Automated Generation of Indoor Accessibility Information for Mobility-Impaired Individuals

Nemanja Kostic and Simon Scheider

Abstract One important issue in developing assistive navigation systems for people with disability is the accuracy and relevancy of the systems' knowledge bases from the perspective of these special user groups. The theory of affordances coupled with computer-based simulation offers a solution for automating the extraction of the relevant information from readily available sources - architectural floor plans. Simulation of movement in a wheelchair can be used to compute the accessible space of an indoor environment by comparing the degree of match between geometrical demands of navigation and the relevant physical properties of the environment. We also investigate what constitutes the right level of representation of the environment and adopt the grid graph model as suitable both for accessibility computation and for deriving higher-level networks of places and their connections that facilitate orientation and user-system interaction.

Key words: building accessibility; affordance simulation; grid graph; user relative navigation support; people with disability

1 Introduction and Motivation

The spatial decision-making process of people with disability can be facilitated by building assistive navigation systems offering access to environmental information that would otherwise either be out of reach or acquirable

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at the expense of much effort and frustration. Historically, such navigation systems have overwhelmingly dealt with outdoor environments since precise localisation techniques (such as GPS) were only available outside. However, recent developments in sensor-based positioning and ubiquitous computing have extended these efforts indoors [2]. Indoor spaces pose their own unique obstacles for attempts to develop successful navigation aids; one such challenge is the availability of navigationally relevant information, especially for architecturally complex buildings.

The type of disability - motor, visual, auditory, cognitive - plays a crucial role in determining the precise contents of an assistive system's knowledge base. To focus our research, we consider an example scenario of a wheelchair user planning a visit to a large public building. Here, the most critical piece of information concerns accessibility: to what extent the indoor environment allows the user to move between indoor locations of interest, and what are the optimal ways to do so.

When information on accessibility is not readily available, we should find a way to obtain it in an exhaustive, reliable and relatively simple way. A common way to assess the accessibility of an environment is to do a survey while making note of potential obstacles for movement (presence of stairs/ramps, ramp slopes, etc.). This raw data can be compared to established criteria for accessibility assessment (such as legally defined guidelines for the design of public buildings; see for example [16]); in this way, accessibility is determined *in situ* and later entered as annotation into a computer model of the environment for use in navigation systems or further analyses. The process is relatively easy to perform (though not always to manage), but also time-consuming and marked by uncertainty: it cannot guarantee exhaustiveness and is often dependent on subjective assessment.

Automation of accessibility assessment has been suggested in research on public transportation planning [13, 14] and ergonomics in the workplace [6]; how to go about this task in the context of assistive indoor navigation systems is the focus of this paper. We propose a method to compute the user-relative accessible space of an indoor environment as well as a set of accessible paths between indoor places. We also discuss the right level of representation of the indoor environment to serve as input for the computation, and opt for one that preserves detailed geometrical properties of the environment while simultaneously allowing a straightforward extraction of a network of accessible places and their connecting paths.

The next section presents previous work related to our goal, before we turn to the specifics of the proposed methodology of accessibility information extraction, a use case of a real-world indoor environment and finally a discussion of open questions and possible ways of integrating the resulting information into different types of navigation systems.

2 Discussion of Related Work

2.1 Affordances

Each kind of disability has its own distinctive effects on navigation in space. One valuable attempt to theoretically model this interdependence of individuals' capabilities and the environment they act in has been made with the theory of affordances. Gibson introduced the idea of *affordance* as opportunity for action offered by the environment: different objects or their constellations are suitable for different types of use, and humans and other animals can perceive and act on these opportunities [10]. In this way, the environment takes on meaning, in the sense that it carries information that can guide behaviour [24]. This role of affordances in cognitively modelling human navigation has been discussed, modelled and tested using computer simulation in [18, 19, 21]. To say that there is an interdependence between these action potentialities and the acting entities means that an affordance is what it is only in relation to a specific kind of agent. A person in a wheelchair faced with a flight of stairs "perceives obstacles where other people just perceive a step they can climb" [17]. For any customised information system, modelling the environment in terms of affordances offers "an experiential view of space, because they offer a user-centred perspective" [20].

2.2 Situated Simulation

What determines the existence of an affordance? The agent-environment complementarity that the notion of affordance models entails that an affordance can be assigned to an object only when a potential action exists that includes the object [24]. Recent developments in cognitive science hint in the direction of action-dependent meaning as well. Barsalou refers to ad-hoc grouping of environmental objects based on their usefulness for the action being planned or executed; in this way dynamic categories arise, such as 'things to stand on' when one is working out a strategy for replacing a lightbulb on the ceiling. This judgement of usefulness of an object depends on mentally performing - i.e. simulating - the action on the object and relies on the object's affordances being encoded in our concept of the object: concepts are toolboxes for action [4, 5]. Building on this, Scheider proposed to ground affordances as perceivable potential events - successful simulations of actions generated while processing environmental input [25].

Experiments have shown that not only are people very good at correctly judging objects in this way, but that this process can be quantified as well. Warren's trials resulted in a numerical value that determined the existence of the affordance of *climbability* of a flight of stairs: a person will perceive the stairs as affording the action of climbing if the ratio between his/her leg length and the stairs' riser height does not exceed 0.88 [28]. Except for simple cases, however, body scales are not enough to solely explain the perception of affordances, because they cannot fully capture what one can do - one's abilities, or functional properties [8]. A paralysed individual's leg length may be the same as that of an able-bodied person but the environment's climbability affordances are drastically different for the two of them.

Two main insights of the work on the emergence of affordances are relevant for our goal. Firstly, treating affordances as agent-action-environment relations means that a record of properties of an environment cannot be equated with a description of its affordances - these emerge only when concrete actors and actions enter into the equation. Furthermore, the set of affordances of a certain environment for a certain action can be derived by situated simulation of the action, where situatedness refers to its grounding in concrete agent-side constraints, and simulation to the possibility of determining the affordances independently of the action being actually performed.

2.3 Automated Mobility Affordance Assessment

The idea of automating the task of obtaining environmental information meaningful for navigation appears in [14]; it is further elaborated in [13]. The authors propose a computer-based "translation of selected environmental attributes [of public park paths] into a scaled suitability value for individual mobility" as an alternative to subjective or rule-of-thumb affordance determination. *Suitability* refers here to an extension of the concept of affordance beyond simple (im)possibility of action to include different levels to which an action can be afforded by an object. For example, a ramp may in principle afford movement to many people but will demand different amounts of effort from each of them, which may significantly influence their spatial decision making.

In a related application area, computer simulation was suggested in [6] to assess the ergonomic quality of workplaces using 3D virtual reality techniques. A wheelchair user was modelled based on statistical data on maximal arm reach to identify zones out of reach of the user and assess the need for a rearrangement of the work environment. A similar goal drove the development of the HADRIAN database and SAMMIE simulation environment; these encompass not only the specific needs of disabled individuals but also the effects of age and/or difference in body scales, thereby allowing increasingly fine adjustments of environments to individual needs [11].

2.3.1 The Environment

To determine the degree to which an an environment affords basic mobility - the environment's accessibility - we must focus on those of its features that enable or impede movement; when the task is being automated, we are immediately faced with the question of choice of an adequate input spatial model, since this will determine the amount and type of environmental features on which to run the analysis. [13, 14] opt for a network model that represents park paths as edges and their intersections as nodes, with navigationally relevant properties such as length or slope - and consequently the resulting suitability values - aggregated on path level.

When we deal with an environment where movement is restricted to clearly delineated objects such as paths in a park, this aggregated approach is justified: mobility affordances can be understood as properties of individual paths. However, in indoor environments such as halls or rooms there are not always obvious paths: such spaces appear not to be discretised into networks but rather exhibit continuity and are better described as scenes [23]. As noted in [27], pedestrians are in general not constrained to linear routes like vehicles are: to exhaustively model indoor movement using a network we would have to identify all possible paths between all possible pairs of destinations, ending up with huge networks even for moderately complex indoor environments.

It is clear then that aggregating environmental properties into discrete objects is not an optimal solution for indoor accessibility assessment. If one can move between two locations in a room, which of the many possible paths between them is the affordance bearer? Selecting one of them arbitrarily would imply unjustified 'gerrymandering' (to borrow a phrase from Lewis as quoted in [24]), whereas modelling each one explicitly is very difficult. In an indoor environment, mobility affordances are better thought of as attributes of the continuous space itself, and only after accessibility has been assessed on the level of the continuous geometry of obstacles and free space can we start breaking down the environment into destinations (which is quite arbitrary below the level of obvious architectural units such as rooms or corridors) and paths between them. For accessibility analysis, therefore, we need an input spatial model preserving the continuity of space.

2.3.2 The Agent and Its Activity

The other side of the affordance relation comprises agent-side properties; which among these are relevant in determining environmental affordances depends on the action in question. As we have seen, body scales are just a stand-in for what one can effectively do, and not always a good one at that; is there another way to encode ability? The procedure presented in [13, 14] builds on the idea of affordances as ratio values as outlined in section 2.2: different levels of various factors of motor ability are expressed numerically and then set against the corresponding physical properties of the environment in order to quantify suitability.

Another way to quantify motor ability is hinted at in [2]. The authors propose a spatial model for indoor navigation that consists of three levels: spatial, feature and action. Whereas the spatial level captures continuous geometric information on indoor environments, the feature level explicitly models objects (mobile and static). One important set of attributes of an object consists of its interaction spaces, which capture the different spatial extents needed to perform actions that include the object ("operational space"). We can use such interaction spaces as a way to derive mobility affordances by simulating actions.

2.4 Space and Place in Indoor Navigation Systems

The basic functions of indoor navigation systems comprise user localisation, path planning, directions derivation and provision of information on surrounding objects [9]. These services rely on two broad categories of spatial knowledge encoded in navigation systems: geometric and semantic, where the former models space as a continuous field while the latter decomposes space into places - chunks of space to which human-readable descriptions are attached (e.g. "You are in *the entrance hall.*"), making it better suited to user-system interaction [3, 22]. As seen, spatial geometry determines some environmental affordances; how affordances may combine to determine the place structure of space is discussed in [26].

Looking back at our hypothetical scenario, what is sought is information on the extent to which the building's space offers basic mobility to the user, while asking for answers in terms of the building's places (e.g. "Can I - and what is the easiest way to - get from the entrance hall to room 3?"). This twofold perspective on environments - space vs. place, geometry vs. semantics (also: continuity vs. topology [15]) - is an integral part of accessibility assessment when its final goal is its use in navigation systems. It appears that there are conflicting demands on the input model for our procedure: it should be both non-network (continuous) and network (discrete/place-based). A model that captures environmental properties in a way that fits both descriptions is discussed in section 3.2.

3 Discussion of Methodology

In this section we propose a methodology to automatically extract accessibility information on indoor environments for use in assistive navigation systems, focusing on the case of wheelchair users. We start with a widespread and readily available information source on indoor spaces - architectural floor plans in CAD format - as a sufficient record of environmental properties for accessibility computation. Integrating the insights presented in [13, 14], [6] and [2], we propose to derive an indoor environment's mobility affordances for a wheelchair user by simulating his/her movement in space. This is done by matching the geometrical constraints of actions involved in moving in a wheelchair with the geometry of obstacles in the environment. Proceeding from this accessibility assessment at the level of environmental geometry we then derive a set of optimal paths between places in the environment. The way we conceptualise agents, their movement and the environment is explained in the following subsections, before we outline the procedure itself.

3.1 Modelling the Agent and Action

We propose an algorithm for mobility affordance derivation that performs an exhaustive analysis of an indoor environment for the possibility of movement. To do this, we discretise continuous path taking into a set of moments; at each moment the moving agent occupies a particular location in space while performing what we term a *movement primitive*: the agent either simply fits into the space - only to move at the next moment to the adjacent location in the same direction - or takes a turn in order to change direction.

At each (non-obstacle) location, then, we test for two conditions: first, with the agent's centroid at the location, whether the surrounding space affords simple fit; second, whether it affords unobstructed spinning so that turns can be made. The two tests rely on three agent-relative movement constraints: the geometries of fit in the $x-$ and $y-$direction, and spinning, with the latter implying the other two. These geometrical constraints depend both on body scales as well as any additional equipment necessary for movement, such as a wheelchair or walking stick. They have been extensively studied and have entered national guidelines for the design of indoor spaces: German DIN 18024-1 standard ([1]) provides useful quantifications (Fig. 1a, b).

If both conditions hold, we say that the location affords full possibility of movement; if only the former is true, the location is a potential point on a path but affords no turns - movement can only proceed straight ahead in the $x-$ or $y-$direction (provided, of course, that the adjacent location itself affords fit). What we obtain in this way is a network of locations with turn restrictions, suitable for routing; we term the set of all such locations *occupiable space* and the corresponding network *accessibility graph*.

The effect of running the tests at each location is similar to running vast numbers of agent-based simulations between pairs of locations, requiring however less time, generating no noise and, most importantly, providing exhaustiveness. It models the possibility of movement in the simulated space without reference to any individual paths: unlike agent-based simulations, mobility af-

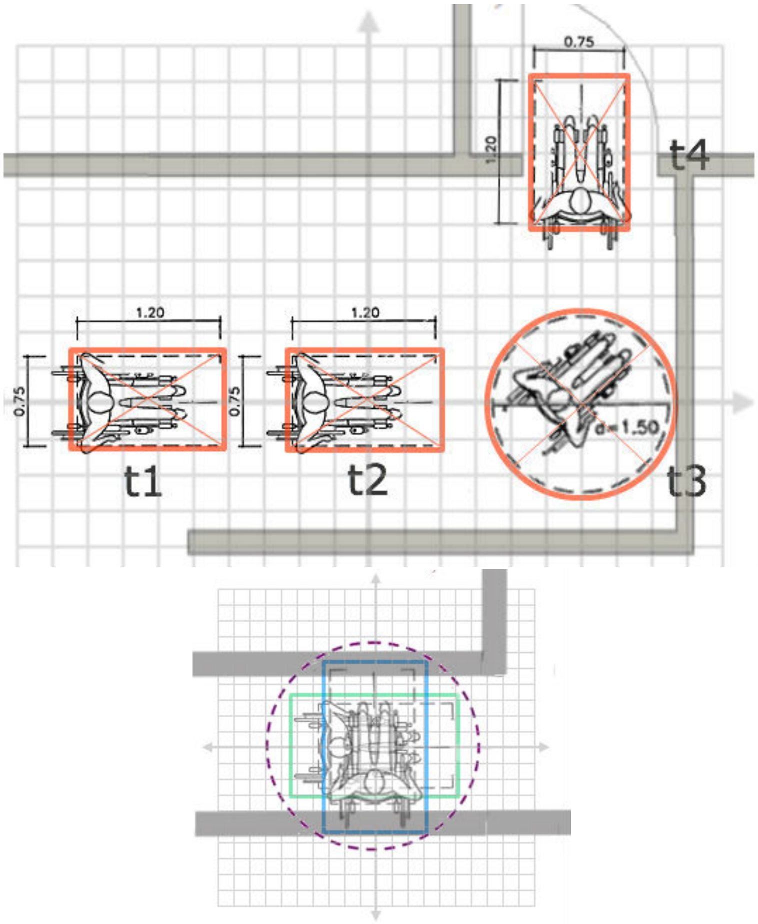

Fig. 1 a. Path taking can be thought of as a collection of discrete moments t_n b. Movement primitives geometry: x-direction fit (green), y-direction fit (blue) and spinning (violet; based on DIN 18024-1); within this layout of obstacles (grey), only x-direction fit is afforded

fordances do not emerge here as a result of executing (virtual) path taking but as a possibility for it. Furthermore, continuous testing across space is in accord with the conclusion that in indoor environments mobility affordances are better thought of as attributes of the continuous space itself rather than any one environmental object.

3.2 Modelling the Environment

Referring to the discussion in section 2, there are conflicting demands on our input spatial model: it should preserve the continuity of the indoor geometry yet either incorporate or enable the derivation of network-based descriptions of the environment and the running of network-based analyses. The various required conceptions of space as inputs and outputs for our analysis are shown in Fig. 2.

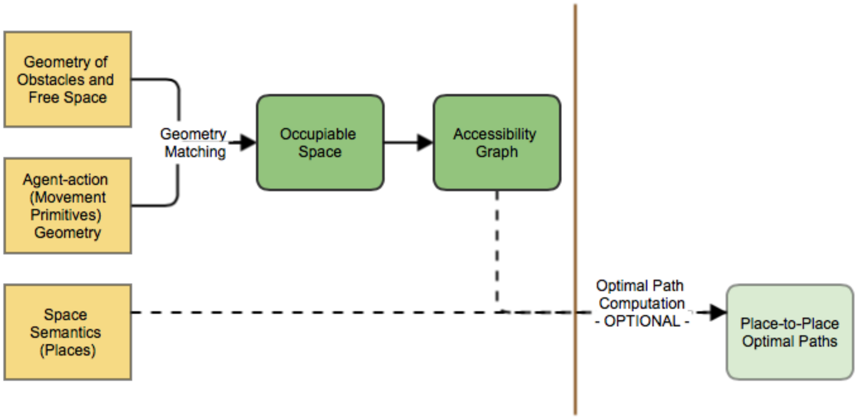

Fig. 2 Spaces as input (yellow) and output (green) of accessibility analysis

Our search for an adequate spatial model is guided by the comparative review presented in [3], as well as the procedure outlined in section 3.1. The geometry of obstacles can be captured with precision in a CAD model; however, its lack of the explicit encoding of empty space prevents easy action-environment geometry matching necessary to compute occupiable space. Moreover, standard network-based analyses such as optimal paths computation cannot be run on CAD models. The issue of continuous coverage of the indoor space can be resolved by using cell-based models (tessellations); additionally, these implicitly model spatial adjacency. This is crucial in our case: to establish the possibility of movement between locations by only testing the locations themselves for mobility affordances, we must ensure that locations - cells - adjacent in the model represent locations adjacent in reality.

We decided that a regular tessellation (grid) lends itself best to our method. While irregular cells in general capture the geometry of obstacles with more precision (as cell borders can trace non-orthogonal shapes), they also have an important drawback from the perspective of our goal. To test locations (cells) for movement affordances as described above, at each cell different neighbourhoods of $i * j$ surrounding cells model the agent-relative geometries of fitting in space and spinning. A straightforward automation of the testing procedure asks for a uniform cell size across the modelled space so that these action geometries can be consistently compared against the environmental geometry. One drawback is that non-orthogonal elements can only be approximated; the finer the granularity, the better the approximation.

To allow routing on the derived occupiable space, we propose to use the idea of the grid graph as outlined in [15]. The grid graph model starts from a regular tessellation of an environment and then builds a base graph on top of it by treating each cell as a network node and the connections between it and the adjacent cells as edges to which weights are attached. In this way it offers the analytical advantages of network representations while retaining the continuity of the environmental geometry. Another welcome feature of the grid graph model is that it stores the semantics of the environment by labelling each node with membership in a named architectural unit (place); the structure of places is modeller-specified. In this way place-based graphs of various levels of abstraction can be derived from the base graph.

Modelling the geometry of obstacles to movement requires a working definition of obstacle. These usually refer to architectural barriers - walls and ceilings - but an advantage of a continuous spatial representation is that fixtures and furniture too can be explicitly modelled. In this way a very precise computation of accessible space is possible: taking as an example our use case of a public library, the stack areas can be tested and fine routing performed on the resulting occupiable space.

Our procedure as outlined below is constrained to two-dimensional space. To take into account differences in the height coordinates of cells and the restrictions to movement in a wheelchair that this can cause, stairs and ramps were treated as obstacles from the outset, with the cells belonging to those areas excluded from the occupiable space computation.

To settle the issue of optimal grid resolution, we performed a comparative analysis of three different resolutions in our use case (section 4) and compared them to the CAD source to determine how the difference affects the resulting occupiable space. This calibration of grid resolution would have to be performed for each environment being analysed.

3.3 Accessibility Assessment: Procedure

The outlined procedure was implemented in the TerraME modelling environment [7], with the conversion from CAD to tessellation done via the TerraView GIS. TerraME's CellularSpace class implements the grid graph idea by allowing the explicit modelling of connection weights between adjacent grid cells so that network analyses can be run on it. The algorithm runs in linear time O(n) for all outlined steps, with n being the total number of grid cells.

Table 1 Symbols Used in Pseudocode

g	grid granularity
Q	set of all grid cells
$createNeighborhood(a1, a2)$	TerraME function assigning to each cell in a set (a1) an array of pointers to cells based on a neighbour selection strategy (a2); here, a cell is selected as neighbour if it is one of the $(i/g) * (j/g)$ surrounding cells
$i * j$	dimensions of an agent-relative movement geometry
O_x, O_y, O_s	occupiable spaces (sets of occupiable cells) for each movement geometry
$state[c]$	cell c's membership in obstacle/empty space
$N_\mathrm{x}[c]$, $N_\mathrm{y}[c]$, $N_\mathrm{s}[c]$	cell c's neighbourhood arrays modelling movement geometries; results of $createNeighborhood()$
$occupiability_\mathrm{x}[c]$, $occupiability_\mathrm{y}[c]$, $occupiability_\mathrm{s}[c]$	attribute describing cell c's occupability: one *occupiability* attribute for each movement geometry
$x[c]$, $y[c]$	cell c's x- and y-coordinate in the grid
O	total occupiable space (union of O_x, O_y and O_s)
$Von\ Neumann\ n'hood$	the four cells orthogonally adjacent to a cell in a 2D grid
$weight[c, n]$	weight of an edge (connection between cell c and a Von Neumann neighbour n)

STEP 0. Convert the CAD files into a grid with granularity g; g should be divisible without remainder into the dimensions of agent-relative movement geometries (fit and spin), so that the geometries can be represented by whole numbers of cells. Unnecessary information should be manually removed from the CAD source so that all that remains are obstacles represented as polygons; it is then converted to a shapefile and finally to a tessellated representation (we used TerraView GIS for the final step as it offers a straightforward conversion procedure).

Each cell belongs either to empty space or an obstacle; this membership value is stored in the cell's *state* attribute. If a cell contains both obstacles and empty space its membership value is decided based on their ratio - if non-empty space comprises 50 percent or more of the cell's area it is counted as part of obstacle space.

STEP 1. For each agent-relative movement geometry (x- and y- direction fit and spinning), assign the cells modelling it to each grid cell by creating a neighbourhood around the cell, for testing in step 2.

```
STEP 1
  function ASSIGNMOVEMENTGEOMETRIESTOCELLS($Q$)      ▷ for each cell, create three neighbourhoods
                                                     ▷ modelling the three movement geometries
      $createNeighborhood(Q, (i_\mathrm{x} * j_\mathrm{x})/g^2)$    ▷ $x$-fit: $i_\mathrm{x}$ = 120 cm, $j_\mathrm{x}$ = 75 cm
      $createNeighborhood(Q, (i_\mathrm{y} * j_\mathrm{y})/g^2)$    ▷ $y$-fit: $i_\mathrm{y}$ = 75 cm, $j_\mathrm{y}$ = 120cm
      $createNeighborhood(Q, (i_\mathrm{s} * j_\mathrm{s})/g^2)$    ▷ spinning: $i_\mathrm{s}$ = 150cm, $j_\mathrm{y}$ = 150 cm
```

STEP 2. For each agent-relative movement geometry, compute the respective occupiable space. To do this, test at each cell whether all the assigned cells modelling the movement geometry belong to empty space; if so, the cell is labelled occupiable and added to the occupiable space. The pseudocode below shows the computation for x-direction fit; the procedure is identical for the other two movement geometries.

```
STEP 2
function getOccupiableSpaceXDir($Q$)
    initialise $O_{\mathrm{x}}$ as empty set
    for each cell $c$ in $Q$ do
        if $state[c] = EMPTY$ then
            for each cell $n \in N_{\mathrm{x}}[c]$ do
                if $state[n] = EMPTY$ then
                    $count \leftarrow count + 1$
            if $count = size(N_{\mathrm{x}}[c])$ then                $\triangleright$ $size(N[c]) = (i * j)/g^2$
                $occupiability_{\mathrm{x}}[c] \leftarrow OCCUPIABLE$
                add $c$ to $O_{\mathrm{x}}$
    return $O_{\mathrm{x}}$
```

STEP 3. Construct the accessibility graph on the total occupiable space by instantiating connections (edges) between occupiable cells (nodes). Each occupiable cell is connected to those of its orthogonally adjacent cells (i.e. cells comprising the cell's Von Neumann neighbourhood) towards which movement is afforded. This is established depending on the types of occupiability of both current and adjacent cell as well as the adjacent cell's location relative to the current cell. For example, based on the limitations of moving in a wheelchair, if a cell affords fit in the x-direction only (no spinning afforded), movement can only proceed in a straight path - that is, to an adjacent cell with the same y-coordinate, and only so if it too allows (at least) fit in the x-direction. Since movement was modelled for the x- and y-directions only, diagonally adjacent cells are not considered when constructing the graph; the encoded turns are therefore 90-degree. Each possible connection is assigned a weight equalling grid granularity g; impossible connections carry very high weights to avoid routing through them.

4 Case Study: ULB

As a test case, we dealt with the university and state library (Universitäts- und Landesbibliothek, ULB) in Münster. In this chapter we shortly discuss the results.

A preliminary occupiable space computation for a section of the ULB was performed on grids with granularity 5, 7.5 and 10 cm respectively (Fig. 3). A comparison to the CAD source revealed that while there was virtually no

```
STEP 3
  function constructAccessibilityGraph($O$)
      for each cell $c$ in $O$ do
          if $occupiability_s[c] = OCCUPIABLE$ then                    ▷ spinning at $c$ possible
              for each Von Neumann neighbour $n$ of $c$ do
                  if ($x[n] = x[c]$ and $ocupiability_y[n] = OCCUPIABLE$) or ($y[n] = y[c]$ and $ocupiability_x[n] = OCCUPIABLE$) then
                      $weight[c, n] \leftarrow g$                       ▷ weight is equal to grid granularity
                  else
                      $weight[c, n] \leftarrow infinity$                ▷ any very large value
          else if $occupiability_x[c] = OCCUPIABLE$ then               ▷ fit in the $x$-direction at $c$ possible
              for each Von Neumann neighbour $n$ of $c$ do
                  if $y[n] = y[c]$ and $occupiability_x[n] = OCCUPIABLE$ then
                      $weight[c, n] \leftarrow g$
                  else
                      $weight[c, n] \leftarrow infinity$
          else if $occupiability_y[c] = OCCUPIABLE$ then               ▷ fit in the $y$-direction at $c$ possible
              for each Von Neumann neighbour $n$ of $c$ do
                  if $x[n] = x[c]$ and $occupiability_y[n] = OCCUPIABLE$ then
                      $weight[c, n] \leftarrow g$
                  else
                      $weight[c, n] \leftarrow infinity$
```

difference between the former two in correctly identifying overall accessibility, the latter rendered some accessible door spaces inaccessible: the coarser resolution meant that some empty space was lost in CAD-grid conversion by ending up in cells mostly comprised of obstacle space (since the conversion used percentage of total area as the criterion in assigning each cell to empty vs. obstacle space). Only a few centimetres lost, however, meant that the constraints of action (passing through) were no longer satisfied. In order to balance geometrical precision with performance (significantly fewer cell count), a resolution of 7.5 cm was chosen for the subsequent analysis.

As a general rule of thumb one should consider that the standard minimum door width for unobstructed wheelchair movement according to the norm [1] is 80 cm, and that it is particularly important to make sure the space of doors of this width is identified in the computation as allowing movement. As explained in step 0 above, in the process of conversion of a CAD source the overlay of the source with a grid of cells inevitably results in some loss of otherwise empty space in cases where a cell covers an area consisting of both empty and non-empty space. In the worst-case scenario a door width of 80 cm can be overlaid in such a way that both doorjambs end up in cells assigned to obstacle space. With a 10 cm-grid up to 10 cm of empty door space can be lost (5 cm on each side) and the door would subsequently not be identified as a valid link; with a 7.5 cm-grid the largest possible loss is only

5 cm (3.75 and 1.25 cm on both sides in the worst case, respectively), which still makes it possible for our algorithm to capture it as a valid connection.

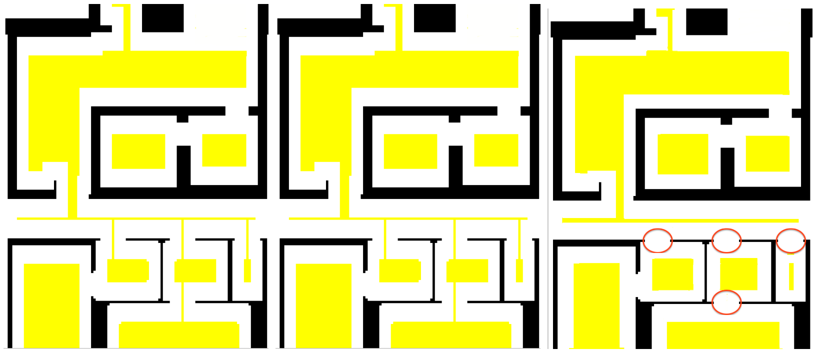

Fig. 3 Occupiable space depending on grid resolution (yellow): a. 5 cm, b. 7.5cm, c. 10cm; red circles mark existing connections lost due to lower granularity

Fig. 4 shows the different ways in which locations (cells) can afford mobility. An agent can simply fit into the surrounding space (in the x- or y-direction) or the full possibility of turning can be afforded. All three subsets of the overall space are needed to model movement and routing algorithms have to take into account the resulting turn restrictions. Fig. 5 shows a shortest path computed using a Dijkstra algorithm. Turns can only occur at those cells that have come out from the occupiable space computation as allowing turns.

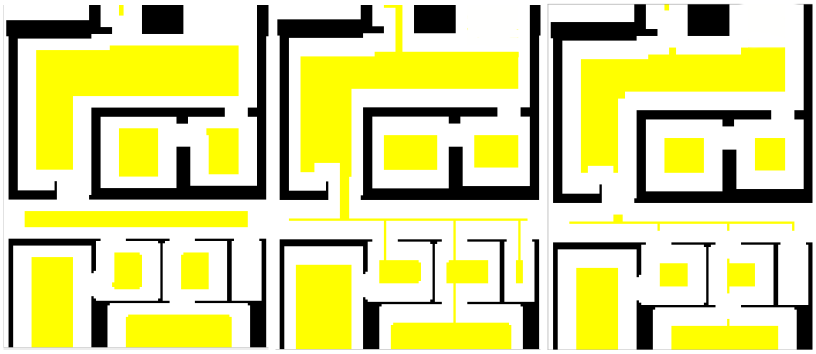

Fig. 4 Occupiable space (yellow): a. x-direction only, b. y-direction only, c. full turn possible

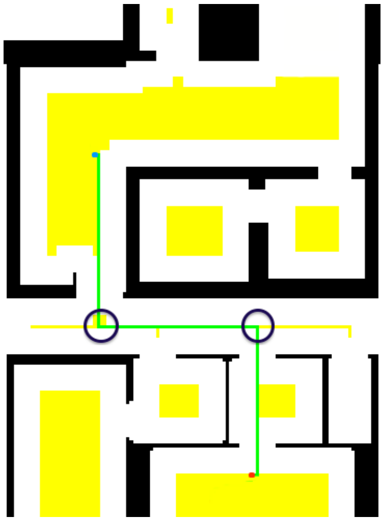

Fig. 5 a. Shortest path (green) between start (red) and goal (blue) cells with turn restrictions: the two necessary turns (circled) are constrained to cells affording full spinning (yellow)

5 Discussion

5.1 Limitations of the Method and Possible Improvements

To fully assess the accessibility of an indoor environment an extension into the third dimension is needed. The present approach assesses vertical connectivity by testing whether elevators afford wheelchair access; cells belonging to the same elevators in different floors can thus be considered connected. In the vertical dimension, the movement of wheelchair users can however be impeded by features such as low ceilings, or even door handles or elevator buttons that are out of reach. A 3D extension of our approach would make it redundant to label stairs and ramps as obstacles in advance and exclude them from the occupiable space computation: ramps could be assessed based on the slope and stairs on the riser/tread ratio within the procedure itself, meaning less effort in the preparation step. As a first extension of our approach, cross-sections of buildings in CAD format can be used and movement primitives (geometries of fit) in the vertical dimension modelled.

A refinement of the method to compute occupiable space is possible. For our present purposes, a rather crude division between fit in the x- and y-direction and full spinning was used. One way to improve this would be to break down full spinning occupiability into four turning possibilities (90 degree turns) and test locations for those separately. Such partial turn restrictions in the accessibility graph would allow finer routing. Additionally, non-90 degree turns can be taken into account by considering the diagonal neighbours of cells, and for this purpose non-90 fit geometries would be used.

5.2 Integration of Procedure Results into an Indoor Navigation System

The outlined procedure is only a first step towards realising a full-fledged navigation aid and the information obtained through it can be used in different ways depending on the way space is encoded in the navigation system in question.

Through steps 1-3 of the procedure we can obtain the set of occupiable nodes and a routing graph for wheelchair users. Depending on the indoor environment a large number of inaccessible nodes can be removed from subsequent computations thus relieving some of the computational costs associated with large numbers of nodes that the fine resolution of the graph implies. Routing can then be performed in a number of ways. The simplest one would be to use a variant of the Dijkstra algorithm that implements turn restrictions, as was done above. Wheelchair users can benefit from least effort paths in addition to shortest, so additional costs for turns can be encoded. Moreover, a less greedy search such as the A* algorithm with the Euclidean distance heuristic can be used to further increase computational performance.

On the other hand, if issues of memory usage are paramount and there is no space for a complex and memory-intensive model such as the grid graph, we can extend the outlined procedure to come up with a pre-computed set of shortest paths accessible for a wheelchair user; this would then constitute the system's sole spatial knowledge base. We begin by using the semantic information on the indoor environment encoded at cell level: each cell is a member of a place (e.g. room or corridor); see section 3.2). For each pair of places we run a shortest path computation, with a randomly chosen occupiable cell within each place as start/goal cell. The resulting path geometries are then turned into semantic path descriptions by querying the constituent cells for their membership values. Routing can then be done simply by retrieving the path description for each start-goal place input. Moreover, the path geometries encode metric information that can be used to compute the time cost of each path as another piece of semantic information.

Referring to Figs. 3 and 4, we can see that although some places are part of the overall occupiable space in virtue of allowing wheelchair users to move within them, they are cut off from the rest of the occupiable space when their doors do not allow wheelchair passage. The shortest path computation as described above is able to identify such cases, and the user can be notified in advance of the places that cannot be accessed.

If the navigational system uses a model based on semantics (see [3] for a thorough review of those) such as a place graph, the results of our procedure can be entered as annotation. Places can be tagged for accessibility in a similar way outdoor elements are in WheelMap [29], while their connections can be labelled with optimal distances and times resulting from a computation such as the one outlined above. To achieve this, however, we first need a definition of what makes a place such as a room accessible. A working definition could be that belonging to the occupiable space of the building and being connected to at least one more place via the occupiable space justifies the 'accessible' tag, but this remains open for discussion. It is also possible to include occupiable space as a category in indoor space ontologies to allow reasoning on navigation-related questions as outlined in [12]. Since affordances are fundamentally about meaning, ontologies are the right places for the results of their automated derivation to come to full fruition[17].

6 Conclusion

Indoor navigation systems can be of great help to the disabled, provided they adopt the distinctive perspective on navigation of these special user groups. Following the procedure outlined in this paper, we have been able to ascertain the extent to which an indoor environment is accessible to wheelchair users as well as lay the foundations for a routing system that takes into account the particularities of movement of this section of the general population. The approach integrates two conceptual models of space: continuous spatial representation required for movement affordance computation, and place-based view used in everyday navigation. It can be used as a general method for affordance computation based on action geometries as parameters and run on a regular grid representation of the space in question. Its most important outcome is its user-relative (adaptive) nature that can be used as the basis for mobile assistance systems for different locomotion types. Future work will concentrate on improving the accessible space computation by refining the movement primitives to align them more to the way wheelchair users actually move. We plan to use the results of our case in developing a resource navigator application for the ULB.

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