Applying Hierarchical Graphs to Pedestrian Indoor Navigation

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ABSTRACT

In this paper we propose to apply hierarchical graphs to indoor navigation. The intended purpose is to guide humans in large public buildings and assist them in wayfinding. We start by formally defining hierarchical graphs and explaining the particular benefits of this approach. In the main part, we suggest an algorithm to automatically construct such a multi-level hierarchy from floor plans. The algorithm is guided by the idea to exploit domain-specific characteristics of indoor environments. Besides this, two particular problems are addressed: first, how to incorporate three-dimensional elements in the hierarchy, and second, the need for extending the hierarchy at complex geometrical regions with implicit decision points. An extended version of this paper is also available [1].

Categories and Subject Descriptors

E.1. [**Data Structures**]: Graphs and Networks; H.2.1. [**Logical Design**]: Data Models; H.2.8. [**Database Applications**]: Spatial Databases and GIS

General Terms

Algorithms, Design, Experimentation, Theory

Keywords

Hierarchical Graphs, Modelling, Multi-Level Partitioning, Wayfinding Strategies, Indoor Navigation

1. INTRODUCTION

Due to the technological advances achieved in recent years, computer-assisted guidance of people in medium and large scale indoor environments (museums, airports, hospitals, office buildings, etc.) has emerged as an increasingly important field of research. Diverse technologies pertaining to mobile devices and positioning systems have enabled the creation of applications which assist humans in wayfinding. The quality of such an assistive system primarily depends on the way the knowledge is *internally* represented: the underlying data model constitutes a crucial part of a system. Keeping this in mind, we propose to use hierarchical graphs for the representation of indoor environments.

What is particularly appealing about using hierarchical graphs? The reasons motivating the use of a hierarchy are twofold:

Cognitive Aspects. Humans adopt, among others, a hierarchical understanding of space [2, 3, 4]. Different parts of the hierarchy may reflect elements in the building at different granularities (floors, sections, etc.). This could be expoited, e.g., to provide more natural-sounding route directions like the following: "*The room is on the first floor, in section 'A'. It is the second room to the left on the corridor [of section A].*"

Heuristic. The hierarchy can be used to solve different problems. We can exploit knowledge about the structure of the environment [5], e.g. to elude the need for exploring branches irrelevant for a given search task.

2. HIERARCHICAL GRAPHS

Hierarchical graphs can be regarded as an extension of flat graphs, in which additional layers of node and edge clusters form the levels of the hierarchy. Although the intuitive idea is rather clear, there are various definitions for hierarchical graphs in the literature [6, 7, 8]. Differences can be found e.g. in the way nodes are grouped into clusters, or how edges between clusters are defined (e.g., whether edges at a higher level are bundles of lower-level edges or if there is a one-to-one correspondence).

We propose a very restricted and simple form of hierarchical graphs for indoor navigation:

Definition 1 (Hierarchical Graph). *A level-(l+1) hierarchical graph H w.r.t. a level-l base graph $G = (N, E)$ is defined by a* complete partitioning *of G into $k \geq 1$ non-empty,* connected *sets of nodes $\{N_1, .., N_k\}$. Each set of nodes $N_i \subseteq N$ induces a subgraph $sub_i(G) = (N_i, E_i \subseteq E)$ with $E_i = \{(n_1, n_2) \in E | n_1, n_2 \in N_i\}$. Each of these subgraphs, in turn, corresponds to a node in the hierarchical graph H. Edges in H correspond to edges in G between nodes n_i, n_j of two different subgraphs $sub_i(G)$, $sub_j(G)$.*

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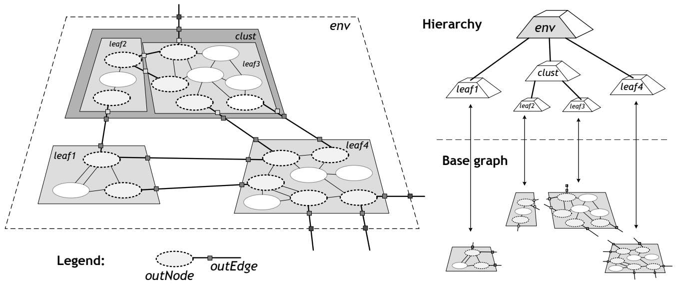

Figure 1: Hierarchical Graphs as Conceptual Model

We further require that the subgraphs $sub_i(G)$ of the partitioning fulfil the following property:

internally connected. $\forall(n_1 \neq n_2 \in N_{sub}) : \exists(path(n_1, n_2) \in transitiveHull(E_{sub}))$

The complement of the edges induced by the partitioning of G, $E \setminus \bigcup_{i=1...k} E_i$, are called *out edges*. An edge in H between $sub_i(G)$ and $sub_j(G)$ corresponds to an *out edge* in G between a node n_i in $sub_i(G)$ and n_j in $sub_j(G)$.

Although the definition allows some subgraphs to be single nodes (when $k = \|N\|$), there is no real gain to this in practice. In a sensibly defined hierarchy, each level should at least cluster *some* nodes into a new subgraph. The other extreme case, $k = 1$, determines the root of the hierarchy. We can define the hierarchical graph H' of H, H'' of H', and so forth to obtain a multi-level hierarchy. Fig.1 shows a three-level hierarchy.

3. BASE GRAPH FROM FLOOR PLANS

3.1 Basic Mapping to Graph

For the extraction of a base graph from a set of floor plans, we follow a rigid, pragmatic approach inspired by the work of Whiting et al. [9]:

Polygons represent areas of walkable space delimited by physical boundaries such as walls. Each polygon maps to a node in the base graph. Two polygons are adjacent if they share a common line segment along their boundaries. However, edges in the base graph are only the line segments representing *accessible* openings, such as doorways. All sorts of different connection types are conceivable, such as internal windows (in case of an emergency) or even bridges between two neighbouring buildings. Only hard physical barriers, such as walls are excluded from the mapping to edges. Note that there can be *multiple* boundary openings between two regions, resulting in a *multi*-edge base graph.

3.2 Taming the Third Dimension

The 3^{rd} dimension is a challenging aspect to model [10]. We examine $2-d$ projections of staircases and elevators common in floor plans. Most staircases fall into the small set of five categories depicted in Fig. 2:

The stairs of type St_1 through St_4, with one entry and exit each, afford movement only *along* their structure. Their geometry is mostly irrelevant for wayfinding, despite its possible complexity (e.g. zig-zagged, several landings). Merely re-orientation after vertical movement [4] needs to be catered for at entries and exits. The final type, St_5, is different in-

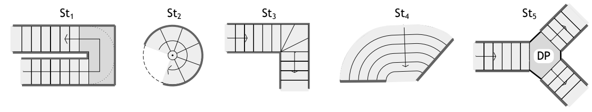

Figure 2: Different Types of Staircases

sofar as it has a landing with two alternative branches – it is a *decision point*[1].

4. CONSTRUCTION OF THE HIERARCHY

The topological structure of buildings, in general, is rather sparse. The typical pattern of movement will not be like moving from room to room arbitrarily, but more often going along main corridors or large halls *before* entering certain rooms [3, 11]. We reflect this notion in the method for constructing the hierarchy (see Algorithm 1):

In lines 3-4, the base graph is partitioned around *coloured nodes*, which express a certain degree of relevance. A node can be *coloured* by virtue of three different reasons:

- it has a connection to the exterior, or
- it represents a vertical connection such as a flight of stairs, or
- it is an *articulation point* [12, 13] in the base graph G.

An articulation point is defined such that its removal would split the graph into two or more connected components. Any neighbour of a dead-end already qualifies as an articulation point. Among *coloured nodes*, all decision points (black) are determined in lines 11-13. They connect at least three other coloured nodes and divide a sequence of coloured nodes into different chains. The hierarchical graph H (determined by the set of subgraphs *partitioning*) is constructed in line 17. If *partitioning* contains more than one subgraph (line 18), the final level of the hierarchy has not yet been attained and the algorithm is recursively called on H. The overall complexity of the algorithm amounts to linear time since the recursion appears outside the for-loop.

Fig. 3 gives a first impression of the output of Algorithm 1. One can retrace how chains of coloured nodes (together with their dead-ends) at one level collapse to a single node at the next higher level. Decision points (black) either become decision points again, or degenerate to ordinary coloured nodes (grey).

5. REGIONS WITH IMPLICIT DECISION POINTS

The hierarchy presented so far is not yet feasible for guiding pedestrains along paths. Spatial regions found at the bottom of the hierarchy can be of such local geometric complexity that humans cannot make the 'right' decision without further guidance. There are basically two factors which influence this complexity:

1. limited visibility in non-convex regions, especially around corners, forces the wayfinder to explore what is 'hidden' beyond. These are implicit boundaries.

[1] A branch could be, as well, of the kind `door`

Algorithm 1: `multiLevelHierarchy`(G, *stairs*, *entries*)

Input: a base graph $G = (N, E)$,
$stairs, entries \subset N$

Output: a multi-level hierarchical graph of G

Set<Subgraph> *partitioning* := $\emptyset$;
Set<Node> $colouredNodes$:= $\emptyset$;

find all articulation points $AP \subset N$ and add them to $colouredNodes$;
add all nodes in *stairs* and *entries* to $colouredNodes$;

create subgraph *sub*($colouredNode$) with one element $colouredNode$ for all coloured nodes;

foreach Node *node* in ($N \setminus colouredNodes$) **do**
  find connected component *cc* of *node* enclosed by $colouredNodes$;
  if *cc* has edges to exactly one coloured node in $colouredNodes$ and *cc.size* < *threshold* **then** merge *cc* with *sub*($colouredNode$);
  else create new subgraph *cc* and add it to *partitioning*;
end

foreach Node *decisionPoint* in $colouredNodes$ connected to at least three other $colouredNodes$ **do**
  add *sub*(*decisionPoint*) to *partitioning*;
end

foreach chain of $colouredNodes$ enclosed by *decisionPoints* **do**
  merge *sub*($colouredNode$) of all $colouredNodes$ in the chain and add result to *partitioning*;
end

Graph H := hierarchical graph of G induced by the subgraphs in *partitioning*;
if *partitioning.size* > 1 **then return** `multiLevelHierarchy`(H, $\emptyset$, $\emptyset$);
else return H;

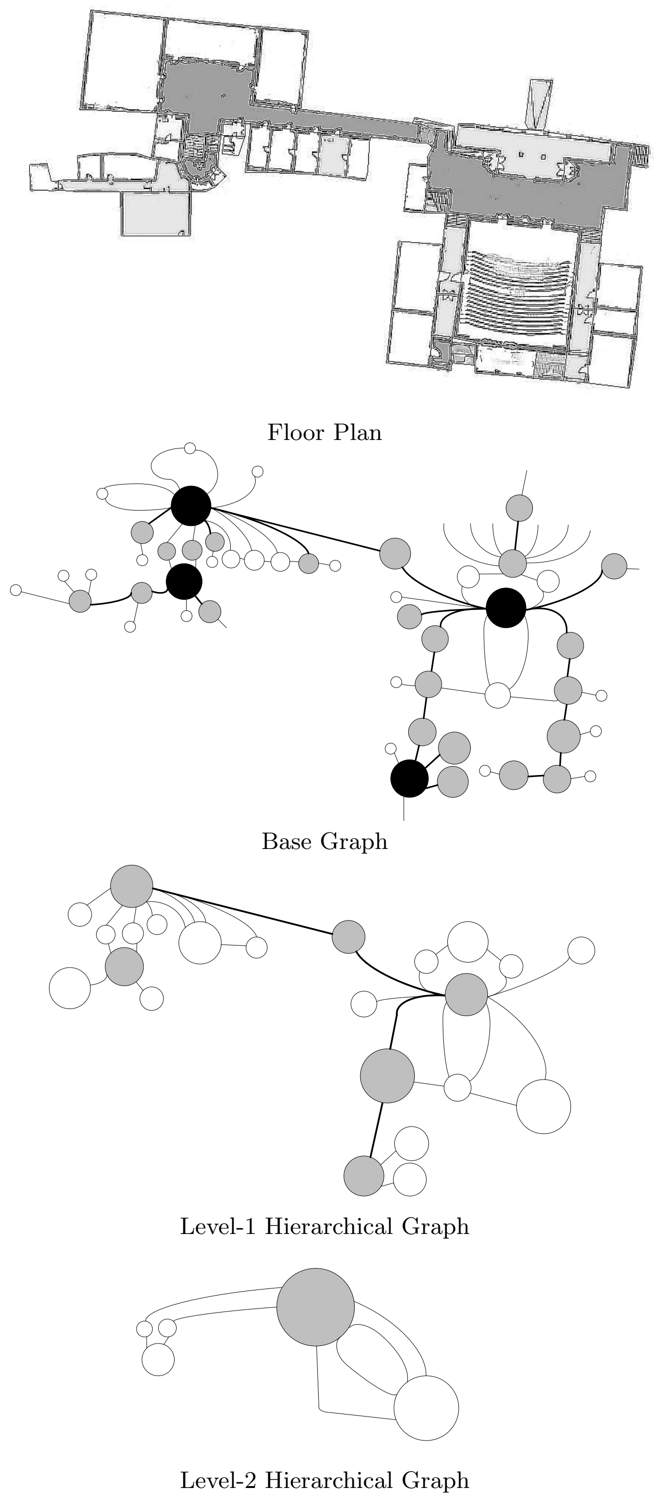

Figure 3: Construction of a 3-Level Hierarchy from Excerpt of a Floor Plan

2. unambiguous descriptions need to distinguish between *each* possible choice for continuing the path. This can be done, for instance, by using a combination of directions and ordering relations [14] among boundary connections (e.g. 'the [second/third] door to your [left]' or 'the stairs [in front of] you').

With respect to the above mentioned criteria, we have proposed a simple decomposition algorithm in Stoffel et al. [15]: A complex spatial region is decomposed into smaller convex regions. Fig. 4 shows the prototypical decomposition of a circular corridor:

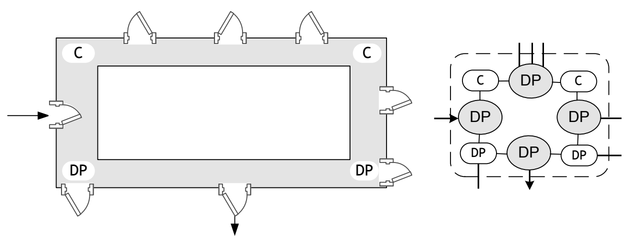

Figure 4: Refining a Circular Corridor

All different kinds of meaningful landmarks, such as corners or junctions can be extracted for such a decomposition. Beyond, we can determine decision points by looking at the refined graph structure of the decomposed regions: The two lower corners in Fig. 4 are decision points because there are the two options of going around the corner or leaving the region through the door. A more extreme example is a maze, which is basically just *one* region with many decision points and dead-ends.

6. CONCLUSIONS AND FUTURE WORK

We have discussed the benefits of hierarchal graphs for modelling indoor environments. The presented algorithm for constructing the hierarchy has been implemented in Java. We have conducted a series of first experiments on various university floor plans. The results are encouraging, since the initial hypotheses have been confirmed: The ground floor of the main university building alone revealed around 50 articulation points in the first of three hierarchy levels, among those were 12 decision points. The hierarchy could also be used by architects to evaluate designs, especially with higher-level organisational structures such as sections or wings. Another idea is to enrich the model with information pertaining to the function or use of subgraphs. This would enable, for example, to take into account constraints such as 'do not go through a classroom' or a 'avoid the laboratory section' to produce better results for path planning.

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