

Documenting Intent: A Survey of Spatial Models for Indoor Navigation

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ABSTRACT: Indoor environments cannot rely on global positioning systems for navigation, which poses a stark contrast to the immediacy and accuracy of positioning and navigation in outdoor environments. The study of indoor navigation has grown in two general topic areas, navigation of indoor space and machine learning of indoor environments. This paper will only review the current research in indoor space navigation and the modes of modeling space for a prescribed route.

Literature reviews of indoor positioning have considered the array of approaches within the network and inertial models, the precision of each approach, and each system's fitness in a mass-market application. Yet, with a significant relationship to the built environment, a review of indoor positioning's impact on the field of architecture and more specifically, its relationship to spatial documentation has yet to be considered.

KEYWORDS: wayfinding, indoor navigation, architectural representation, semantic wayfinding

INTRODUCTION

This paper will review current spatial models and map generation used for indoor navigation and wayfinding. The intent of this review is to provide a relationship of current spatial models to the field of architecture. Recent literature presents a wide range of spatial models for representing the indoor environment. These differences are dependent on several parameters within the building type, program, and users of the environment. The variables surrounding these decisions will be reviewed in concert with the associated spatial model. Unlike outdoor navigation which has a generally common path structure (roads) to follow. Indoor environments vary greatly in size, vertical circulation, use, structure, and complexity. The range of possible indoor spatial configurations has prompted some hybrid approaches in the development of navigable indoor models while others seek a universal approach to defining these spatial models.

The task of indoor navigation requires location, routing, and guidance. (Worboys 2011) The first, location, refers to marking the positions of a start and endpoint. This initial task of navigation requires positioning in space and thus requires an adequate reference system as a *map*. A map, as referred to in navigation systems, could be a two-dimensional plan or three-dimensional model. The derivation and translation of these maps to a legible model for navigation are of interest. Many systems use existing documentation of a space (*a priori*) and derive a spatial model from architectural drawings or models. Other systems have the potential to build their own maps in unknown environments through SLAM (Simultaneous Location and Mapping) technology.

Typically, the *a priori* building information used in indoor navigation models are the floor plans of a building. In architecture, these types of documents are typically in service of communicating tangible information such as scale, material, and assembly for purposes of construction. However, the rise of BIM (Building Information Modelling) and life-cycle considerations in the field of architecture has placed increased value on analysis, building life-cycle, and occupation. Forecasting of use and occupancy within a building can play an important role in the design and should be considered relative to research in indoor navigation and wayfinding. A recent study analyzed occupant behavior and movement to investigate how workspace layout affects communication and team interaction amongst nurses and doctors in an emergency room department of a large urban hospital. The hospital staff's movement, perception, and experience were overlaid onto an existing floor plan to reveal information about communication and use within the existing ER environment and ultimately to provide evidence for future design work. (KieranTimberlake 2017)

There is significant overlap in literature related to indoor navigation and wayfinding in cognitive science, artificial intelligence, architecture, and geo-information science. (Franz et al. 2005) This paper intends to parse out parallel language and dialogues related to spatial models for indoor navigation and communicate the needs and advances of indoor navigation technology in the field of architecture. Leveraging the inherent spatial intelligence of the design process in architecture could yield better responses to human behaviors in

navigation. Similarly, understanding and developing spatial models that more closely align with those necessary to foster successful indoor navigation can serve to illuminate architectural intent and help to preserve the qualitative value of spatial experience.

Section one will introduce related vocabulary in the fields of geography and navigations, cognitive theory and architecture. The outlined vocabulary will serve as a bridge between fields and serve as a foundation for the paper. Section two will review graph-based spatial models and the inclusion of spatial information, such as semantics, into navigation systems. The paper will conclude with considerations for future research and applications.

1.0 RELATED VOCABULARY

1.1 Geography and Navigation

Navigation is the ability to plan and execute a goal-directed path. (Gallistel 1990) The term *wayfinding*, while closely linked to navigation, presumes the ability to organize information about the physical environment into a cognitive map. (Passini 1992) Two distinct forms of human navigation are path integration (originally referred to as dead reckoning) and landmark-based navigation.

The *dead reckoning* system of navigation allowed for early explorers to travel over long distances without an exact geographic position or location within a system of coordinates. (Passini 1992) Dead-reckoning relies on the continuous calculation of one's speed and bearing, incrementally charting this information to create a continuous path made up of individual vectors. (Denny 2012) *Path integration* and *inertial navigation* are used synonymously with dead reckoning and, similarly, do not rely on landmarks for positioning. The term path integration is often referred to in cognitive science research and literature on the topic considers a human or animal's ability to return home along the same path without the use of landmarks and emphasizes the cumulative nature of movement. (Ariane S. Etienne 1992)

Landmark navigation relies on visual cues to guide movement to a given location. (Sjolund, Kelly, and McNamara 2018) Two types of visual cues have been identified; geometric and "featural" cues. (Gallistel 1990; Cheng and Newcombe 2005) Geometric cues relate to the overall geometric form of an environment. These cues rely on unique conditions and geometric changes in a space, shape, proportion, corners and spatial axes are examples of geometric cues referenced within a given space. (Gallistel 1990; Cheng and Newcombe 2005) Featural cues as introduced by include non-geometric features such as wall color, elements on walls or objects in space.

Some research has reviewed the overlap of path integration and landmark navigation in human cognition to determine prevalence or weight of one over another in a given wayfinding task. (A. S. Etienne, Maurer, and Séguinot 1996) In addition, the prominence of geometric cues or landmarks within wayfinding scenarios has been considered. (Davies and Peebles 2010)

1.2 Spatial Cognition

Research in spatial cognition relates to the way in which people obtain and implement knowledge about their environment to determine their location and how to find their way to a given destination. (Waller and Nadel 2013) Cognitive Map theory and the term *cognitive map* is widely referenced in wayfinding and navigation literature. The notion of a cognitive map was introduced by (Tolman 1948) as a means of describing an animal's ability to store spatial information between the point of origin and destination. The term has evolved and since been rooted in the study of human spatial cognition. The landmark study by (O'keefe and Nadel 1978, 86) defines the cognitive map as "a representation of a set of connected places which are systematically related to each other by a group of spatial transformation rules." These "rules" differentiate the cognitive map from a one to one representation of space and rather, propose it to be a generalization and inference of spatial information beyond the details of a direct experience. (Golledge 1999)

Localization refers to the locating of oneself or objects within a given frame of reference or map. (Kiefer, Giannopoulos, and Raubal 2014) A frame of reference is required to locate or describe the location of objects or oneself in space and a similar condition is required for spatial memory. (Mou and McNamara 2002) Two types of spatial reference systems are considered for understanding spatial cognition. Egocentric reference systems provide location relative to the observer or self, while environmental reference systems use spatial geometry or landmarks to provide a frame of reference.

Typical navigation involves both internal and external cues in combination and studies have tested variables in the "weight" or relative importance of these cues. (Ratliff and Newcombe 2008) Several variables considered in this realm are landmark distance, room size and shape, intrinsic axes, and rotation. (Sjolund, Kelly, and

McNamara 2018) The integration of these cues is the subject of several cue-combination studies that seek to define the priority and optimality of cues in varied environmental conditions. Related work on spatial reorientation, or the process by which one regains their orientation in an environment determined that spatial geometry, or the shape of space, have a greater influence on the reorientation of one's cognitive map within an environment than view-matching. (Keinath et al. 2017)

1.3 Architecture

To distinguish *architecture* from the building, (B. Hillier 2007) states that architecture, "introduces into the creation of buildings an abstract concern for architectural possibility through the principled understanding of form and function. The distinction between architecture and building is of importance to this paper and its relationship to indoor navigation. Literature in indoor navigation and wayfinding almost exclusively reference simplified buildings floor plans.

A *floor plan* represents a horizontal cut through the volume of a building at a given level. Floor plans are typically cut at 3'-0" to 4'-0" above the finish floor of a given level. The floor plan graphically represents solid (wall) and void (space). Floor plans can be viewed as figure and ground; the inverting of which preferences void, or space, over solid forms. The floor plan is a primary tool for organizing space relative to design intent. The underlying structure of a floor plan can reveal inherent spatial patterns such as repetition, rhythm, and sequence. And while grids or other underlying patterns may govern architectural decisions, additional value is seen in the breaking of those rules and the blurring of discrete spaces or rooms. (Plummer 2016)

Spatial organization describes the way in which the spaces of a building are organized, this is typically seen in plan. Common forms of spatial organization are centralized, linear, radial, clustered and grid based. While each underlying organization predicates a natural form of movement through the spaces. (Ching 2014) The term *axis*, in architecture, relates to the organization of space as opposed to the movement through it. Most types of spatial organizations rely upon a single axis or set of axes. The axis of a building or space represents a "symbolic direction" organizing elements or spaces along it and often operates to relate them to a larger context. (Norberg-Schulz 1971, 49) Axes are typically seen in the arrangement of a plan and often correspond with the centerline of a circulation space.

Circulation is a term broadly recognized in the field of architecture as the means of human movement within or around a building. The term circulation was borrowed from physiology and the mechanics of the circulatory system. (Forty 2004) Circulation spaces are commonly considered as hallways or stairways but are not always defined in such narrow ways. (Hertzberger 2000) The boundaries of circulation space can be implied by movement and defined in less material ways, making it common for architects to isolate circulation as a "system" of the building in drawing form to study the space and surfaces of that system independently. Related to circulation, are *paths*, these are described by (Lynch 1960, 47) as "channels along which the observer customarily, occasionally, or potentially moves". However, this modern view of "potential" circulation space was not always such, the term circulation was adopted by the field of architecture late, c. 1850 and was not considered independently before that point. It was found that the word *distribution* preceded circulation, favoring functionality, organization, and rigidity of axes and communication between discrete spaces. (Forty 2004)

Threshold, as used in architectural discourse, relates to transitional spaces in building most typically, doorways or passages. (Boettger 2014) The simplest definition in architecture is "a place or point of entering or beginning". (Ching 2014, 418) In science, threshold refers to the magnitude or intensity that must be exceeded for a certain reaction, phenomenon, result, or condition to occur or be manifested. Both definitions relate to a change, either in place or state. The term threshold is important in the context of indoor navigation because it defines neither here nor there (start or end) as more than a doorway or staircase, more than a connecting element. Thresholds differ from boundaries in that they are spatial and not linear.

Viewshed is commonly used in landscape architecture and architecture to define the extents visible from a given location. A related term, *isovist* is also referenced in the literature on spatial analysis. "An isovist is the volume of space visible from a given vantage point in space and with respect to an environment." (Benedikt 1979, 47) The concept of isovists and their subsequent representations, isovist or visibility graphs, can provide designers a measurable way to map spatial experience.

The related vocabulary from architecture discussed above is intended to be a reference in reviewing the spatial models discussed in section two. This small cross-section of architectural terms also seeks to provide context to many terms co-opted in the literature on indoor navigation and consider the presented survey of spatial models beyond a building's hallways, doors and rooms and within the broader context of space and architectural intent.

2.0 NAVIGATION AND WAYFINDING

Indoor navigation is a growing field of research yet, a ubiquitous mapping, localization or navigation system for the indoor space has not been implemented. While GPS is widely used for outdoor navigation a primary limitation of it within indoor environments is its signal strength. (Fallah et al. 2013) Additionally, outdoor spaces are easily recognized within Euclidian space or an absolute coordinate system. These coordinates can provide an exact location in outdoor space without relationship to a fixed point or element and distances are measured as absolute dimensions between x_1 , y_1 , and x_2 , y_2 . Generally, positioning within indoor space is communicated through relative or semantic directions; “you are in Room 201” or “take the second door on your left”. (K.-J. Li 2008)

Indoor navigation systems are also developing in commercial applications. The primary applications being in airports, hospitals, and museums. Additionally, retailers have shown interest in point to point consumer wayfinding and navigation within their distribution centers. Location-based provider, Google Maps launched an indoor navigation system that redraws owner-uploaded floorplans of public buildings and has since published over 10,000 floor plans to their online platform. (Anonymous 2012) Both floor plans and BIM models can serve as strong foundations for spatial models in indoor navigation but are not typically used 1:1 because they have varying styles of partitioning space. (Zlatanova, Liu, and Sithole 2013) The graphic conventions of architectural drawings do not easily translate into a spatial logic required for navigation. The way in which indoor spaces should be visually represented for navigation is a methodological issue that is still under discussion in the field. Some literature in this area suggests the need to identify a set of modeling principles that fit the properties of indoor spaces and to be as “generic as possible” to support different applications and various levels of detail. (X. Li, Claramunt, and Ray 2010)

2.1 Spatial Logic

Graph-based representations topologically organize the structure of an indoor spatial environment. (Franz et al. 2005) Graph-like models can be more appealing as representations because of their flexibility and disassociation with the fixed geometry of space in a floor plan. (Franz et al. 2005) These graph-based spatial models are referenced in cognitive science, architecture, robotics, and navigation. They seem to cross disciplines due to their visual abstraction and ability to represent spatial and non-spatial information. Graph-based models are built on a system of nodes and edges (points and lines) that convey a network of spatial relationships rather than a scaled geometric model. Types of graph-based models include occupancy grids, place graphs, view graphs, access graphs, axial maps, and visibility graphs. (Franz et al. 2005) *A priori* building documentation, typically a floor plan is generally available and used as a basis for design in these studies; though the geometric information is not always evident in the final model.

Connectivity graphs are the most abstract spatial graph based on the definition of spaces and access of one space to another. This type of spatial graph is derived from a floor plan and generates a topological representation of spaces. (Fig. 1) Access graphs provide an additional level of information. For instance, while two spaces are connected, they may not necessarily be accessible in both directions, this would likely be due to security reasons. Both connectivity and access graphs require the definition of unique rooms or spaces to define their relationships. (Jensen, Lu, and Yang 2009)

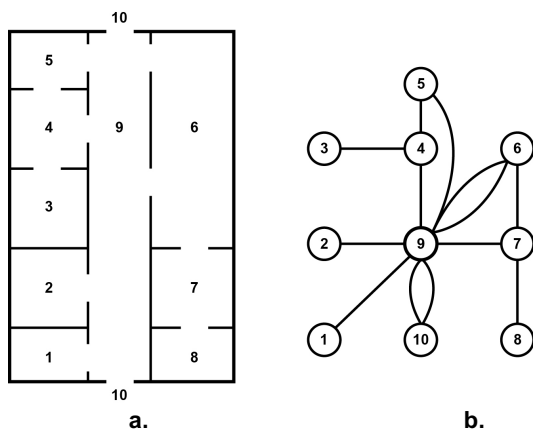


Figure 1: An example of a. base floor plan and associated b. connectivity graph

Occupancy grids were originally proposed in the field of artificial intelligence and are used as a way of representing space for robots to navigate. Space is mapped on a regular grid and each unique cell is connected to its surrounding eight cells. Every cell is assigned a probability value, high values are assigned to cells with more accessible space, while lower values are given to cells containing obstacles. (Moravec and Elfes 1985) When overlaid on a floor plan, the occupancy grid can provide a simple abstract system for navigation while maintaining a relationship to the physical dimensions of a space. In (X. Li, Claramunt, and Ray 2010) the occupancy grid is orthogonal with square cells, the resultant geometry used for navigation is developed through the triangulation of the grid. The connecting lines become edges or paths and the corners of each cell the nodes. The neighboring occupancy values following each move generate the path in a probabilistic method. This model requires a base map (floorplan) of a space and clarity in the definitions of walls, doors, and other access points or obstacles.

Axial maps were developed in the field of architecture and created as a means of representing spatial syntax or the patterns by which different societies develop buildings forms and settlements. (Bill Hillier et al. 1976) Through the use of axial maps, the inherent relationships of social structure are made manifest. This concept presumes that one does not exist without the other and that the relationship is dynamic and changes over time. (Bafna 2003)

Visibility Graphs are built off the idea of an *isovist field*. Isovist fields map the area visible from a given point, while visibility graphs extend that concept to an array of points within a space. By configuring the visibility of all points to one another, the density of lines on the graph define an area as being more visually accessible. Spaces that are more or less visible from nearly all vantage points are made evident. Research in this area has looked at important works of architecture such as the Farnsworth House and Villa Mairea for testing new methods for visibility models. This particular study translates the visibility graph from line to space, using a grid system to show visibility as a field rather than points and vectors. The authors also note that the outcomes would be vastly different had they taken into account the view to the outside. (Alasdair Turner et al. 2001) This is rare evidence of context, or view to the outside, being considered within indoor navigation modeling.

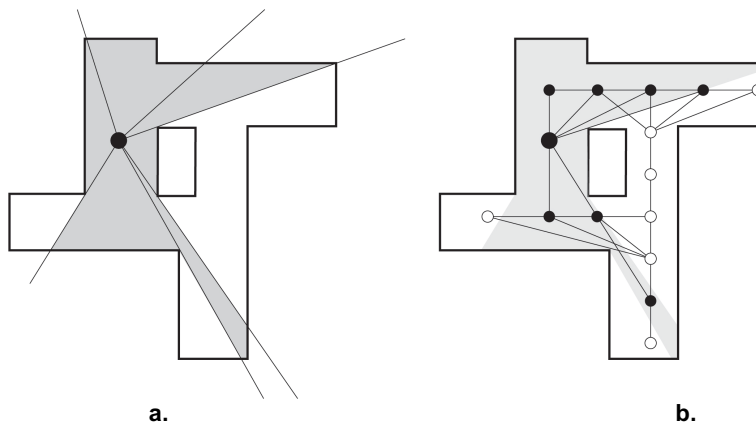


Figure 2: Example of a. isovist field and first-degree b. connectivity graph

Navigation graphs provide the foundation for translating physical space into digital information. The abstraction of spatial information is clearly organized and legible, however, the binary nature of these graphs does little to reveal the continuity of space that relates to the cognitive perception of the environment. Semantic information included in these 2D approaches includes construction elements such as doors, rooms, and stairs that are essential to navigation tasks. (Xiong et al. 2017) Additionally, the role of human behavior is not widely considered and is stated as difficult to approximate in the structural representation of spaces. (X. Li, Claramunt, and Ray 2010)

2.2 Spatial Information

A *semantic map* augments spatial models with descriptive information about physical elements such as walls, floors, and doors that are located in space. (Nüchter and Hertzberg 2008) First introduced within artificial intelligence research, the spatial semantic hierarchy (SSH) is a structuring of spatial information that considers the following information within a space: sensory, control, casual (views), topological (relationships), and metric information. (Kuipers 2000) The SSH is widely referenced in indoor navigation and provides a definition

of components within the human cognitive map. Because the original intention of SSH was clear communication between humans and robots, the basis for the structure is inherently embedded in human experience and behavior. Spatial information in this regard encompasses more than physical features. Sensory information could greatly impact metric information as suggested, “two rooms of the same size will feel altogether different if one has natural light and the other is lit artificially ... A space with a lot of windows will almost always pull you toward the view, and sometimes it can even feel more like an open balcony facing a vista than an enclosed architectural space...” (Goldberger 2009).

Early research on perception suggested that all perceptual systems “can serve to govern directed locomotion. They are all orienting systems insofar as they can guide the individual to a goal.” (Gibson 1966, 73) Recent work in artificial intelligence and indoor navigation is focused on perceptual systems and understanding the role of semantics and spatial definition in wayfinding. A recent study by (Krūminaitė and Zlatanova 2014) used Rotterdam Central Station as a model for indoor navigation. This proposed navigation model presumes that human movement is governed by spatial configuration and lines of sight. By quantifying these conditions and assigning a value to various landmarks in the station, the results provide evidence that qualities such as *attractiveness* to a landmark or user *necessity* are beneficial parameters for defined nodes within an indoor environment. Another important point of distinction within this study is its subdivision of a navigable surface. The navigable surfaces of the space are subdivided using Delaunay Triangulation providing a wider array of decision points (nodes) for navigation. This subdivision approach is related to navigation meshes used to simulate movement in crowd dynamics. (Fig. 3) The options available within this subdivision provide choice and variation for potential routes based on a set of parameters.

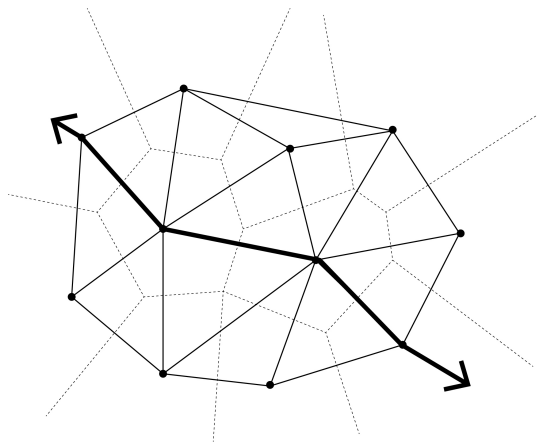


Figure 3: Routing option in spatial subdivision using Delaunay Triangulation

The use of BIM models as a basis for navigable spatial models is growing. (Isikdag, Zlatanova, and Underwood 2013; Xu et al. 2017) Because Building Information Models contain rich data about building components and are three-dimensional, spatial information can be more easily extracted and built upon. Common elements used from BIM for navigation models are: semantic information (levels, element names), properties of building elements (materials, opening direction, exit doors), functional states (obstacles, door open/closed), structural element information (columns, stairs), spatial relationship (hosting of elements), and interoperable geometric representations (exportable format). (Isikdag, Zlatanova, and Underwood 2013)

Additionally, in 2015, the Open Geospatial Consortium (OGC), which is an international voluntary consensus standards organization, introduced “IndoorGML” as a standard for open source models related specifically to indoor navigation. This standard supports a broader language relative to building semantics; defining the following types of space within a model: Anchor Space (entrance), General Space (room), Transition Space (stair or hallway), Connection Space (doorway). An additional type of space, *virtual space*, was proposed in response to these standards and introduced a *threshold* condition or implied space that connects but also differentiates two other spaces without defined edges. (Xiong et al. 2017) A notable distinction in this particular study is the introduction of a building section (vertical cut) to define potential connections between spaces outside of the x and y-axis. Three-dimensional spatial models such as this, use *voxels*, or 3D grids, to identify unique instances in space. Advantages to this cellular division of space can be located through a set of (x,y,z) coordinates and have neighbors, or common boundaries. Much like the occupancy grid, this subdivision of space provides a framework to define the parameters of unique points in space.

3.0 CONCLUSION

The navigation of indoor space is an important topic for architects to gain awareness of. Likewise, developers of spatial models for navigation could benefit from an awareness of architectural design principles. The collection and attribution of experiential data could give needed value to the field of indoor navigation and wayfinding. For example, in building types such as hospitals, using materiality, privacy and light levels as parameters for navigation can promote positive health outcomes. (Huisman et al. 2012)

Architects should also consider seeking new ways of documenting *a priori* building information for purposes of indoor navigation. The sharing of architectural drawings and models with navigation consultants may be on the horizon; developing an architectural convention of intent and analysis for indoor navigation is a viable area of research. The re-drawing of space for indoor navigation is *efficient* but does not place *sufficient* value on design intent or architectural possibility.

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