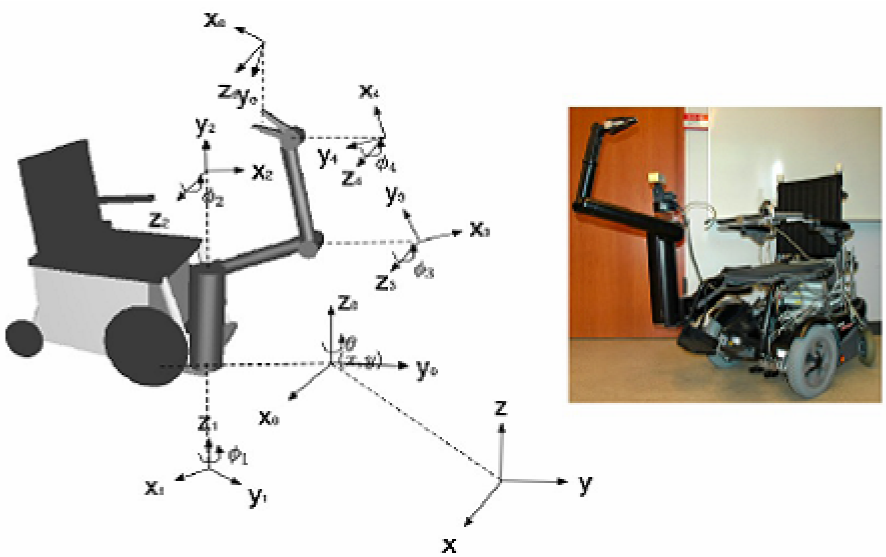

Figure 9: The PlayBot Robotic Wheelchair consists of a wheelchair-like base under differential drive and an attached manipulator.

5. A practical assessment

This section presents an experimental application of the methodology for accessibility assessment presented in the previous section. We evaluate the methodology using a wheelchair robot model and a typical living environment (Figure 8). The goal of this testing is to demonstrate the motion planner's ability to estimate the reachable workspace.

5.1. Experimental setup

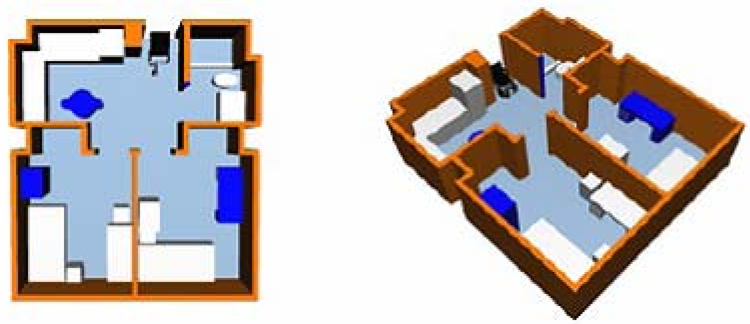

Figure 10: A 3D model created based on the standard suite in the Pond Road Residence. $\mathcal{A}$ is placed initially at the entrance of the residence. For purposes of the evaluation performed here the three pieces of furniture (colored in dark blue) will not be considered in performing accessibility assessment.

To perform the experiments of our algorithm we require a kinematic model of the wheelchair and user and an environmental model.

Kinematic model: In the experiments, the kinematic model $\mathcal{A}$ was developed based on the PlayBot Robotic Wheelchair [24] shown in Figure 9. The wheelchair base $\mathcal{A}_{base}$ is powered by the front wheels using a differential drive. The attached kinematic chain $\mathcal{A}_{arm}$ has four revolute joints with no limit on the angles that these joints can make. This is a 7-DOF vehicle. The configuration of $\mathcal{A}$ is written as an ordered vector $(x, y, \theta, \varphi_1, \varphi_2, \varphi_3, \varphi_4)$, where (x, y) is the position of the center of the front wheels in a global coordinate system, θ is the angle that the vehicle's main axis makes with the positive x-axis, and $\varphi_1, \varphi_2, \varphi_3, \varphi_4$ are the corresponding angles of each link of $\mathcal{A}_{arm}$.

Environment: The environment assessed for accessibility is a two-bedroom suite in the Pond Road residence at York University (see Figure 8). The Pond Road residence was opened in September 2004 and is home to approximately 430 undergraduate students. Among the 14 student residences at Keele campus the Pond Road residence is the newest one. Figure 10 shows the 3D model of this environment and the furniture is represented by simple polygon structure. Assume the doors are absent and there is furniture in the rooms.

5.2. Implementation details

Choosing c_{init}: The size of the computed $\mathcal{W}_{reach}$ depends on the part of the roadmap that is connected to the initial configuration c_{init} of $\mathcal{A}$. Let the wheelchair robot be placed initially at the main entrance of the residence as shown in Figure 10. This is a reasonable assumption -- the front door of the unit must be accessible.

Local planner: There is tradeoff between completeness and efficiency in the choice of local planner and a fast and deterministic local planner is commonly preferable. Concerning the kinematic model of the wheelchair and its user, we choose a local planner that can be applied generally to a mobile vehicle with a manipulator. The local planner is divided into two parts, planning for the base and planning for the manipulator. A simple straight line local planner for the manipulator which has been widely used in the PRMs for holonomic robots [12] was chosen. The method connects two given configurations by a straight line segment in configuration space and checks this line segment for collision in the workspace. Planning for the mobile base is more complex due to the existence of non-holonomic constraints. A simple and deterministic planner was implemented as a concatenation of a rotation, a straight line and another rotation. The edges that are computed by the local planner during the construction step do not need to be stored since they can be quickly recomputed.

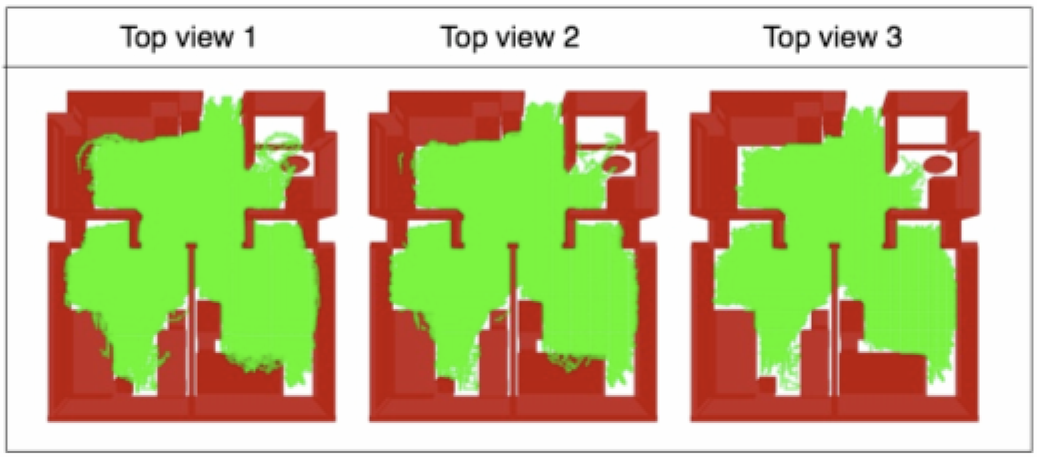

Figure 11: Views of $\mathcal{W}_{reach}$ (at different heights) computed from the hierarchical roadmap. $\mathcal{W}_{reach}$ is represented using uniform cell decomposition.

5.3. Reachable workspace estimation

Given the kinematic model and the environmental model, Figure 11 shows the reachable workspace mapped from a hierarchical roadmap that contains 2000 nodes. It shows that the bathroom is only reachable at higher elevations as the wheelchair cannot enter the stall. There are also regions in the lower left and lower right portions of the environment which clearly present problems for reachability. The workspace $\mathcal{W}$ is represented using uniform cell decomposition (discritized into 42 × 42 × 20 cells). The computation runs approximately 30 seconds on PC. As more nodes are generated, the covered workspace as well as the running time increases.

6. Summary and future work

This paper investigated accessibility assessment of an environment using advanced planning methodologies. The methodology depends on an efficient motion planner which can be generally applied to any kinematic structure including wheelchair users and other users requiring mobility assists such as walkers. The motion planner is based on a PRM, which uses a hierarchical strategy to maximize the reachability of each configuration. Unlike traditional PRMs and most of its variants, which treat the DOF of the kinematic structure equally, the planner developed in this paper applies a hierarchical strategy in the construction of the probabilistic roadmap in C_{free}. This approach makes the PRM particularly useful for accessibility assessment.

This hierarchy exploration improves the planning process through two critical computations. First, it accelerates collision detection in open regions by approximating the robot using a conservative occupancy analysis. Validation of the configuration begins by doing fast tests on simple representations and only progresses to more accurate (and more expensive) evaluations as necessary. As for reachability analysis, because randomness is involved it is hardly possible to estimate the size of the entire reachable workspace by mapping from the PRMs within reasonable time. However, by iteratively computing the maximal reachable workspaces from each node and edge the hierarchical PRM can be more effective in the computation process than traditional PRMs.

Ongoing work is exploring a more sophisticated definition of reachable workspace that involves establishing the number of configurations from which the kinematic structure can reach a given location. This may provide insight into different levels of accessibility. A space that is reachable from many different directions and locations should probably be considered more accessible than one with just a few. Finally, although the authors have given demonstrations of the tool to occupational therapists and wheelchair users and received positive feedback, a systematic user study of the usability of the tool should be performed. The current developed tool provides a visual display for the user to assess accessibility, but more quantitative results are desired.

Acknowledgements. The financial support of NSERC Canada is gratefully acknowledged.

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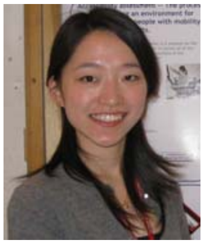

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