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# Indoor Spatial Awareness Project and Indoor Spatial Data Model

Ki-Joune Li*


## ABSTRACT

With the rapid progress of location based services, GIS, and ubiquitous computing technologies, the space that we are dealing with is no longer limited to outdoor space but being extended to indoor space. Indoor space has some differences from outdoor space, therefore to provide integrated spaces and seamless services, it is required to establish new theories, data models, and systems. For this reason, ambitious project has been launched last year to establish a theoretical background, develop a core technologies and systems, and provide services of indoor spatial awareness. In this paper, we present an overall sketch on the project and major research topics. First, we present the ISA (indoor spatial awareness) project with its goal and research topics. Second, a simplified 3D spatial model, called prism model, is proposed as a basic data types and operators of indoor spatial DBMS. Third, a indoor feature data model, developed T. Kolbe et al. who is a member of this project team, is introduced in this paper. This model provides a basis for the integration of different spaces.


**Keywords** : Indoor Space, GIS, Spatial Awareness, Indoor GIS, Indoor Spatial Awareness


## 요 약

LBS, GIS 및 유비쿼터스 컴퓨팅의 기술의 빠른 발전과 함께, 우리가 다루는 공간은 더 이상 실외공간에 한정되지 않고, 실내공간으로 확장되고 있다. 그런데 실내공간은 실외공간과 다른 특징을 가지고 있으므로 실내외 공간의 통합되고 연속적인 서비스를 제공하기 위하여서는 새로운 이론, 데이터모델 및 시스템을 개발하여야 한다. 이러한 이유로 실내공간인지를 위한 기초이론을 개발하고, 핵심기술 및 시스템을 구축하고, 서비스를 제공하기 위한 프로젝트가 시작되었다. 본 논문에서는 실내공간인지(ISA) 프로젝트의 목표와 연구주제들을 소개한다. 그리고 실내공간데이터베이스 관리시스템의 기초적 데이터타입과 연산자를 위한 프리즘데이터 모


* Department of Computer Science, Pusan National University (lik@pnu.edu)

델을 소개한다. 또한 T. Kolbe가 제안한 실내공간 모델도 함께 소개한다. 이 모델은 다양한 공간을 통합하는데 기초가 될 것이다.

**주요어** : 실내공간, 지리정보시스템, 공간인지, 실내 지리정보시스템, 실내공간인지

## 1. Introduction

The space that deals with GIS is evolving from huge areas covering for example the entire territory of a country to relatively small areas. At the frist stage of GIS, the areas of GIS were mostly a country or a city, which we call *geographic space*. However the extent of area has been reduced to *environmental* or *vista space* after the second or third stages of GIS. While the users of GIS have been mostly professional, such as urban planners, the user group of GIS is expanding to public such as pedestrians and car drivers as the evolution of space.

Indoor space belongs to the scope of GIS as well as outdoor space, even though very few attention has been paid to this area. In particular, the recent progress on mobility technologies in indoor space, including indoor positioning technologies, wireless communication, and tiny devices gives strong motivations and demands for indoor GIS. While several applications have been developed for indoor GIS, they lack of a structural and systemic approach from theoretical background and indoor spatial modeling, indoor spatial data management systems, to applications and infrastructure of indoor space.

For this reason, a project called ISA (Indoor Spatial Awareness) project, has been launched since 2007 not only to develop application systems but also to establish theoretical basis of indoor GIS. The project aims to cover the entire scope of the life cycle of spatial information as depicted by figure 1, including theoretical background and indoor spatial data model, indoor spatial database management systems, and the applications and infrastructure for indoor services.

This paper is organized as follows. In section 2, the overall structure of the project and the scope will be given. The subsequent sections will cover the research topics of each group of the project. First in section 3, the data types of indoor spatial database management systems will be given and a multi-layered indoor spatial data model contain research will be proposed in

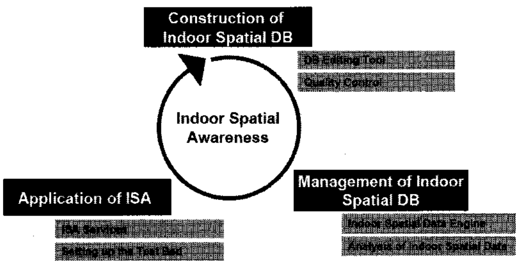



Figure 1. Scope of Indoor Spatial Awareness Project

section 4. This paper is to be concluded in section 5.

## 2. Overall Structure of the ISA Project

This project is composed of three parts as illustrated by figure 2. First the development of tools for building and quality control of indoor spatial data belongs to the group 2 of the figure 2. Second, the group 1 is responsible to develop an engine for the indoor spatial awareness, which provides the storage, management, and analysis of indoor spatial data. The establishment of indoor spatial theory and data models are covered by this group. Third, by group 3, several pilot applications are developed in a context of *ubiquitous convention* (*u-convention*) services. The development of a test bed is also developed by this group.

Editing and Quality Control: The most expensive and time-consuming procedure during the development of ISA applications and services is to build and maintain the indoor spatial databases as the outdoor GIS. Efficient tools and environments to build indoor spatial databases therefore not only reduces the cost of indoor GIS development but also improves the quality of services. For this reason, we are an authoring tool of indoor spatial databases including the quality control functions. The objectives are to develop a light and easy authoring tool, and to import existing CAD or BIM data like IFC.

Indoor Spatial Data Model and Theory: The indoor space differs a lot from the outdoor space in that it is no longer based on Euclidean geometry. It means that the properties of Euclidean space used by GIS and spatial database systems, are no longer valid for indoor space. For example, a position in outdoor space is specified by the coordinate reference systems, while a position in indoor space is identified by symbolic reference systems such as room number.

We first establish a theoretical basis of indoor space and develop several indoor spatial data models from the most basic one to the model for the applications based on the indoor spatial theory. The eventual goal is to replace the data model defined by ISO 19107 and its applications depicted by figure 3.

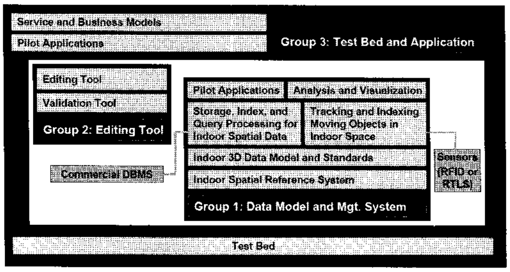



Figure 2. The Structure of Indoor Spatial Awareness Project

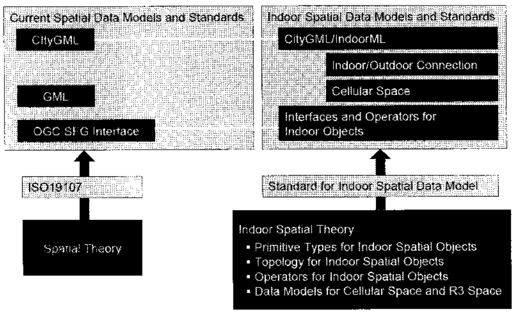



Figure 3. New Spatial Theory and Data Models

**ISA Data Engine:** Since the properties of indoor space differ from those of outdoor space, the systems developed using the properties of outdoor space are no longer proper for indoor data. In particular, the indoor GIS is tightly coupled with ubiquitous infrastructure such as sensors and digital broadcasting network, the core system, which is called *engine* should be developed for indoor spatial data. The functions of the ISA data engine include

- storage of indoor spatial data using commercial DBMSs,
- indexing and query processing of indoor objects including mobile ones,
- indoor spatial analysis, such as routing analysis, and
- tracking indoor mobile objects from RFID sensor data.

The overall architecture of ISA data engine is shown in figure 4.

**Test Bed and Pilot Applications:** In order to validate the system developed by this project

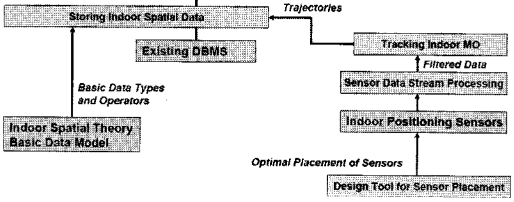



Figure 4. Overall Architecture of ISA Data Engine

and improve the performance and reliability of the system, we are planing to provide a test bed. For this purpose two types of test beds are being developed. First, a virtual test bed is develop to provide an environment of a virtual infrastructure for sensors, indoor spatial data, and users. It consists of two parts, indoor spatial databases of structural components such as wall, rooms, and stairs, and second data streams from sensors. In addition to the virtual test bed, we are also implementing a real test bed system with a indoor spatial data server and hardware infrastructure including position sensors and mobile devices.

## 3. Prism Model - Data Types for Indoor Spatial DBMS

With the recent increase of demands for 3D information, we need a robust data model of 3D spatial objects to meet the requirements from diverse applications. For this reason, several studies have been done out by ISO/TC211 and OGC, among which the data model of ISO 19107[2] and the data model for KML[6] are the most important ones. The data model of ISO 19107 provides a strong expressive power of 3D spatial information with a sophisticated model for full 3D solid object. And GML[4] is based on the spatial data model of ISO 19107. However this data model has a serious drawback that the size of data in GML is large and the implementation of ISO 19107 is difficult and heavy, due to the complicated structure of this data model.

On the contrary, the data model employed by KML, which has been developed for the use of Google Earth, includes a simple 3D spatial data model to offer visualizaton services of 2D and 2.5D spatial objects. Compared with GML, the size of data in KML is smaller than GML and most of systems supporting KML are lighter than those for GML However the expressive power in KML is limited due to its simple spatial data model and COLLADA, which is another data format for 3D spatial objects, must to be used if the 3D information is complex.

In this paper, we propose an alternative 3D data model, called prism model, to provide an enough expressive power and achieve a satisfactory efficiency at the same time. Note that the prism means not only the triangular prism but also polygonal prism. Our model is based on the extrusion technique to represent 3D objects from 2D footprint spatial objects like the model in KML. But we generalized it to handle more diverse shapes with upper and lower geometries as shown in figure 5.

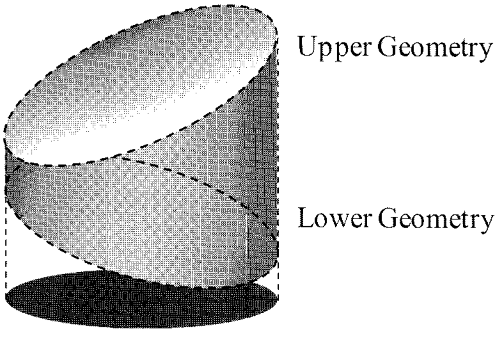



Figure 5. An example of prism geometry

### 3-1. Schema of Prism Model

The geometry schema of the prism model is based on the simple feature geometry model of OGC. Figure 6 shows the diagram of basic prism model. It contains three types of extrusive geometry, extrusive point, extrusive curve, and extrusive surface, which are a subclass of curve, surface, and solid respectively. Each extrusive geometry is bounded by one lower and one upper geometries, which have the same 2D footprint geometry. The vertices of an upper geometry have higher z-values than lower geometry. These properties are described as follows.

**Property 1:** Footprints of lower and upper geometries

$$\forall p \in G_{upper}, \forall q \in G_{lower} \rightarrow p.x = q.x \wedge p.y = q.y \wedge p.z \geq q.z$$

**Property 2:** the hight values of lower and upper geometries

$$G_E = \{(x,y,z) \mid z_{lower} \leq z \leq z_{upper}, (x,y,z_{lower}) \in G_{lower}, (x,y,z_{upper}) \in G_{upper}\}$$

For example, a solid is represented by an extrusive polygon with a lower and an upper

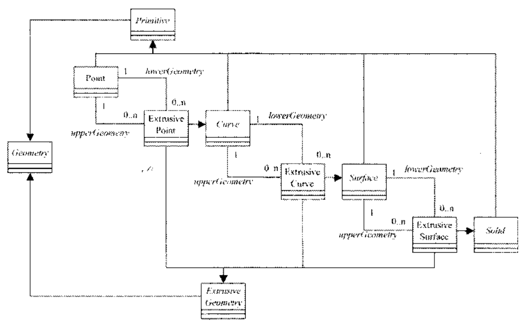



Figure 6. The diagram of extrusive geometries

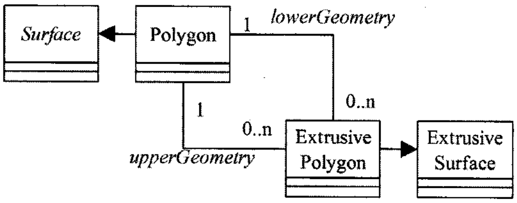



Figure 7. Diagram of data model for extrusive polygon

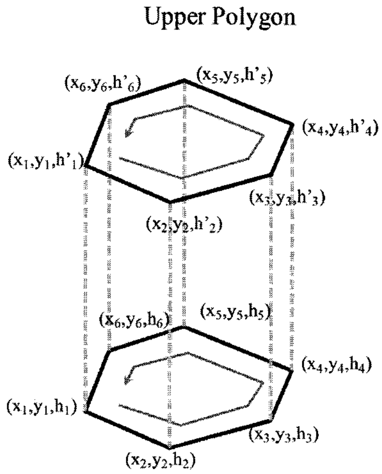



Figure 8. An example of extrusive polygon

polygon, which are in fact a subset of surface as depicted by figure 7 and 8.

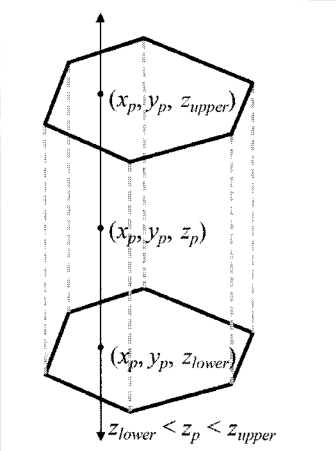
## 3-2. Comparison of Prism Model with Other 3D Models

The prism model has several advantages as follows. First the prism model is simpler and contains less geometric component than the ISO 19107 and consequently the size of data by our model is smaller than GML. For example, a cube is composed of 8 vertices, 12 lines and 6 faces by the model of ISO 19107, while it is described by 8 vertices, 8 lines, and 2 faces. It means that the storage, data transfer, and geometric computation efficiency by the prism model is better than the ISO 19107 because of the smaller size of data.

Second, we apply the 2D filtering technique to process 3D spatial queries, which is a common query processing policy for 2D spatial databases. For example, given a 3D range query, we first filter only the spatial objects contained by the 2D footprint of the query region and then refine the small number of candidates obtained from the filtering step to check if they are really in the given 3D range. It is possible and efficient since most 3D objects such as buildings and facilities are placed on the terrain.

Third, the 3D geometric computation by the prim model is more efficient than full 3D geometric computation. For example, in order to compute the point-in polyhedron, we first check if the point is lower than the upper geometry and upper than the lower geometry and second if the point is contained by the footprint polygon as shown by figure 9. This algorithm is much simpler than the geometric computation with full 3D.

Fourth, most 3D geometries can be described by the prism model. If a 3D geometry, for example an arbitrary polyhedron, is complex, then we can decompose it into a set of prisms and represent the geometry by the set of decomposed prism. However the 3D objects with curved surfaces can not be represented by the prism model.




```
Algorithm 1 Point    in extrusive polygon
PointInExtrusivePolygon( p, polygon_upper,polygon_lower)
if ( PointIn2DPolygon( p, polygon_upper))then
  if    (polygon_upper.z≤p.z≤polygon_lower.z)then
    return    true
  endif
endif
return false
```

Figure 9. A query example of point in extrusive polygon

Figure 10 shows the relationship between the expressive power of the 3D spatial data models. The model of ISO 19107 or GML contains most of 3D geometries, while the model of TEN (TEtrahedronized Network) includes only polyhedron. The expressive power of prism model is almost equivalent with that of TEN model except that it may include not only plain face but also curved face for upper and lower geometries. It means that the expressive power of the prism model is slightly stronger than TEN.

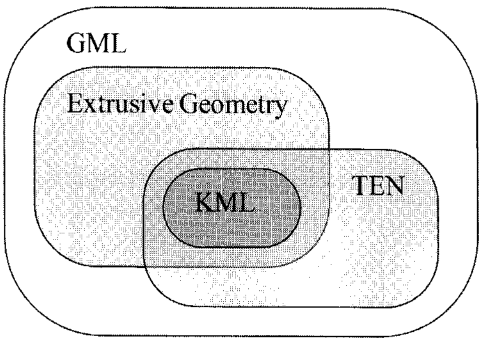



Figure 10. Relationship between 3D data models

We validated that 3D geometric computation by the prism model is efficient. Therefore we will develop efficient algorithms of processing of 3D geometric operations such as intersections between polyhedrons by the model and verify by experiments for the future.

## 4. Indoor Spatial Data Models

In this section, we introduce an indoor data model developed by T. Kolbe (Kolbe 2008) to handle several types of spaces in a unified model. Note that this section is a summary on the paper of T. Kolbe (Kolbe 2008). Due to limitations of existing modeling approaches we propose a novel framework for a multilayer space-event representation. A crucial aspect of this framework is the clear separation of different space models, e.g., topographic space and sensor space. This approach allows for the decomposition of a specific space into smaller units according to respective semantics, without influencing other space representations.

Furthermore, we show how to connect the layers, i.e., space models, in a well-defined way and to derive a valid and unique joint state embracing all linked layers at a given point in time. Based on joint states, e.g., between topographic space and sensor space, the proposed multi-layer modeling approach can be utilized to enable localization and route planning strategies. Figure 11 illustrates the proposed modeling framework.

Within the framework, alternative space models are represented as separate layers. In figure 11, the layer to the front represents topographic space, whereas the sensor space is depicted by the layer in the back. Each layer can further be divided into four segments (indicated by black cutting planes). The vertical division corresponds to space representations within Euclidean space respective topology space on the one hand. The horizontal partitioning indicates primal and dual space on the other hand. Consequently,

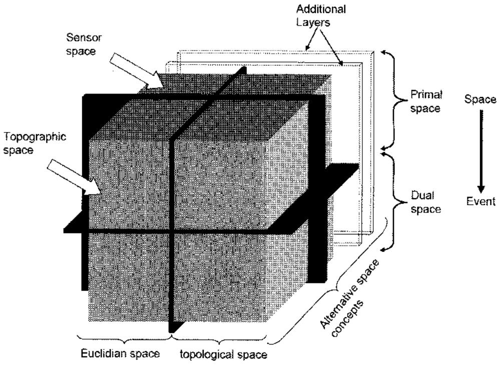



Figure 11. Multilayer combination of alternative space concepts

each space model is given by four distinct space representations. The separation of layers results from different space models with different partitioning schema. For example, in topographic space geo-objects such as buildings may be represented using semantic 3D building models (see [Groger 2007, 12]). Further semantic decompositions into, e.g., rooms, walls, doors, etc. can be applied within these model. However, the notion of sensor space substantially differs from topographic space. The sensor space is rather decomposed according to signal characteristics such as propagation and signal coverage areas. Besides topographic and sensor space, further alternative concepts of space can be incorporated into the framework by adding additional layers. The number of layers is unbounded. For example, in the area of philosophy different definitions for space (e.g., movement space, activity space, visual space etc.) can be encountered which can also be used to describe a built environment. However, the notion of space and its semantic decomposition again differs from topographic or sensor space.

Since each layer provides a valid and consistent representation of space, the common framework itself is to be seen as a valid multi-layered space representation, which can be used as a whole to describe, for example, the indoor environment of buildings. For each layer, topological relationships such as connectivity and adjacency relations between 3D spatial objects are represented within topology space (i.e., the right side of fig. 12). In primal space, topology is induced by the corresponding 3D geometry in Euclidean space. By applying a duality transformation based on Poincaré duality, the 3D cells in primal topology space are mapped to nodes (0D) in dual space. The topological adjacency relationships between 3D cells are transformed to edges (1D) linking pairs of nodes in dual space.

The resulting dual graph represents a Node-Relation-Structure as proposed by Lee (Lee 2008). Furthermore, the dual graph can also be seen as a state transition diagram. The active state is represented by a node within the dual graph and denotes the spatial area the guided subject or object is currently in. Once the subject or object moves into a topologically connected area, another node within the dual graph and thus a new active state is reached. The edge connecting both nodes represents the event of this state transition. Therefore, events are related to the movement of subjects or objects through the explicit topological representation of space. Accordingly, our modeling approach is a space-event model. Under the assumption that the space is subdivided into disjoint areas, exactly one node within the NRS respectively the state transition diagram can be active.

### 4.1 Topographic Space / Layer

The topographic layer is illustrated in figure 12. For indoor navigation, the topographic space represents the interior environment of buildings and its semantic decomposition into building elements like rooms and doors in order to enable route planning. Semantic building models for the representation of topographic 3D objects nowadays become increasingly available in the context of Building Information Modeling (BIM), such as the Industry Foundation Classes (IFC) (Adachi 2003) and in the field of 3D city modeling.

The City Geography Markup Language (CityGML) (Groger 2007, Kolbe 2005) defines a geospatial information model for the representation of 3D topographic urban objects including buildings. According to the general space concept of layers, the topographic space can be described by four distinct representations. The upper left element of figure 12 illustrates the non-overlapping 3D geometry representation of built environment in Euclidean space. This geometry information can be directly derived from IFC and CityGML building models. The upper right element represents the induced natural topology of the 3D spatial objects according to ISO 19107. Since disjoint partitioning of Euclidean space is assumed, the relation between both upper elements can be expressed with the "Realization" association between geometric and topological objects defined by ISO 19107. Accordingly, associated objects in either space must share a common dimension and are related by 1:1.

Whereas the upper part of figure 12 represents the primal Euclidean respectively topology space, their dual representations are depicted by both lower elements. For the lower right part, topology is represented as dual graph based on the NRS model and is derived from topology in primal space by Poincaré duality transformation. The NRS (Node-Link Relationship Structure) does not contain metric information which is, however, necessary in terms of spatial 3D queries such as shortest path calculation. In order to integrate metrics, one possible solution could be the usage of the methods "representativePoint()" and "centroid()" defined for GM_Objects in ISO 19107. For 3D solids, these methods return a point geometry representing the centroid of the volumetric object. This point representation could be stored attributively within the NRS. Since nodes of the NRS are directly related to TP_-Solids in primal topology space, which, in turn, are directly related to GM_Solids in primal Euclidean space (depicted by dotted arrows in figure 12), this metric information can be uniquely derived. Furthermore, weights representing, for example, distances between rooms can be assign to the edges of the NRS. These weights could be derived from primal Euclidean space accordingly.

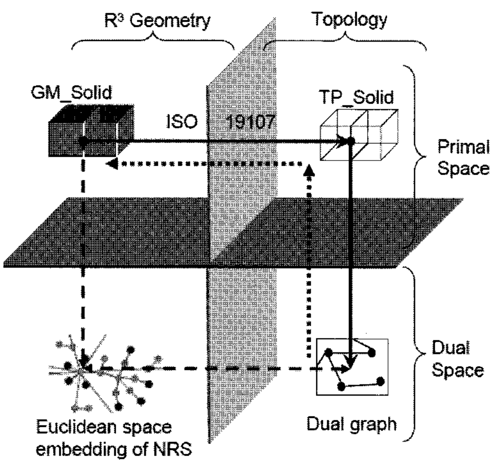


Figure 12. The topographic space (Kolbe 2008)

The lower left element of the topographic layer finally represents the Euclidean space embedding of the NRS. The dual transformation of Euclidean space results in a geometric network model (Lee 2008). This dual graph representation is derived by mathematical functions such as skeletonization processes.

## 4.2 Sensor Space / Layer

The concept of space-event modeling allows for consistent specification and interpretation of various space concepts (Kolbe 2008). This ensures equivalent interpretations of sensor space and topographic space. When arranging sensors within a building (e.g., Wi-Fi), transmission ranges may overlap, which requires their decomposition into disjoint regions in order to define unambiguous states. As a state one can define the

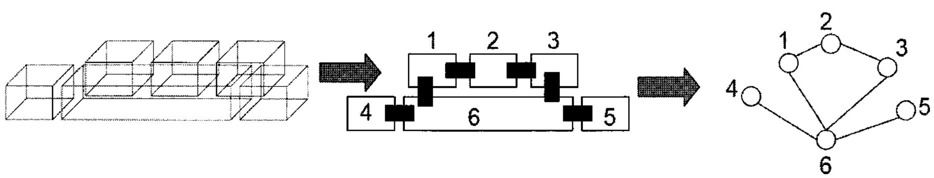


Figure 13. Example for the partitioning of building interior into rooms and its representation in dual space (Kolbe 2008)

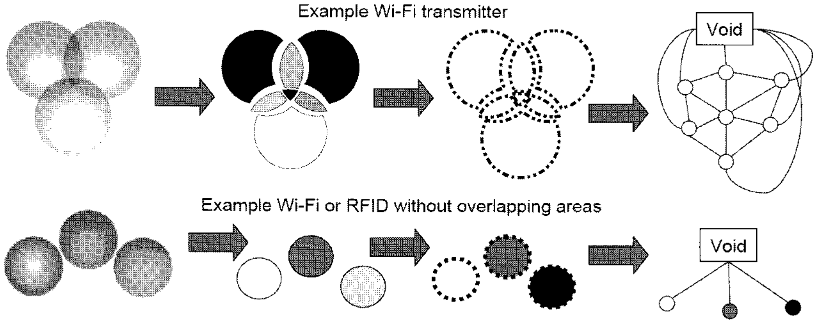


Figure 14. Example for partitioning into cells and their representation in dual space (Kolbe 2008)

range or different signal strength areas. The event can be understood as an entry into a sensor area or as the crossing of a certain threshold value.

Like in the topographic layer, the accuracy of positioning correlates to the granularity of partitioning. Hence with smaller cells, navigation gains in precision. To describe areas with no sensor coverage, an additional state called "void" is defined for every sensor system. This state is needed when the navigating subject or object leaves the range of a sensor without other sensors around, e.g., when leaving the building. For sensor systems covering the whole interior building area, the state "void" only represents the outside building environment. Figure 14 illustrates the modeling of sensor space in the case of overlapping transmitter/ sensor ranges. Figure 15 further specifies different geometric and topological representations of sensor space.

In IR³, the partitioned sensor areas are represented as GM_Solids (upper left part) and their topological representation as TP_Solids (upper right part). The two representations are

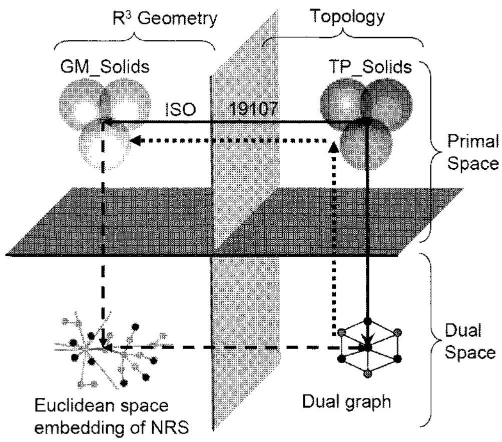


Figure 15. Sensor space (Kolbe 2008)

linked by the "Realization" association defined in ISO 19107. The Poincaré Duality defines the mapping from the topological representation to a dual graph structure (lower right part), representing a state transition diagram. To allow for quantitative evaluation of state distances, a metric is needed within the graph structure (like in the topographic layer). This metric is defined by explicit linking of nodes and corresponding GM_Solid objects. The distances between GM_ Solids are then assigned attributively to the graph edges, resulting in a geometrical network of sensors in $IR^3$ (lower left part). The link between GM_Solids and the sensor network (both defined in Euclidean space) embodies potential mathematical algorithms for network derivation, e.g., Delaunay Triangulation, Voronoi Diagram, etc.

## 5. Conclusion

Indoor space is a new notion of space with different properties from outdoor space. And we have a strong demand of indoor spatial awareness services from the industry, which is an evolution of space to micro-scale. For this reason, we have launched an ambitious project to establish theoretical background and develop core technologies of indoor spatial awareness.

In this paper, we presented the recent work of Indoor Spatial Awareness project. In particular, this paper focus on the data model issues, the basic data types of indoor spatial objects as primitive types of indoor spatial DBMS. And a multi-layered model, which has been developed by T. Kolbe team of this project group is also presented. These two models will play key roles for further research of this project.

## Acknowledgement

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