Modeling indoor space

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ABSTRACT

This paper begins by reviewing the motivation for an informatics of indoor space. It then discusses application domains and consider why current geospatial technology, with its focus on outdoor space, needs to be extended. We review existing formal models of indoor space, along with their applications, and introduce a new model that is the subject of the author's current research. We conclude with some observations about the development of a unified model of both indoor and outdoor space.

Categories and Subject Descriptors

H.2.8 [**Database applications**]: Spatial databases and GIS; H.1.2 [**Data structures**]: Graphs and networks

General Terms

Design, Theory

Keywords

indoor space, ontology, GIS, navigation, graph, tree

1. INTRODUCTION AND MOTIVATION

The proportion of our day that we spend in indoor space (I-space) is considerable. A series of studies in different continents at different times indicates that the average person spends around 90% of their time indoors (see, for example, [17]). Informatic support for indoor space applications has up to now lagged well behind outdoor space applications using GPS and GIS technologies. A possible reason for this is that satellites and aerial photography have provided both a means of data collection and positioning (using GPS) in outdoor space. In addition, some of the early work on GIS was a natural outgrowth from traditional cartographic applications, and was driven by the force of the market for such applications as store location, utilities, and defense.

However, with the growth of location-based service applications and ubiquitous computing, there is now a much stronger motivation for informatic support for indoor space applications. Also, the spaces themselves (e.g., airports, shopping malls, and hospitals) have become increasingly complex; the data is now slowly becoming more readily available; and an increasingly aging population requires more assistance indoors.

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1.1 Technologies

As already mentioned, for an informatics of indoor space to be effective, several technologies need to be in place. Indoor positioning is currently the main concern, as GPS cannot be used indoors, at least not without some enhancements. Techniques for indoor positioning include radio frequency identification (RFID), infrared (IR), sensor networks, standard Wi-Fi positioning, and inertial navigation systems [1].

Positioning determines the location of an object in some reference system. For outdoors, it is usual to use a 2D coordinate frame, such as latitude-longitude. However, devising an appropriate reference frame for indoors, where connectivity and level are often more important than location in a 2D Euclidean frame (plane or sphere), poses interesting questions and is the subject of geocoding [22].

Accurate and complete data is the foundation of any indoor spatial information system. Owing to the number, size, and complexity of indoor spaces, it is impractical to use wholly manual methods for data acquisition. Therefore, there has been research in academia and the industry on automatic and semi-automatic methods of data acquisition. Acquisition can range from purely topological data (e.g., [20]), through topological and metric information (e.g., [31]), to complex textured renderings of indoor scenes (e.g., [3]) and semantically rich scenes (e.g., [39]).

1.2 Applications

Many of the indoor applications are the same or similar to those for outdoors. However, because of the structure of I-space, and the types of users, many of the application have different flavors. By far the most common application discussed in the literature is navigation, but there is also research on machine learning of indoor space (robotic exploration), indoor tracking of mobile objects, location-based service applications specific to indoors, and spatial analysis.

The task of navigation involves:

Location: Determination of the locations of the source and destination is a positioning and geocoding task, as discussed above.

Routing: Algorithms are required to find appropriate routes

between source and destination. Optimal routes are dependent upon distance, time, or some other criterion such as simplicity. These algorithms will depend on the space model chosen. They will also depend on the context, user type, situation type, etc.

Guidance: There is a need to present routes to the user and guide the user along the chosen route. This is partly a human-device interaction task, and relies on research on human spatial cognition and language as well as provision of visual aids such as maps on mobile devices. It is also dependent upon suitable tracking techniques, as guidance cannot be given if the system does not know the current location of the traveller.

Research that considers I-space models in the context of navigation includes [5, 6, 13, 14, 15, 25, 24, 26, 29, 30, 32]. Research that considers navigation in the specific context of emergency management includes [22, 33].

Tracking of mobile objects in I-space is another important area of research, upon which navigation depends, as well as a range of applications related to security and crowd management in indoor space. An example of a graph-based model of I-space that is designed to facilitate tracking applications can be found in [18]. Related to this is research on ubiquitous computing and indoor ambient environments, for example [7].

Many of the methods of spatial analysis, so prevalent in outdoor applications can be used indoors. Outdoor spatial analysis has social applications in epidemiology, through geodemographics, to physical analyses of the terrain such as viewshed analysis. Indoors, the same dichotomy between the social (human occupants) and physical (building fabric and structure) holds. It is important to know general patterns of usage, including movement and flow, of a building, as well as physical analyses. For example, indoor space syntax can be used to improve 'usability' of a building [23, 19].

1.3 Outline of paper

For the remainder of the paper, the focus will be firming in the modeling area. We will begin by surveying existing work on models of indoor space. We will then present some work of our own on extensions to graph-based models as well as a new graph structure that we call the maptree.

2. SURVEY OF MODELS

Models of indoor space fall into several categories, as shown in figure 1. This figure is, of course, a gross over-simplification. For example, there are models that focus on spatial granularity and provide a hierarchy of structures, and there are models that combine spatial and semantic elements. There are also models that are concerned with a wider domain than I-space. For example, CityGML [9] provides a standard model for 3D urban space, including elements of I-space. Also, models have different purposes, ranging from models of the structural elements (design, construction, facilities management) of the indoor environment [16] to graphical models supporting navigation. Our focus will be on models that are formal in character, and will exclude models that lean more towards a descriptive representation or are concerned with data standards.

2.1 Semantic models

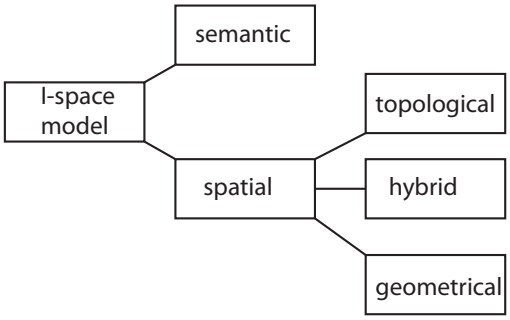

Figure 1: Top level taxonomy of indoor space models

Semantic models represent the variety of types of entities in indoor space, as well as their properties and relationships. If such models not only have representational but also reasoning capabilities, then they are often referred to as ontologies. A useful distinction that we can make at the outset is between the fixed structure or fabric which supports the I-space (walls, rooms, doors, windows, floors, etc.) and the entities, often mobile that the structure contains (furniture, people, equipment, etc.).

In [2, 32] the authors develop an ontology of indoor space within the context of navigation, extending a graph-based model (see section 2.2) to account for semantic elements. In [7], there is a development of an ontology of 'spatial artifacts', dividing the domain into operational, functional, and range spaces. For example, the operational space of a door is the region needed for its opening and closing, the functional space is where an agent should be to open or close the door, and the sensor space is the region of space within range of sensors in the case that the door is monitored. Yang and Worboys [38] develop a hierarchy of 'microworlds' related to indoor space, distinguishing between the upper ontology containing very high-level concepts, domain ontologies (structure and artifacts of indoor and outdoor space), and task ontologies (e.g., navigation).

Semantic entities such as landmarks play an important role in location-based and navigation applications. Research on image schemata and bigraphs has also been brought to bear on understanding the combination of spatial and semantic constraints that an indoor space provides (see [34]).

2.2 Topological models

Topology is concerned with the connectivity properties of a space. An early paper in the topological modeling of I-space is [26]. A survey of topological models of indoor space shows two aspects of I-space that are the subject of these models:

Topographic space: Also called *primal space* or *structural space*, and is the space of structural components of the building: rooms, walls, doors, corridors, etc.

Dual space: Also called *path space*, and is the space of paths within the topological space. It is the Poincaré dual of topographic space [21].

Topographic space may be modeled either as a fully 3D space, using for example cell complexes [21] or as a linked collection of 2D layers. The path space is modeled as a

graph, often called the routing graph [13]. We should distinguish between the *adjacency graph*, where nodes represent regions, and edges between nodes represent that the regions are adjacent (e.g., rooms sharing a boundary wall), and its subgraphs:

Connectivity graph: Edges between nodes occur only if there is some physical means of connection between regions (e.g., rooms sharing a boundary wall in which there is a door).

Accessibility graph: Edges between nodes occur only if one region is directly accessible from another (e.g., rooms sharing a boundary wall in which there is an unlocked door).

Note that the connectivity and accessibility graphs may be distinct, as for example security may not permit movement between boundaries or one-way movement only may be permitted, even though there is a physical portal [18]. These graphs may be extended to account for sensors in the space (e.g., the RFID deployment graph in [18]).

2.3 Hybrid models

While topology has an increased importance for indoor space over outdoor space, we cannot of course neglect the geometry of I-space. Purely geometric models are required for building design, construction, and management. For our purposes most models will be hybrid, combining topological and geometric features. Geometry adds quantification of distance and angle to the connectivity and accessibility provided by topology.

Hybrid or multilayered models are well studied in the literature (see, for example, [5, 6, 30, 24, 25]), providing combinations and linkages between topographic, dual, topology, and geometry.

2.4 Granularity and hierarchical models

In many applications, variable levels are detail or granularity become important. For example, in a navigation task often users require more detail at the beginning, end, and some critical decision points of the journey. For such purposes researchers have developed a class of models that allow for the representation of a collection of levels of detail [27, 30, 29, 15]. Often such models are called hierarchical models. Perhaps the most formally developed of such models is described in [29], where regions may be nested inside each other, with a given level of detail of topographic representation affecting the level of detail of the dual graph. These papers show application to navigation: both route generation and visualization.

3. EXTENSIONS TO GRAPH-BASED MODELS

The remaining sections of this paper briefly describe some of the work undertaken by the author and his group. The first issue raised is that of accounting for non-transitivity in graph-based representations. Consider, for example, the plan and route graph in figure 2. Suppose we wish to go from node a to node f along the edges of the graph. Suppose also that the room represented by node g is a private office. Then, although path $abgef$ contains fewer edges than $abcdef$, we would expect to be routed along the latter path.

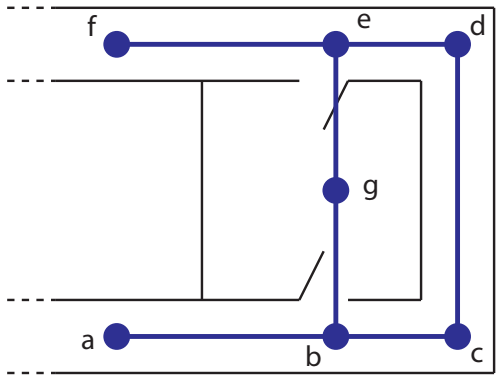

Figure 2: Non-transitivity example

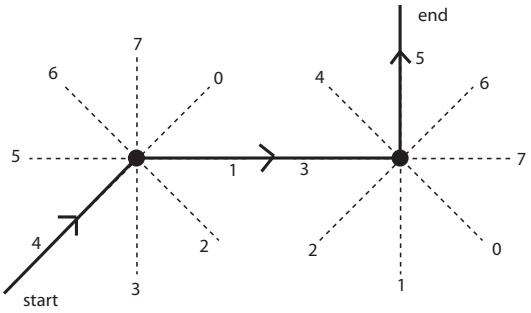

Figure 3: Routing using a rotation graph

Note that although there are paths bg and ge, there is no path bge, so the edge relation is not transitive. This constraint is similar to turn-restrictions in transportation routing graphs. There are several possible solutions, involving adjusting the weights to be very high on bg and ge or introducing extra nodes.

A second extension we describe here is introducing a qualitative rotation scheme to the graph-based models. In a route description, some guidance on direction is often essential. Directions can be derived in hybrid models. However, if we do not want the added complexity of co-ordinates, we can extend our graph with a collection of cyclic labelings of edges around nodes. In our work, we introduce an 8-point system, as shown in figure 3. Using this labeling system, we see that we come in from the start to the first node via label 4 and exit via label 1 (bear right) and then come in to the second node via label 3, exiting via label 5 (turn left). The directions 'bear right' and 'turn left' can be computed using the pairs of labels around the nodes. Note that the cyclic labelings for the different nodes do not need to be all aligned for this process to work. Graphs with cyclic orderings of edges associated with each node are called rotation systems in the graph theory literature [35], so we call our structure a *qualitative rotation system.*

4. MAPTREE MODEL

In this section we briefly introduce the author's work on a representation of the embedding of a non-connected graph in the Euclidean plane. This was originally motivated by some

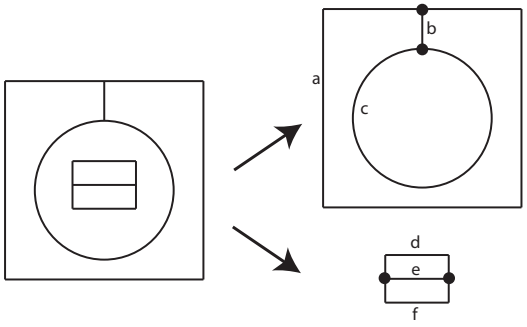

Figure 4: Spatial scene decomposed into connected graphs

of the spatially complex configurations that the topography of I-space presents to us. Actually, the representation works for embeddings of graphs in any closed surface but here we just present the planar structure, called the *planar maptree*. A maptree is a combination of two representations:

Adjacency tree: This provides a topologically uniques representation of regions nested one inside the other [8, 28]. The representation is in the form of a tree, where nodes represent regions and edges between nodes indicate that the regions represented by the nodes share a common boundary.

Combinatorial map: This provides a topologically unique representation of a particular kind embedding (called a 2-cell embedding) of a connected graph [10]. The representation is in the form of a triple of cycles of semi-edges, or darts, and is embodied in such spatial data structures as the winged-edge representation [4].

Space precludes a full treatment of maptrees here, but full formal details can be found in [36]. In this section we illustrate by means of a highly simplified example. The lefthand part of figure 4 shows an imagined and highly schematic indoor scene. The task is to capture symbolically the full topology of this scene. The right of figure 4 shows the decomposition of the scene into two connected graphs embedded in the plane such that each region is homeomorphic to a disc (a 2-cell embedding). It is well know that such embeddings may be represented by combinatorial maps. With the convention that each edge x is decomposed into a pair of semi-edges x and $\overline{x}$, the combinatorial maps $\mathbf{M}_1$ and $\mathbf{M}_2$ for the two 2-cell embeddings are given by the maps, where (xyz) denotes the cycle x to y to z to x. (Strictly, $\mathbf{M}_1$ and $\mathbf{M}_2$ provide topologically unique representations of 2-cell embeddings on the sphere. We need to distinguish the outer regions to make the representation work for the plane.)

$$\mathbf{M}_1 = (a)(\overline{a}bc\overline{b})(\overline{c})$$
$$\mathbf{M}_2 = (de)(\overline{e}f)(\overline{df})$$

The next step is to bring the two embeddings together. For this purpose we use a particular kind of adjacency tree, as in the following definition:

Definition 1. *A* bw-adjacency tree *is an adjacency tree with the node set partitioned into two subsets, being the black nodes and white nodes, respectively subject to the conditions that:*

1. *Black nodes are not connected to black nodes and white nodes are not connected to white nodes.*
2. *Leaf nodes are all white nodes.*

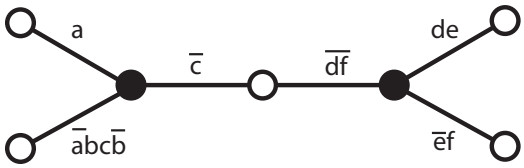

Figure 5: Maptree of the the embedding in figure 4

The black nodes of the bw-adjacency tree represent the mass of each connected component of the non-connected graph, and the white nodes the regions that are carved out by the embeddings. The configuration of black and white nodes shows how the connected components are embedded, one in another. In order to bring in the topology of the embedding of each component, we need to label edges of the bw-adjacency tree using the cycles of the combinatorial maps. The result is the maptree construction. The maptree for our example is shown in figure 5. Note how the incidence of edges labeled $\overline{c}$ and $\overline{df}$ shows the embedding of one component in another, while the configurations of labellings around each black node show the topological embeddings of each separate component.

We have been able to show in [36] that the maptree construction provides a unique (up to homeomorphism of the embedding surface) representation of the embedding of a non-connected graph in a closed surface. Further work is on-going to see how changes in the embedding are reflected in changes in the maptree.

5. MODELING OI-SPACE

Indoor spaces do not of course exist in isolation, as they are part of the entire geographic environment (indoors and outdoor, built and natural) in which we live. A further strand of work is concerned in bringing these two spaces together into a unified model. Parts of CityGML [9] are concerned with the same issue. A typical goal here would be to provide users with consistent and seamless informatic support as they moved between indoor and outdoor spaces.

Some of the research issues that need addressing to bring about a unified informatics of outdoor and indoor (OI) space include:

1. Similarities and differences between outdoor space (O-space) and I-space at the ontological, topological, geometrical, data, functional, and application levels
2. Construction of unified conceptual and data models for OI-space

The first item has begun to be addressed in [12, 37]. Various methods have been proposed for finding models. At the ontological level, the author has used Gibson's theory of affordances [11] to identify functions that entities in indoor and outdoor spaces have or have not in common. For

example, a corridor and a road both have the affordance of providing passage from a source to a destination, and so may be subsumed by a generalized entity such as 'path' at the OI-ontological level [38]. Research on unified OI models is still at an early stage.

6. CONCLUSION

In this short paper we have tried to survey some of the main strands of research in indoor spaces, with a focus on models that have some degree of formality in their expression. The treatment has been necessarily brief, but it is hoped that the categorization of areas of research and the references will prove useful. Research on I-space is considerably less developed than its elder sibling, GIS. Indeed, some classifications do not even include indoor space as part of the geographical domain. For example, the following is a quotation from the Cyc ontology: "No instances of GeographicalRegion are wholly indoor locations." However, this is not the viewpoint of the author.

On the contrary, the premise of this article is that indoor space, and unified OI-space are important areas of research, both for the intrinsic interest that the domain offers but also in the wealth of applications that are thereby supported.

7. ACKNOWLEDGMENTS

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