Versatile Route Descriptions for Pedestrian Guidance in Buildings – Conceptual Model and Systematic Method

Hans Jürgen Ohlbach and Edgar-Philipp Stoffel

Institute of Informatics, Ludwig-Maximilian University of Munich, Oettingenstr. 67, D – 80538 Munich, Germany, stoffel@pms.ifi.lmu.de

Abstract. In this paper, we tackle the challenging problem of guiding pedestrians in buildings. We propose a conceptual model for indoor environments, based only on regions and their boundaries. It needs to be computed just once. Our approach covers different phenomena, in particular irregular, non-convex regions which are not trivial. Visibility is modelled implicitly and can be determined efficiently. We illustrate by examples how route descriptions can be derived from the model.

1 INTRODUCTION

Nowadays, a plethora of commercial car navigation systems are in use, assisting drivers on their way. The underlying software solutions are be-coming increasingly mature. Since these systems typically rely on a graph representation, they allow for route descriptions to be determined fairly easily, turn by turn. For the most part, however, generated descriptions resort to distance ("*turn left after 144m*") rather than to landmarks. Hence they are not so intuitive or easy to follow for humans.

In this paper we consider another application domain – indoor navigation, specifically for pedestrians unfamiliar with the environment. It is a common misbelief that techniques from outdoor navigation can be adopted to work similarly well for guiding pedestrians through the interior of buildings (although it would be desirable). We believe that there are several reasons why this is not the case – indoor environments are more challenging:

- Pedestrians move at a much slower pace than automobiles. Consequently, their perspective of the environment is richer in details; the granularity of the modelled features is finer.
- Except for corridors, stairs, or doors, no evident navigational structures are present in buildings. The dominant theme is rather a hierarchy, with layers of nested and adjoining regions.
- Humans can move freely, especially in halls and other comparably large areas. There is no guarantee that they will stick to an imposed network structure (whereas a robot will try to follow a simplified structure, e.g. to keep appropriate distance to all obstacles on the way).
- Motion in road networks is constrained by traffic regulations (turn restrictions, lanes, etc.). The network structure is clearly defined and regular: every junction is a decision point, and road segments are linear.
- Wide areas, in contrast, such as halls can be highly complex and irregular in shape. It may take several instructions to describe motion with reference to the shape.
- When entering larger spaces, only parts of them may be visible for the wayfinder, or there may be quite a number of different exits. Intricate situations as these call for guidance, in form of precise descriptions of the local environment.
- In contrast to outdoor environments, indoor areas often lack persistent landmarks (such as television towers). Furniture, often subject to change, is not appropriate for reference. Instead, salient features in the architecture could qualify as natural landmarks.

- There may be ambiguous situations: for instance, when advised to *"follow the main corridor to the end"* it may be unclear whether the corridor continues around a corner or ends at the door in front.

To the best of our knowledge, these aspects have not been fully addressed from a computational perspective.

We believe that the main contributions of this work are the following:

1. We propose a conceptual model of the environment based only on regions and their boundaries. No additional path structure needs to be overlaid.
2. The model needs to be computed only once, in a pre-processing step.
3. Our approach covers in particular irregular, non-convex regions which are not trivial.
4. Visibility is modelled implicitly and can be determined efficiently.
5. We illustrate by examples how route descriptions can be derived on basis of the proposed model.

The remaining part of this paper is structured as follows: In Section 2, a conceptual model with two distinct perspectives is presented. Section 3 illustrates by examples how to derive route descriptions. Section 4 covers related work. Finally, Section 5 concludes the paper and discusses future work.

2 THE UNDERLYING CONCEPTUAL MODEL IN A NUTSHELL

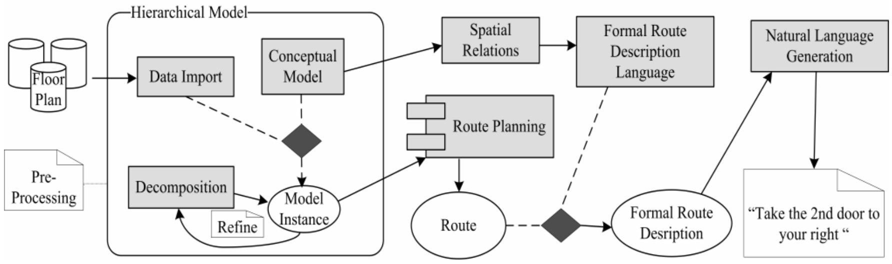

Fig. 1. Top-Level System Overview with Components

In previous work, we have proposed a model to represent the interior of buildings based on a convex decomposition of regions [16], along with a hierarchical representation [5]. Due to the present space limitation, we will only sketch the principal ideas behind this research necessary for the understanding of the subsequent considerations.

The first question that arises when trying to generate route descriptions is how to assess the complexity of navigating through a region. In order to answer this, we have to consider two different perspectives of the environment, and how to obtain one from the other.

2.1 Allocentric Hierarchical Model of the Environment

A basic representation of the environment can be pre-computed from the available geometric data of a building's blueprints [20], meaning it is initially *allocentric*: The perspective is not centred on an individual navi-gating in the environment, but absolute on the environment itself (top-down, from a bird's-eye view). Information represented in such a model is complete and can, in particular, be used at the stage of route planning.

We are adhering to an abstract hierarchical representation (cf. [16]): The overall spatial configuration and topology is represented at multiple levels of granularity (beginning from the building as a whole, over its constituent floors and sections, down to individual rooms): Every polygon corresponds to a spatial region, and all entries and exits on its boundary (termed boundary nodes [16]) represent connections between different regions. This way, one obtains a planar graph of the environment where spatial regions are modelled by nodes, and each individual connection among two regions (e.g. door, window) by a (multi)edge.

The representation of locations inside a building is moreover dependent on the considered level of detail: A composite region (e.g., a floor) consists of a bundle, that is, a connected sub-graph of smaller regions. It can be modelled exactly the same way, except that it also functions as a black box – interior boundary nodes of a composite region, i.e. between two contained regions, remain hidden from outside. When shifting the level of detail, however, they become visible.

A concrete benefit for route planning is that search can be focussed on the concerned regions and refined successively. All other regions are not affected, thus needn't be expanded. A succinct summary of traversal costs is sufficient to find out if a shortcut can exist, so that in the end the determined route is optimal.

2.2 Egocentric Perspective of the Wayfinder along a Route

Based on the allocentric model, a route can be planned from any location *A* to another location *B* inside the building. When we are talking about a route in this context, we mean an ordered sequence of spatial regions leading from *A* to *B*. The linking elements are shared boundary nodes.

Once a route has been determined by means of an appropriate routing component using the allocentric model, we can switch perspectives; we can take on that of the wayfinder, who tries to follow the suggested route. In this *egocentric* perspective, motion through every region on the route has to be represented. The local structure of each region has to be considered for this purpose, with the particular entry and exit points fixed by the route. Additional information may be required, since a spatial region can be too complicated to navigate through without precise instructions given.

Factors which affect this complexity are: the number and configuration of boundary nodes of the spatial region (some could be close to each other), the number and configuration of non-convex corners (limited visibility around them). Not only boundary nodes are decision points. The structure of a non-convex region allows several decisions to continue movement, e.g. at corners or between two corners.

3 DERIVATION OF ROUTE DESCRIPTIONS BY EXAMPLES

First, we have a closer look at convex spatial regions, as shown in Fig. 2 below. The only influential variable is the number and configuration of boundary nodes.

3.1 Handling Convex Regions

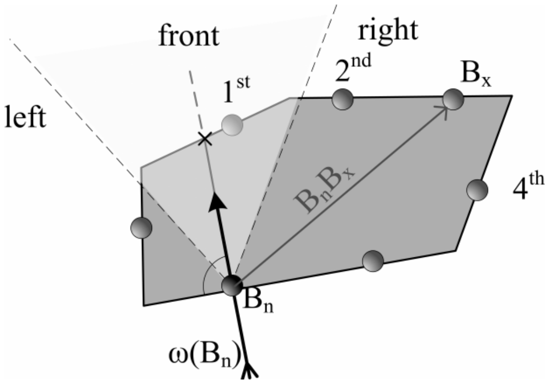

Fig. 2. Deriving Route Descriptions in Convex Regions via Orientation

We assume that a routing algorithm has provided the boundary nodes B_n and B_x through which the convex region is entered and left. Now we need to take into account information on orientations: In order to determine how to reach B_x from B_n, the orientation $\omega(B_n)$ of the wayfinder at the entry point B_n is crucial (see Fig. 2). By default, it is perpendicular to the wall enclosing B_n. Now comparing it with the vector B_nB_x, it is possible to determine whether B_x is to the left or to the right of B_n, or straight ahead. In the latter case, the instruction might be chunked with the previous and next one, unless a directional change occurs.

There is only one special case to pay attention to: If both B_n and B_x incidentally lie on the same boundary line, two reorientations are necessary for moving along the common wall. In this case, we need not consider the vector B_nB_x at all.

The ordering of B_x with respect to B_n, i.e. whether it is the 2nd or 3rd to the left/right, can be obtained by inspecting in counter-clockwise/clockwise order the boundary nodes starting from the elongation of B_n (marked by the small ***x*** in Fig. 2) until B_x is encountered. The problem boils down to counting the number of boundary nodes of the same kind as B_x (e.g., doors or outbound corridors) along the way between B_x and the intersection ***x*** of ▯(B_n) with the polygon.

Referring again to Fig. 2, a formal route description to get from B_n to B_x could finally look like this, in an XML-based syntax:

```
<route-description>
    <instruction action='take'>
        <boundary-node id='Bx' type='door'>
            <color>white</color>
            <destination-region ref='room 1.04' />
        </boundary-node>
        <orientation>right</orientation>
        <order>3</order>
    </instruction>
</route-description>
```

3.2 Handling Non-Convex Regions

Compared to their convex counterparts, *non-convex* spatial regions are admittedly rarer encountered in floor plans. Despite this fact, it is important to handle these cases since they are a place likely to get lost in – especially without proper guidance.

For this, the processing of non-convex regions is more sophisticated.

A first idea is to decompose non-convex regions into smaller convex regions [4,10,16]. The decomposition should not be arbitrary, but specific for the task of route description. We therefore consider in the first place corners with extreme reflex angles, i.e. far beyond 180°. As Peponis et al.[11] pointed out, convex decomposition of spaces intuitive for humans are hard to express in a rigorous, mathematical sense, in accordance with our previous findings [16].

Nevertheless, as initial step (already done in the pre-processing), the region is decomposed into convex sub-regions, but not arbitrarily, such as by triangulation: each non-convex corner is linked with two other corners/Steiner points on the boundary. Unless there is a next non-convex corner to connect to along the shape of the region, the two half-lines delimiting the corner are elongated beyond the corner until they hit another boundary (wall) at a Steiner point. The newly created connections during this matching process split the polygon into two sub-polygons. They are – from an ontological viewpoint – *soft boundaries*, unconsciously passed but nonetheless existent. A very simple algorithm for generating this sort of decomposition has been proposed in [16].

At this point, we have to point out an important remark: not every non-convex corner is worth being resolved by decomposition. For instance, in the extreme case of an angle of, say, 182° or 184° (give or take a few degrees), the corner might still be tolerated as almost convex [4] without necessitating a decomposition. There is an intuitive reason behind this: Corners with an enclosed angle slightly greater than 180° are not salient enough in order to qualify as landmarks. However, this notion of being ‘slightly greater’ is fuzzy.

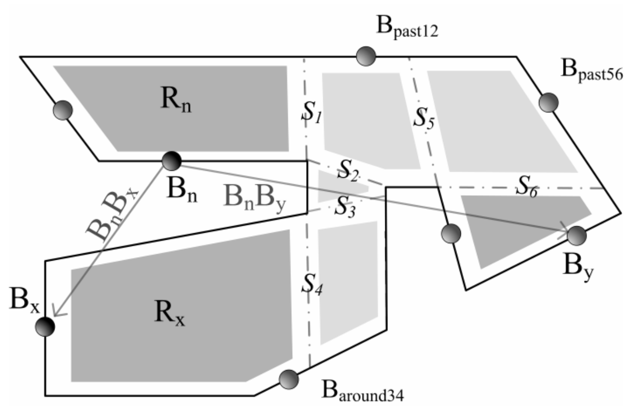

Fig. 3. Using Soft Boundaries of a Convex Decomposition for Route Descriptions

For generating route descriptions, we assume that the non-convex region in question has already been decomposed during pre-processing. Fig. 3 illustrates an exemplary non-convex region decomposed into convex parts. Especially, the six soft boundaries S_1 to S_6 have been created during the decomposition process.

According to the result of a routing component, the non-convex region is entered through a boundary node B_n in the convex sub-region R_n and left through another boundary node B_x in sub-region R_x. First, we inspect how R_n and R_x are connected in the abstract region graph. For this purpose, the ordered sequence of all soft boundaries $S_{n => x}$ on the way from R_n to R_x is considered. In the case depicted in Fig. 3, these are S_1, S_2, S_3, S_4.

Now we try to connect B_n and B_x directly (via the vector B_nB_x) and check whether B_nB_x intersects the soft boundaries in $S_{n => x}$ in the order of their appearance from R_n to R_x. Since none are intersected, B_n and B_x are not mutually visible (if *all* soft boundaries were intersected, B_n and B_x would be mutually visible). For instance, the vector B_nB_y incidentally intersects S_3 although the way from B_n to B_y leads through the sequence S_1,S_5,S_6. Consequently, S_3 cannot be on a route to B_y. So the route that leads from B_n to B_x has to be described by means of the soft boundaries S_1, S_2, S_3, S_4. Since S_1 and S_2 emanate from the same non-convex corner (as do S_3 and S_4), we can describe how to reach R_x via S_4 by turns *around* these corners.

Especially with the decomposition of corners, we can distinguish between the two spatial relations "*past* the corner" and "*around* the corner". The former holds if one outbound soft boundary is intersected, while the latter holds only in case both soft boundaries of a non-convex corner are intersected.

In order to determine the direction of the turns around the corner joining S_1, S_2 and the corner joining S_3, S_4, we have to examine two orientations – first, between B_n, centre(S_1), and centre(S_2) which is a right turn and second, between centre(S_2), centre(S_3), and centre(S_4) which also yields a right turn. The only remaining part is how to reach B_x from the center of S_4.For this purpose, only sub-region B_y is involved, so that we can use the method described in Sect. 3.1.

Putting it all together, the provided route description looks the following way:

```
<route-description>
    <instruction action='turn'>
        <corner>
          <boundary-node id='S1' type='soft'>
          </boundary-node id='S2' type='soft'>
        </corner>
        <orientation>right</orientation>
        <order>1</order>
    </instruction>
    <instruction action='turn'>
        <corner>
          <boundary-node id='S3' type='soft'>
          </boundary-node id='S4' type='soft'>
        </corner>
        <orientation>right</orientation>
        <order>1</order>
    </instruction>
    <instruction action='take'>
        <boundary-node id='Bx' type='door' />
        <orientation>front</orientation>
        <order>1</order>
    </instruction>
</route-description>
```

4 RELATED WORK

There has been substantial research pertaining to pedestrian guidance in outdoor environments, mostly in urban areas [1,15]. In the course of this, indoor environments have emerged as topic of interest [9,13,17,18] as well.

In particular, underlying positioning technologies and robot navigation [3,7] have been investigated. Based on a precise geometric representation, Generalised Voronoi Graphs and visibility graphs have been devised for navigation tasks.[1]

Albeit convenient for the steering of robots, these techniques are not, to the same degree, adequate for human navigation. For this purpose, the concepts behind route descriptions have been studied deeper [3,6,9,14], not least from the point of view of natural language generation [2,8,12].

Based on various experiments in cognitive science [19], findings suggest that topological and hierarchical models seem to be plausible for humans as mental models of space. The spatial configurations in buildings, much in line with this view, have been modelled more and more in a qualitative manner, abstracting away from underlying geometries.

For instance, halls and other large open areas, called *scenes* [15], can be elegantly modelled by cognitive image schemata and affordances [13]. Whiting et al. [20] have shown a systematic method to derive topological models from architectural plans. Moreover, the model proposed in Tsetsos et al. [18] is topological and based on ontologies. It is 'human-centered' in the sense that personal preferences are taken into account for path selection by rules. On the other hand, simplified assumptions on the geometry are made (also a drawback of the approach proposed by Mizzi [8]).

Our work is inspired by Peponis et al. [10,11] who point out that visibility and potential movement play a major role in human wayfinding. These points are respected in the decomposition.

5 CONCLUSION AND FUTURE WORK

We have illustrated by two concrete examples how route instructions can be generated in buildings. The quality of these descriptions for complex regions arguably depends on the decomposition chosen. A comparison of different decomposition methods is still due, determining the influence on the generation of route descriptions as well as the general robustness of the method. Furthermore, the method has to be extended to the third dimension, in order to handle features like staircases or elevators typically present in multi-level buildings.

The simple algorithm proposed for decomposition requires some fine-tuning. Special phenomena and features, such as Spanish walls or obstacles/holes in regions have to be transferred into a canonical form before the algorithm can operate on them.

One major benefit of the decomposition is the implicit notion of visibility. Per definition, all points in a convex region are mutually visible. For non-convex regions, one only needs to test whether all soft boundaries between two points are intersected by the direct connection between the two points. Performing such a test is cheap. Moreover, this idea can even be extended to moving points (when will two persons meet/see each other?).

For computing physical distances, the convex decomposition guarantees that no short-cuts for the case of non-convex regions through adjoining exterior regions are left out of consideration.

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[1] Evidently, there is not only one correct way for representing indoor environments. Every model has its individual advantages and drawbacks.

An implementation of the proposed method and model is currently under way. We expect to gain more insight on their characteristics once the implementation allows for a comprehensive evaluation. Generally, two kinds of evaluations are conceivable: on the one hand, a setting in which persons have to perform wayfinding tasks in real buildings given the generated instructions (requiring more effort to carry out the experiments and evaluate them subsequently) and, on the other hand, by giving persons the instructions and letting them find their way in a virtual environment (primarily requiring effort in building up the environment and simulation).

Acknowledgements

This research has been co-funded by the European Commission and by the Swiss Federal Office for Education and Science within the 6th Framework Programme project REWERSE number 506779 (cf. http://rewerse.net).

We would also like thank Kai-Florian Richter for the ideas brought in during joint discussion.

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