The informatics of indoor and outdoor space: A research agenda

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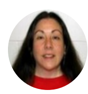

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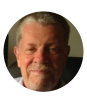

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ABSTRACT

As indoor spaces become more complex, and information technology develops, there is a growing use of devices that help users with a variety of tasks in indoor space. Outdoor spatial informatics is well developed, with GIS at their core. Indoor spatial informatics is less well developed, and there is currently a lack of integration between outdoor and indoor spatial information systems. This paper reports on the development of a research agenda for the integration of outdoor and indoor spaces that has proceeded as part of two research projects funded by the USA National Science Foundation and the Korean Land Spatialization Group. The paper discusses potential application domains. Also discussed are a variety of models of indoor space and unified outdoor-indoor space, from formal models through data models, to functional models related to usability of indoor and outdoor-indoor information systems

Categories and Subject Descriptors

H.1.1, H.1.2 [**Models and Principles**]: Systems and Information Theory – *Information Theory,* User/Machine Systems – *Human information processing.*

General Terms

Design, Experimentation, Human Factors, Theory

Keywords

indoor space, formal models, indoor-outdoor space

1. INTRODUCTION

Imagine a scenario in which emergency response personnel rush to the scene with the task of locating and evacuating the survivors. Current advances in technology should make it possible to provide workers with navigation assistance enabling them to locate all reachable survivors regardless of whether their locations were initially known or not. For example, mobile access to online geographic and building model database services could provide city street maps and floor plans for the buildings in the area. Advances in portable sensing technology could provide real-time information from a worker's PDA of her current outdoor or indoor location, her proximity to other workers and equipment, her current mobility status (e.g., direction, speed, or angle of ascent), and access to environmental data such as temperature or the presence of dangerous gases. In addition, visual, auditory and haptic sensor data could be used to identify myriad other features of her current physical environment. However, the ability to integrate and reason using these differing types of data in information systems has lagged behind data acquisition technology. Challenges to achieving the goal of this kind of data integration and analysis include dealing with incomplete information, differing models of indoor and outdoor environments, computational problems arising from the quantities of available environmental feature types, and uncertainty about which features are the most salient in different environments.

This paper reports on the development of a research agenda for the integration of indoor and outdoor spaces that has proceeded as part of two research projects funded by the USA National Science Foundation and the Korean Land Spatialization Group. In what follows we will discuss motivations and application domains, and then a variety of models of indoor space (I-space) and unified outdoor-indoor space (OI-space), from formal models, through data models, to functional models related to usability of systems that support I-space and OI-space applications.

2. MOTIVATION

There is a considerable body of theory and practice associated with the informatics of geographic space, called geographic information systems or science, depending upon the emphasis. However, there is usually an assumption that the geographic spaces under consideration, whether urban or rural, are outdoors. Of course, a considerable portion of our lives is spent indoors, and so the question arises how much of the body of traditional geographic information science is applicable to I-space and unified OI-space. Unfortunately, while indoor spaces share many characteristics in common with outdoor space, as we shall see there are also many differences. As a starting point, the following general questions for a research agenda suggest themselves.

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- What are the commonalities and differences between O-space and I-space? The question can be addressed at many levels, including ontological, topological, geometrical, data, and functional.
- Can a unified model for OI-space be built, and would it be suitable for most tasks we can conceive of now (and in the future)?
- Can a unified model of OI-space be used to effect transitions between O-space and I-space, and vice versa?
- What are the criteria for evaluating models? Expressiveness? Ease of use? Performance? Inter-operability? Formal verification?

So as to further motivate a research agenda, in this section we will discuss the kinds of applications that arise in O- and I-spaces. Also, it is important to know which applications need to span seamlessly both O-space and I-space.

Location: Finding one's location is one of the most fundamental spatial functions for both indoors and outdoors. A georeferencing scheme is required that we can use as a framework for measurement. Outdoors, by far the most common scheme is the geographic coordinate system, whereby two coordinates, latitude and longitude enable unique and complete specification of each point on the Earth's surface, and we can also include the z-coordinate to measure height. Beyond that we have georeferencing systems such as place names, postal addresses, and administrative areas. In contrast, inside a building, latitude and longitude are not much help, and we have systems based on room numbers and levels. Once a framework is established, we need to take location measurements with respect to the framework – the subject of positioning, and make connections between O- and I-space referencing. With respect to positioning technologies, a very common outdoor system is based upon GPS or Galileo, but indoors there is no universally used technology, and this is a topic for our research agenda.

Navigation: Positioning is a prerequisite for navigation. Spatial informatics can support navigation at various levels, by providing efficient routing and providing representations of the routes that make sense to humans. Both outdoors and indoors, routing algorithms presuppose a network, so network models are required for both indoor and outdoor environments. Indoor navigation has the added complication of multi-level routes. Research is required into common descriptors of such routes; for example, the meaning and functions of landmarks in indoor spaces. Indoor navigation is more focused on pedestrian rather than vehicular traffic.

Transportation and related infrastructure: This is a large outdoor application area that includes positioning and vehicle routing, but also embraces inventory of transportation infrastructure (roads, bridges, sidewalks, etc.) as well as network flows. Planning is an issue, as is traffic analysis and real-time response to traffic problems. Utilities are closely linked to roadways, and their inventory and analysis come into this application. Indoors, network flows become important in the case of emergency evacuation. In general, the planning of a building, taking account of pedestrian flows, cabling and other infrastructure are in this domain.

Resource location/allocation: GIS is now a well-developed tool that can assist in the location and allocation of resources, for example in situating stores or health centers to optimize usage by neighboring populations. Indoors, this is also an issue, where appropriate positioning of indoor resources (toilets, stairwells, fire canisters, etc.) can allow the building to function well. It can also become a critical issue, for example in a hospital, where the positioning of life-saving equipment as well as knowledge of critical personnel (in motion) can be important.

Spatial analysis: This covers a wide field, with 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 [1]. Consideration of this motivation and application domains leads to the following items for a research agenda.

- What specific tasks and application areas require informatics models of I-space?
- What specific tasks and application areas require informatics models of OI-space?
- What are appropriate indoor georeferencing schemes, and how do they interface with outdoor schemes.
- Is there a generic route description nomenclature that supports efficient OI-space navigation?
- How should landmarks be used in I-space and is their usage fundamentally different than in O-space?
- What is the best technique affording accurate indoor localization and tracking?
- How do traffic flow and usage patterns differ between O- and I-spaces?

3. MODELS

3.1 Formal models of space

Many high-level formal models of space are applicable to both indoor and outdoor spaces. For example, geometrical and topological models that relate to generic properties of two and three dimensional spaces are generally applicable. However, structures in I-spaces generally have more "regular" geometries. Consider the boundary of a room compared with a coastline. Also, an I-space has a different dimensionality (3-D or layered 2-D) than an O-space (often a surface). The literature from both animal and human spatial cognition suggests that information about 2-D layout topology is most important for spatial learning [2-5]. As we saw in section 2, the emphasis on networks for many applications and the layered structure of buildings point towards enhanced network models as being especially important. If the regional structure of the indoor spaces (e.g., modeling rooms, hallways, etc.) is important, then such network models may be extended to three dimensional cell complexes. For the integration question, there needs to be clear pathways provided by a general theory between formal entities and concepts in I-space and O-space (see Figure 1).

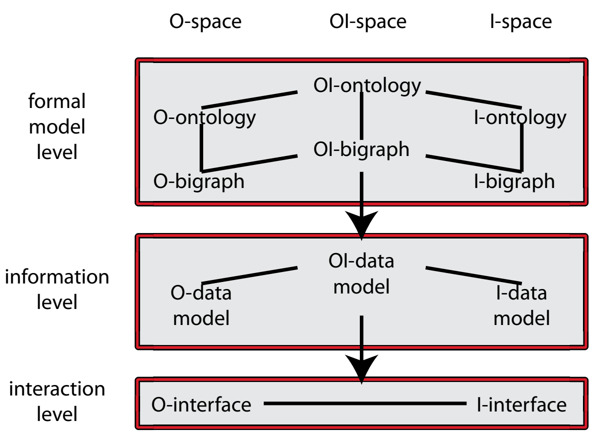

Figure 1: Three levels of seamless Outdoor-Indoor Integration

Integration at the top level provides formal ontological and design models (see Sections 3.2 and 3.3). Bigraphs are one type of formal design tool that provide "a rigorous generic model for systems of autonomous agents that interact and move among each other or within each other" [6]. Data model integration provides a translation between the theoretical model and the concrete data model (see Section 3.4) that could support behavioral studies with human navigation. At the interaction level functional integration (see Section 3.5) is required to provide a translation between the data model and an end-user system that supports seamless navigation between outdoor and indoor settings.

3.2 Domain ontologies

"An ontology describes the concepts and relationships that are important in a particular domain, providing a vocabulary for that domain as well as a computerized specification of the meaning of terms used in the vocabulary" [7]. They are typically used to store, share, process, and reuse domain (e.g., semantic web services, information management systems, electronic commerce, and scientific knowledge portals). Smith developed the Basic Formal Ontology (BFO) that provides an upper ontology which can be used in support of domain ontologies for scientific research [8]. Mid-level ontologies serve as a bridge between specific low level domain ontologies (e.g., cell biology) and abstract upper ontologies such as the BFO. When expressed in a logic-based language, ontologies can be checked for various logical properties including consistency and soundness [9]. Typically, an ontology describes

(i) classes of things in the domain of interest
(ii) relationships existing among things
(iii) properties (attributes) of things

Models of both indoor and outdoor spaces need to account for the types of entities that inhabit such spaces, as well as the geometric properties and relationships that the type and instance collections possess. We can broadly divide these entities into those structural entities that form the fabric of the space (e.g., roads, buildings, lakes, rooms, hallways) and those transient entities that populate the space in a less permanent manner, oftentimes changing location or other characteristics (e.g., vehicles, people, equipment). Grenon and Smith [10] focused on the distinction between **continuant entities** that endure through some extended interval of time (e.g., buildings, tables, and people) and may have spatial parts, and **occurrent** entities (e.g., journeys, meetings, and explosions) that happen and may have temporal parts. Figure 2 shows a schematic that represents the upper ontological framework for this work. There is a two-way participation relationship between continuants and occurrents, and both continuants and occurrents are situated in space-time settings. For example, a person may undertake a journey, and both the person and the journey have a setting in space-time.

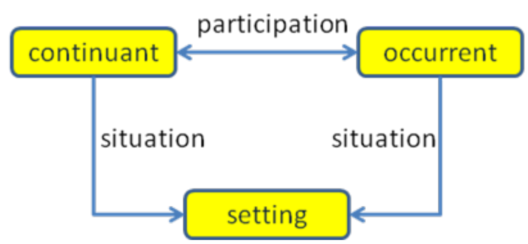

Figure 2: Fundamental entities and relationships in a spatiotemporal ontology

Many of the applications related to I-space point to a housing structure in which there is a heterogeneous mix of highly dynamic scenarios. So, we have two space-time scales: that of the building and that of its occupants. Any ontological study needs to take this into account. In particular, there are a few key questions when creating OI-space ontologies:

- What are the key static and dynamic aspects of the hybrid OI environment?
- What are the occurrent and continuant entities in the domain?
- How can upper ontologies (e.g., BFO) be integrated with mid-level OI-space ontologies and low level domain ontologies (e.g., for a hospital)?
- How can the ontology serve as a useful foundation for formal design models?

3.3 Models of I-space

Good models of indoor space include far more than physical geometry. In 2006 the US General Service Administration (owner of over 300 million square feet of rentable space) demanded that all major building design projects submit a spatial program Building Information Model (BIM) because: "Spaces are one of the most important object types in conceptual building design. During pre-design, many, if not most, client requirements are described in terms of spatial program requirements; furthermore, throughout building design and operation many performance metrics utilize spatial data" [11]. Of critical importance is the creation of models that are more expressive than traditional architectural building models (e.g., CAD models) in which "abstract objects, such as a space, can be defined by the relationships between physical building elements, identified (e.g., room number, room name, etc.), described (e.g., area, volume, use, occupancy, etc.), and referenced (e.g., listed in a room schedule, counted to calculate total floor area, etc.)" [12]. Other models of I-space extend traditional network models of space to

3D cell complexes, useful for reasoning about key physical or functional properties of the space. They allow locations in the space to be specified by levels (e.g., floor number), cells (e.g., rooms, portions of corridors, etc.), and (*x, y, z*)-coordinates in Euclidean space. They can also determine the types of such locations (e.g., dimension) and their spatial relationships. A cell complex model of indoor space can be augmented with an accessibility graph model which incorporates elements of both the indoor structure and the sensed indoor space. A sensible constraint is to keep within current standard three dimensional standards and contexts, such as BIMs and Industry Foundation Classes (IFCs), which are commonly used open source specifications for building modeling (see Section 3.4.2).

Built environments and indoor structures have complex 3-dimensional spatial structures, and are inhabited by a multiplicity of dynamic entity and sensor types. Such spaces demand theories and design tools that go beyond traditional building modeling and geospatial methodology. They must support the representation of building elements in terms of their 3D geometric and non-geometric (functional) attributes and relationships. Key questions when creating a formal design model include:

- What elements from the domain ontology should be included in the design model?
- What environmental features are needed for inclusion and how should they be best represented?
- How can traditional network models be extended to include the third dimension, as is needed for representing I space?
- Can a common framework for O and I space be built? Would it be suitable for most tasks we can conceive of today (and in the future)?

3.4 Data models

Indoor spaces are typically perceived in 3 dimensions, and are modeled (e.g., in a CAD system), as some sort of vector-based model ranging from simple 2D drawings to parametric 3D object models. Relative locations of indoor objects can be mapped to relative or absolute reference frames. However, orientation strategies (such as choice of landmarks and reference frames) can be markedly different indoors [13]. Outdoor or geographic spaces are usually perceived as 2D, with the vertical (the "half" dimension) either thought of as an attribute of location or ignored altogether. Most GIS use some sort of surface model (also called 2.5 D or pseudo 3D) of space, to visually represent 3D space. Terrain models are typically of this type where an added z-index for every 2D location represents depth or some other attribute. **Digital Surface Models** (DSM) such as those used by architects and landscape designers include buildings, vegetation, and roads, as well as natural terrain features. **Digital Elevation (Terrain) Models** (DEM or DTM) used in GIS applications often exclude objects such as buildings and vegetation. Relative locations of outdoor objects are typically expressed through external reference frames based on cardinal directions or distant landmarks. Absolute locations can often be mapped to a precise coordinate system such as the WSG84 datum.

3.4.1 Geometric and topological data models

Although traditional modeling strategies for indoor and outdoor spaces differ, there is one kind of representation that is found in both indoor and outdoor domain models**. Boundary representation (BRep)** models describe the topography of either 2D or 3D shapes using geometric representations of the object's boundary. Common topological features of BReps are: vertices, edges (bounded pieces of a curve), faces (bounded portion of a surface), shells (sets of connected faces), loops (circuits of edges bounding a face) and loop-edge links (also known as half or winged edges). Examples include the 3DFS, TEN, and Prism models. The **3D Formal Data Structure (3FDS)** model [14] consists of features (related to a thematic class), elementary objects (point, line, surface and body) and primitives (node, arc, face and edge). To overcome difficulties in modeling objects with indeterminate boundaries, the **Tetrahedral Network (TEN) model** [15] models 3D objects in a network of simplexes [16] using four primitives (tetrahedron, triangle, arc, and node). The **Prism** data model [17] is a 3D geometric model designed to improve the ability of spatial information systems to perform efficient spatial reasoning about the topology of indoor spatial objects. It uses extrusion techniques based on triangular prisms to produce 3D objects from 2D footprints. The Prism Model uses polygonal rather than triangular prisms, and hence can produce more diverse 3D shapes from 2D footprints.

3.4.2 Building Information Models

Building Information Modeling (BIM) is the process of creating and maintaining building data during its life cycle using three-dimensional, real-time, dynamic building modeling software to decrease wasted time and resources in building design and construction. This process produces the Building Information Model (also abbreviated BIM), which incorporates spatial relationships, geographic information, building geometry, and quantities and properties of building components, including the life-cycle processes of construction and facility operation [18]. It began as a common name for a variety of activities in object-oriented computer-aided design (CAD) that support the representation of building elements in terms of their 3D geometric and non-geometric (functional) attributes and relationships. **Industry Foundation Classes** (IFCs) are a commonly used format for BIM (the data model). They are architectural, engineering, and construction (AEC) open data model specifications for data representation and file formats for defining graphic data as 3D real-world objects that enable CAD users to transfer design data between different software applications. They are intended to provide an "authoritative semantic definition of building elements, their properties and inter-relationships" [19].

3.4.3 Models for data exchange

The Open Geospatial Consortium (OGC) defined the **Geography Markup Language (GML)** as an XML grammar to serve as an open interchange format for geographic transactions on the Internet [20]. It supports the description of a rich set of geographical features and serves as a general modeling language for geographic systems. Another widely used XML-based language schema is the **Keyhole Markup Language (KML)**, developed for use with Google Earth which supports expressing geographic annotation and visualization in web-based 2D maps and 3D Earth browsers. Another important geographic modeling language is **CityGML** [21] an XML-based format for the storage and exchange of virtual 3D city models. See Figure 3 for the relative expressiveness of some of these models.

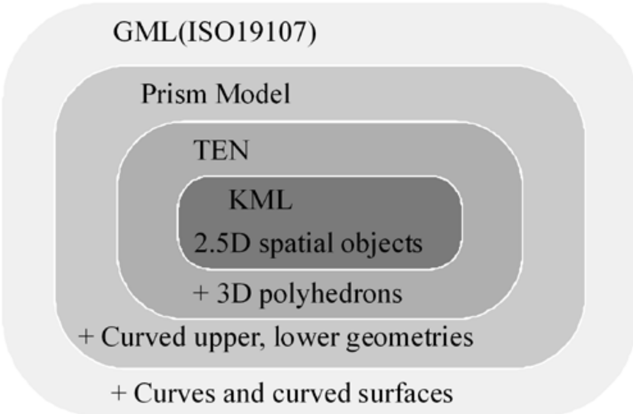

Figure 3: Relative expressiveness of 3D spatial models (Source: [17])

A more recent development is **IndoorML**, a data exchange format based on CityGML which seeks to improve the expressiveness of the schema by including indoor spaces and objects. IndoorML is currently being developed by members of the Indoor Spatial Awareness (ISA) project [22] to support the development of spatial database systems for indoor environments such as hospitals and convention centers. It incorporates the Prism data model, the Indoor Spatial Data Model (ISDM), and the multi-layered model.

3.4.4 Other data models

The **Indoor Spatial Data Model** (ISDM) is a schema for representing indoor and outdoor built spaces in 3 dimensions. Based on CityGML, it includes specifications of the topology and appearance of the 3D objects in the built space. The ISDM incorporates the Node-Relation-Structure (NRS) model [23] which derives key complex topological relationships (e.g., adjacency and connectivity) from indoor 3D spatial object geometries and topologies and provides a means to simplify them. It supports efficient implementations of complex indoor navigation and routing problems [24]. The **multi-layer model** [25] was developed specifically to support indoor navigation, and is based on the 191xx ISO standards family and hence can be mapped to GML. It combines built space models with geometric and topological information to support route planning and localization techniques for indoor navigation tasks. It is also based on CityGML and incorporates the NRS model.

There are many highly task specific data models for indoor space. Open questions include:

- What elements from the domain ontology should be included in the design model?
- What queries should a location-based system be able to answer about a referent (indoor space or object) and its relation to other referents?
- Is there a common data model that could be used to represent O-I spaces and objects?
- Is a unified model preferable to multiple interoperable models?
- Is there a gold standard metric that a data model should be able to support?

3.5 Functional models and human performance

Thus far, we have discussed formal models of indoor spaces, data structures for representing this space, and some of the elements that differentiate O-space from I-space. Another aspect of indoor space involves a functional level understanding--how human agents learn and represent these environments in order to support spatial behavior. At the functional level, the primary difference for both spatial knowledge acquisition and mental representations of space is related to environmental structure and the amount and type of environmental information available to support behavior.

3.5.1 Spatial knowledge acquisition

The goal of spatial learning is similar between O- and I-space--the navigator generally has a destination and wants to get from one place to another in a safe and efficient manner. However, there are some significant environmental differences which make apprehending and learning indoor spaces more challenging than the same tasks outdoors. The availability and type of navigational landmarks are one such difference. Where landmarks in outdoor environments are often large visible persistent objects (e.g., a building, lake, mountain range, etc) indoor landmarks represent physically smaller objects (e.g., a salient painting, fountain, lobby, etc). The advantage of outdoor landmarks is that they are often accessible from multiple locations in the environment and are independent of the route traveled. Thus, they afford an excellent fixed frame of reference which helps ground what is perceived from the local environment into a global spatial framework [26] By contrast, the advantage of these global landmarks is often greatly reduced (if not completely eliminated) when learning and navigating indoor spaces. The constrained field of view imposed by the structure of indoor environments, i.e., limited sight lines in hallways and occlusion from walls, ceiling, and other architectural elements, means the navigator must depend more heavily on local (proximal) landmarks. As a result, it is generally much easier to learn particular routes through a building than acquiring survey type knowledge of the global spatial configuration through navigation of indoor layouts [27].

Spatial learning in outdoor settings also benefits from the consistency of city blocks, naming of streets, and addressing conventions of buildings. These cues provide important spatial information about one's distance traveled, direction of movement, and location in the city. By contrast, indoor navigation lacks most of these orienting cues, as hallways are not laid out in blocks or given spatially meaningful or uniquely identifiable names. Although rooms usually have numbers, beyond indicating the floor, the numbering convention provides no reference system to help semantically structure the space.

3.5.2 Mental Representations

Space can be represented in different ways in memory depending on information availability and movement behavior during learning. The nature of this representation can have a large effect on the behaviors supported. If a person navigates a route between A and B, they may encode the lengths of the constituent segments, the number of turns, their direction, and perhaps even the magnitude of the turn angles. However, even if represented and recalled correctly, this type of representation is limited in that it does not readily permit mental transformations and spatial inference (e.g., shortcutting, detouring, inferring straight-line connections between nonlinear path elements, or developing a globally coherent representation of spatial relations). The ability to build up a global representation of space, called a cognitive map, means that the space has been learned and represented beyond a sequence of procedural route operations. This is obviously a more flexible type of representation but one which is also harder to build, especially for indoor spaces (largely due to availability of local vs. global landmarks). Floor maps can aid in gaining a global perspective but such maps are usually depicted as a 2D representation and do not provide knowledge of multiple floors. Indeed, the cognitive map is generally discussed in terms of 2D or 2.5 D spaces. Rarely is elevation considered (i.e., object or boundary height). The manner which 3D environments are layered (e.g., as is the case with vertical displacement of different floors within the same building footprint) is also poorly understood. Research has clearly shown that people can remember the locations of places on the same floor, assessed by pointing the Euclidean direction to an unseen endpoint, but are significantly less accurate when pointing between floors of the same building [28].

A research agenda investigating functional aspects of human performance in indoor spaces must consider such factors. Some important questions are:

- What are the differences in environmental information availability, structure, and content between O- and I-spaces?
- Can a core set of environmental features be defined that promote learning, cognitive mapping, and navigation behavior in indoor spaces?
- How do humans encode and represent 3D structure in complex buildings?
- What are the technological solutions for providing location-based information and real-time navigational assistance in indoor spaces?

An important starting point for this research agenda is to establish a core set of building features (primitives) that promote learning. Currently, there is no consensus on the amount, content, or structure of information that is needed to support indoor navigation or how usage of salient cues may differ across environments. A recent effort by Wiener and colleagues described a taxonomy of the cognitive processes and structural properties supporting outdoor navigation [29] but a functional taxonomy for navigation of indoor spaces does not yet exist. As is described in section 3.2, a key starting point is development of robust domain ontologies of indoor spaces. Although layout topology is particularly important for spatial learning, non-geometric cues (e.g., landmarks like wall color or salient objects) increase efficiency and place memory when navigating highly complex environments [30] or when geometric cues are ambiguous [31]. However, to determine the critical feature set supporting spatial knowledge acquisition and wayfinding behavior, more research is needed that parametrically manipulates environmental variables of indoor spaces and compares performance to known differences with outdoor spaces (e.g., different scale, coordinate system, field of view, etc). In addition, formal studies are needed on the z-axis representation of indoor environments (i.e., how vertical displacement and inter-floor relations are represented in cognitive maps). Taken together, this knowledge will not only provide insight into the information processing and representation of spatial cues needed for theories of human spatial learning and representation, it will also benefit advances in the informatics of indoor space which is critical for developing formal models, data structures, and navigational technologies.

4. CONCLUSION

This paper discusses the development of a research agenda for the integration of indoor and outdoor spaces that has proceeded as part of two research projects funded by the USA National Science Foundation and the Korean Land Spatialization Group. The paper uses potential application domains to motivate a list of research questions. We have considered a variety of models of indoor space and unified outdoor-indoor space from formal models, through data models, to functional models related to usability of indoor and outdoor-indoor information systems.

It would not really be appropriate to talk about specific future work here as, in a sense, this is all future work. However, it might be useful to give the authors' views as to the most important questions to be addressed. There are really two fundamental research issues, the creation of an appropriate framework for an effective informatics of indoor space, and the development of a means by which O- and I-spaces can be integrated. Fundamental to this are the underlying ontologies, for only by understanding the ontologies of O- and I- spaces can we ever hope to effectively integrate them at any level. In our view, the way forward is the development of an generic ontology, of which O-space and I-space are special cases. This OI-ontology can then be used as an integration tool. In order to test the effectiveness of such integration, it will be vital to validate at the functional model level.

The assignment of priority to the ontological questions of course reflects the authors' interests. Indeed, much progress has already been made in this direction, using the theory of affordances and image schema. What is certainly true is that the entire area of I- and OI-spaces is an important and timely research agenda, which we commend to researchers for further investigation.

5. ACKNOWLEDGMENTS

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