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Review Article

Towards Mobile Information Systems for Indoor Space

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With the rapid development of Internet of things (IOT) and indoor positioning technologies such as Wi-Fi and RFID, indoor mobile information systems have become a new research hotspot. Based on the unique features of indoor space and urgent needs on indoor mobile applications, in this paper we analyze some key issues in indoor mobile information systems, including positioning technologies in indoor environments, representation models for indoor spaces, query processing techniques for indoor moving objects, and index structures for indoor mobile applications. Then, we present an indoor mobile information management system named IndoorDB. Finally, we give some future research topics about indoor mobile information systems.

1. Introduction

Over the past years, with the rapid development of indoor localization technologies, such as Wi-Fi and RFID, mobile information systems for indoor space have emerged as a hot research topic. Indoor space has some unique features, which calls for new techniques to develop mobile information systems towards indoor space.

Comparing with Euclidean space and road network space, moving objects in indoor space have several unique features:

(a) Indoor space is a limited three-dimensional space. The movement of objects in indoor space is limited by walls, doors, and obstacles. Some other restrictions on doors may also exist. For example, one-way doors can only be accessed during a specific time frame, for example, from 8 AM to 5 PM. Such constraints combining temporal and spatial properties bring new challenges to modeling and querying indoor moving objects.

(b) Both Euclidean space and road network space use GPS (Global Positioning System) to get their latitude and longitude coordinates, which is not suitable for indoor space. New positioning techniques such as Wi-Fi, RFID, and Bluetooth are employed for the localization in indoor space. In addition, instead of geographic coordinates, symbolic coordinates like "Floor 5, Room 503" are usually used in indoor environments. The change of positioning technologies and coordinate systems calls for redesigns of moving object databases for indoor space.

(c) In outdoor space, distance between two objects is computed by their latitude and longitude coordinates. However, in indoor space, a new distance measurement method needs to be defined based on symbolic coordinates, which has to consider the influence of indoor elements like elevators, stairs, and obstacles. Distance-aware queries (such as KNN queries and navigation queries) in outdoor space need to be adjusted to the new distance measurement in indoor space.

These new indoor-space features make it difficult to use existing technologies in outdoor mobile data management for indoor space. On the other side, there are many potential applications in indoor space, which are summarized as follows.

(a) Indoor Navigation. Since indoor environment is a limited space with a series of constraints and obstacles, a navigation system is needed for guiding users to their destinations. For example, an airport navigation system on mobile devices can help foreign tourists find an optimized path of shopping, waiting, and boarding. An indoor park guiding system can help drivers find their way to an empty parking space or the exit [1].

(b) Information Acquisition and Recommendation. Information acquisition and recommendation are an important component of indoor location-based services. It allows users to have an interaction with nearby interest points or other users. In a large shopping mall, customers can use such information system on their mobile terminals to find stores which are conforming to their interest or have a high score. On the business side, they can push ads or discount messages to customers based on their location and interest.

(c) Objects Monitoring and Management. In some situations, applications of monitoring indoor objects are in demand. These situations include products on a pipeline, stocks in a warehouse, and equipment in a hospital. A well-built indoor object monitoring system can help administrators in control of these objects' movement and they can be informed immediately when error occurs.

(d) Outliers Detection. Outliers can be detected from a large number of indoor moving objects by analyzing their trajectories [2, 3]. This technology can be helpful in the field of public security. People with an abnormal behavior pattern can be seen as a threat in some specific indoor space, such as metro and museum.

(e) Indoor Social Network Service. So far, SNS (Social Network Service) has become one of the most popular forms of communication on network. Some SNS applications like Foursquare are famous for their location-based service. Users can "check in" their current "venue" and share it to friends. However, GPS based localization technology cannot recognize people's indoor position precisely, so we need indoor information systems to improve the user experience in SNS [4, 5].

Since there are many kinds of new applications in indoor space and previous knowledge in Euclidean space or road network space cannot support indoor space, new designs have to be considered towards indoor mobile information systems. Recently, the research is just beginning and in rapid developing stage now.

The first light of research on indoor mobile information system appears in 1990s, which was focused on indoor robot navigation system in the beginning. Surmann et al. [6] designed a fuzzy indoor mobile robot navigation system with the technology of artificial intelligence. Later, several indoor navigation systems were implemented by using kinds of physical sensors [7, 8]. But lacking effective way to acquire the precise position of indoor objects makes these systems hardly practical. In the last decade, with the development of indoor localization technology and smart mobile devices, researchers gradually began to pay attention to the management of indoor moving objects. Jensen et al. started to work on indoor moving objects database in 2009; his first research included modeling indoor space and analyzing uncertainty of indoor moving objects [9]. After Jensen's step, Baniukevic et al. in Aalborg University, Denmark, have got a series of achievements in this field such as improving indoor positioning [10], indoor query processing [11, 12], and indoor-space indexing [13]. Worboys in University of Greenwich mainly pays attention to modeling indoor space [14, 15] and the correlation between indoor and outdoor [16, 17].

Although there have been many researches on indoor mobile information systems, a large number of them are aimed at implementing an indoor positioning or navigation system. Research on modeling, querying, and indexing for indoor mobile information systems is still in an early stage. Some complex problems are urgently still to be considered.

In this paper, we summarize the features of indoor mobile information systems and give a survey on several key technologies which support indoor data management. Then, we introduce our prototype system that is called IndoorDB. Finally, we propose several future research topics in indoor mobile information systems. Briefly, we make the following contributions in this paper:

(a) We make a survey on the key issues in indoor mobile information systems. We analyze the special features of indoor spaces and summarize the recent advances in this area.

(b) We present a preliminary indoor mobile information system which is called IndoorDB. It integrates a number of technologies in indoor-space-related studies such as indoor positioning techniques, indoor models, and indoor query processing. We describe the data model as well as the implemental details of IndoorDB. To the best of our knowledge, this is the first prototype system in the area of indoor mobile information systems.

(c) We propose some future research topics for indoor mobile information systems, including privacy protection in indoor spaces, indoor trajectory analysis, and integration of indoor and outdoor spaces.

The rest of this paper is organized as follows. Section 2 reviews the key issues of indoor mobile information systems. Section 3 presents the design and implementation of our indoor mobile information system IndoorDB. Section 4 gives a glimpse of future research directions and Section 5 concludes the paper.

2. Key Issues in Indoor Mobile Information Systems

2.1. Indoor Positioning Technologies. Indoor positioning technology is a hot topic in past several years. Since GPS cannot be deployed for indoor use, researchers have come out with dozens of indoor positioning technologies. Each technology derives many prototype positioning systems. There have been already several surveys about indoor positioning technologies and systems since 2007 [18–21]. Among these positioning technologies, a constant theme is the trade of accuracy and cost. This cost includes the spending of infrastructure, the time complexity of positioning algorithm, the durability of batteries, and the usability. For example, [22] proposed an infrastructureless indoor positioning system by taking advantage of sensors in smartphone. However, the accuracy of the system was sacrificed in large indoor space. In contrast, a Bluetooth-based positioning system implemented in [23] has an accuracy of 1–3 meters, but the cost of setting up Bluetooth base stations cannot be ignored.

Usually, indoor mobile information systems need an accuracy of a few meters, low power consumption, and a short response time. And indoor spaces often have a range of dozens to hundreds of square meters so that the cost of the infrastructure construction must not be too high. According to these features in indoor space, the most suitable and also the most widely used positioning technology is RSSI (Received Signal Strength Indicators). Wireless radio waves can pass through walls and human bodies so that the positioning system has a larger coverage area and fewer infrastructures than other systems. WLAN and RFID are two typical positioning systems making use of RSSI method.

2.1.1. WLAN. WLAN (Wireless Local Area Networks, IEEE 802.11 standard) is the most popular positioning method today. Since WLAN has become the most common way to connect to internet from a wireless device, many indoor environments already provide a deployment of WLAN infrastructures, which lower the cost of indoor positioning. The performance of WLAN positioning, like accuracy or consumption, is able to satisfy the demand of indoor mobile systems and can be improved by using other existing sensors (gravity and inertial sensor, etc.) in users' mobile devices.

There are some different positioning strategies in WLAN positioning method. Empirical fingerprinting approach needs to measure and store a "fingerprint map" of radio signal strength offline first. When a new RSS measurement comes, compare it with signal strength in "fingerprint map" and locate it to a position in the map with a nearest signal distance. In [29], the authors proposed an effective approach to measuring the map, while, in [30, 31], the authors considered the changes of environment and provided a way to adjust it. Already some commercial fingerprinting systems have been implemented. Gallagher et al. [32, 33] proposed a commercially available location system with an average accuracy of 7 m for indoor environment. Reference [34] provided a fusion system of WLAN, sensors in mobile phone, and landmarks. Sensors and landmarks are used to modify existing fingerprinting, and finally they achieved a mean localization accuracy of 1 m. Reference [35] discussed the applicability of multiwall multifloor propagation models to fingerprinting technology and proved that the model can be a promising solution.

2.1.2. RFID. RFID (Radio Frequency Identification) is a system including a number of RFID readers, RFID tags, and the communication system between them. In the system, data can be transmitted from tags to the readers via radio waves within the valid range. When an RFID tag moves into the dominating area of a certain reader, the signal received by the reader can help system locate the position of tag. According to the principle of RFID system, the accuracy is depending on the density of reader deployment and reading ranges. It means that RFID systems usually have a higher accuracy as well as a higher cost in comparison with WLAN technology.

RFID systems can be categorized as passive or active by the transmit type of RFID tags. Passive RFID tags work without a battery. They receive the signals from readers passively and reflect signals after modulating. But the ranges of this system are very limited; also the readers can be very expensive. Researches have shown the ability of passive systems in some field such as vehicle guidance [36] and inventory control [37]. Active RFID tags equipped with internal battery power can actively transmit their ID or other data to readers. It enables a long detection range of 10–30 m. So active RFID can be well used for indoor positioning, which has been shown in recent research [38–40]. Also, there have been some systems that use a hybrid of WLAN and RFID technology like [41].

2.2. Modeling Indoor Space. As discussed in Section 1, indoor space usually has some unique properties. With the growth of indoor mobile information systems, there is a need for modeling indoor space to find out how to represent the features of indoor space appropriately and properly [42]. We will talk about 4 kinds of existing indoor-space models in this section: object feature model, geometric model, symbolic model, and hybrid model.

(a) Object feature model represents the features of indoor space and the relationship between operations and types. CityGML/IndoorML [43] is a UML- (Unified Modeling Language-) based class model. IndoorML categorizes indoor element into subspace, wall, door, floor, moving object, and so forth and shows semantic information and spatial topology relations by the use of UML class diagram. Object feature model has a good expansibility but cannot express the geometrical feature of indoor elements and cannot support indoor distance-aware queries either.

(b) Geometric model focuses on the geometric representation of indoor space, which is mainly used in visualization, indoor navigation, or computer aided design (CAD). Raster model is a kind of typical geometric model, which divides the indoor space into a numbers of regions without overlap. There is a benefit that the relationship of adjacency can be inferred from other regions implicitly. The regions can be regular shapes like square [44]. Also regions can be divided irregularly into triangle [45], quadrilateral [46, 47], or Voronoi graph [48]. Geometric model can effectively support the representation of location and direction and the calculation of indoor distance. However, geometric model is lacking in the representation of connectivity; it is not helpful in indoor navigation queries.

(c) Symbolic model is the most widely used model in indoor space so far. In this model, each indoor element is given a symbolic ID. The relationship within symbolic entities in symbolic space can express the topological relation in indoor space. The representations of symbolic space can be classified into set-based, topology-based, lattice-based, and graph-based. Becker and Dürr [49] presented a set-based model to express indoor location information. This model can improve range query by making use of set operations but cannot support connectivity related queries. Ben et al. [50] presented a semantic-based model for indoor space and moving object. Li and Lee presented a topology-based semantic model in 2008 [51] and a lattice-based semantic location model [52]. Graph-based model is the most popular

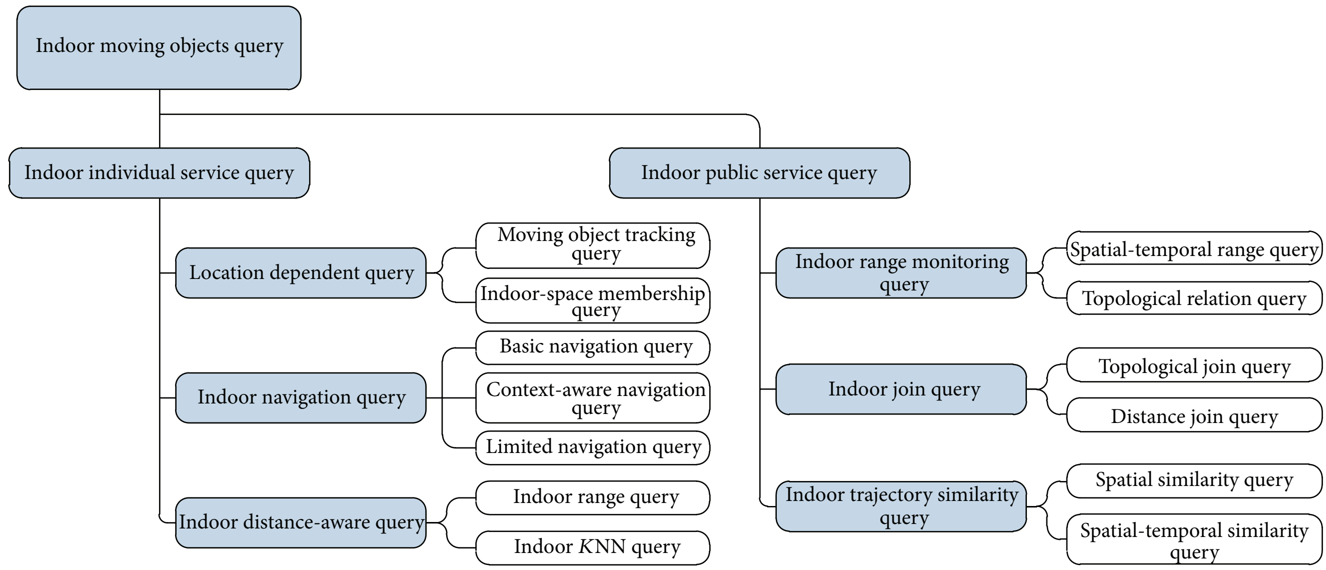


FIGURE 1: Classification of indoor queries.

symbolic model. Jensen et al. presented a deployment graph model in 2009 [53–55] to support tracking and monitoring moving objects in an RFID positioning system. The door graph model proposed in [12] is good at dealing with indoor distance query like *K*NN query. Lu et al. presented an extended graph model in 2012 [11], which can handle several kinds of indoor distance-aware queries. These models take advantage of the representation of indoor connectivity but often focused on only one certain area. At the same time, symbolic model can hardly support indoor geometric features, so it is hard for symbolic model to work out indoor uncertainty query.

(d) Since symbolic model and geometric model both have a limitation of representing indoor space, there have been some hybrid models to improve them. The 2D-3D hybrid model proposed by Kim et al. [56] uses a 2D floor layer as data structure and stores 3D visualization data with 2D symbolic data. It can support both the visualization of indoor space and the navigation in indoor space. Li et al. presented a grid graph-based hybrid model in 2010 [57]. The model is a combination of grid representation and gird graph. Grid-based model can express the geometric information in indoor space and a gird graph is used to show the connectivity among grids. Jamali et al. proposed an automated 3D indoor topological modeling [58]. The model includes 3D building modeling and topological navigation networking, which makes the indoor space visually without losing connectivity information.

2.3. Queries on Indoor Moving Objects. According to the application area of indoor mobile information system, indoor application service can be divided into two categories: individual service and public query. Individual service provides users with not only basic location service but also navigation, recommendation, SNS service, and so on. On the other hand, public service can help administrator with indoor monitoring, behavior prediction, outlier detection, public safety management, and other public requests. The query type for these two kinds of service is different. The classification of these query types is shown in Figure 1.

2.3.1. Indoor Individual Service Query

(1) Location Dependent Query. Location dependent query is a basic query in indoor space. Since indoor positioning technology cannot provide the locations of moving objects continuously, for each location dependent query or other location-based query, it should be a query for moving object's location first. Moving object tracking query [59] and indoor-space membership query [60] are two kinds of typical location dependent query. The former tracks one or some moving objects for a series of time, and the latter returns a result of whether moving objects are in a specified indoor area. In [61], the authors proposed a location dependent predictive query. The query extends moving object's movement by its current location and velocity and generates a trajectory to predict its location in the future.

(2) Indoor Navigation Query. Indoor navigation query gives a start point and a destination in indoor environment and returns an optimal path from start point to destination. In [62], a basic indoor navigation query in a hybrid indoor model is discussed. In this case, the shortest path is the best path. In [63], the authors proposed a context-aware navigation query based on a multilayered indoor-space model. The path selection is influenced by semantics, so that the query can still provide best path in case of emergency. References [64, 65] also drew attention to the context in indoor navigation systems. It shows that the context includes the interest and physical condition of users, the memory and network condition of mobile devices, and the external causes like time and temperature. Reference [60] gave an example of limited indoor navigation query: users may have some additional demands when planning their way to the destination. For

example, go to a shop in upper story but do not use the lift. Reference [60] arranged the limit to regular expression and put it into the query; thus, the result path can satisfy the additional demands.

(3) Indoor Distance-Aware Query. Distance-aware queries in indoor space have similar definition with outdoor space. But the differences between indoor and outdoor space models make the researches on these queries significant. Indoor range query [11, 53, 66] and indoor KNN query [11, 12, 24] have attracted many researchers to work on them. According to the different temporal predicates, distance-aware queries can be categorized into snapshot queries or continuous queries. And continuous queries also have several types. Reference [53] proposed a continuous query where query point is moving and query objects are static. In indoor situation, it can be a walking user looking for a nearest staircase. Then, [66] gave another kind of continuous query where query point is static and query objects are moving. This kind of continuous query can be useful when a shop owner in a shopping mall wants to know who will come into the shop among the outside customers.

2.3.2. Indoor Public Service Query

(1) Indoor Range Monitoring Query. Indoor range monitoring query mainly includes two kinds of spatial-temporal query. One is indoor spatial-temporal range query, used for searching moving objects that stay in a certain indoor range during a period of time. The other one is indoor topological query, used for searching moving objects that enter, leave, or pass through a certain indoor range during a period of time. Both of them are aiming to monitor indoor moving objects in time and space domain. Jensen et al. designed two indexes for supporting indoor range monitoring query in 2009 [26]. Both indexes are extensions of R-tree. Reference [53] came out as a continuous spatial-temporal monitoring query, which continuously monitors the entering and the leaving of moving objects.

(2) Indoor Join Query. Reference [55] worked on indoor join operation and proposed a query named PTISSJ (Probabilistic Threshold Indoor Spatiotemporal Join). The query returns object pairs where the two objects meet in their tracking history with a probability greater than the given threshold. Since indoor positioning technology cannot get the dense trajectory data like GPS data, there is an uncertainty in indoor trajectory query. So a probabilistic threshold is given to fit indoor environment. Reference [67] kept an eye on indoor distance-aware join query. They considered both range join and neighborhood join.

(3) Indoor Trajectory Similarity Query. Traditional idea for the comparison of trajectory similarity is LCSS (Longest Common Subsequence) or ED (edit distance). But common methods are not quite suitable for indoor space. In [68], the authors designed a comparison algorithm by taking use of history trajectories of moving objects. Both Euclidean distance and edit distance are considered in the algorithm. In [69], the authors brought more information to judge the similarity of two trajectories and use the result of query to improve the performance of personalized recommendation. The added information includes visited locations, residence time, and the popularity of visited location.

2.4. Indices for Indoor Mobile Information Systems.

Index is needed in indoor information systems to improve the query performance. So far, indexes for moving objects or moving objects' trajectory are usually based on R-tree in outdoor space. There are varieties of R-tree-like indexes such as 3D R-tree [70], HR-tree [71], and TPR-tree [72]. However, indoor space has the components of rooms, doors, floor, stairs, and so forth, so these should be taken into consideration when developing an index for indoor environment. Recently, research on indoor indexes is just beginning. Most of the indexes only support a few queries based on some specific models. These indexes can be divided into two groups by the object they index: indoor-space index and indoor moving objects index.

2.4.1. Indexing Indoor Space.

Reference [11] proposed an index called DPT (Door-to-Partition Table). A precalculated distance index matrix is used to represent the distances of each door pair. The DPT stores the relationship between doors and partitions of indoor space. Thus, it is easy to figure out door-to-partition distance by DPT and distance index matrix so the index can support indoor distance-aware query. Reference [24] developed a Composite Index which can adapt to the change of indoor environment. Firstly, an R-tree index is implemented based on the location of rooms, then, for each room, a hash table is built to index the moving objects in the room. The work in [25, 73] focused on connectivity query and came out as an indoor-tree index. Indoor-tree has a similar structure with Composite Index, except that the R-tree it implements is based on the connectivity of rooms.

2.4.2. Indexing Indoor Moving Objects.

Based on R-tree, [26] designed two moving objects trajectory indexes RTR-tree and TP2R-tree. RTR-tree treats the trajectory as several horizontal lines, and TP2R-tree compresses the trajectory into a point with time parameters. Indoor range query and indoor trajectory query can benefit from these structures. The work in [27] added another R-tree to RTR-tree and became a new index called Dual R-tree. The purpose of the new added R-tree is to index moving objects so that the performance of trajectory query can be improved. ACII index in [28] also has a double structure: MC uses R-tree to index the indoor space and a hash table to index location of moving objects at current time; MEMO stores the history trajectory with a primary key of moving objects. With the double structure, ACII index can support full temporal moving objects query.

A summary of indoor indexes introduced above is in Table 1. According to the table, many issues need to be worked out, including the exploration of new index structure, the extension of supported query, and the implementation of useful indoor model.

Table 1: Summary of indoor indices.

Index	Structure	Query type supported	Update cost	Storage cost
Indoor-space index				
DPT [11]	Hash	Indoor distance query	High	High
Composite Index [24]	R-tree and hash	Indoor distance query	High	High
Indoor-tree [25]	R-tree and hash	Indoor connectivity query	High	High
Indoor moving objects index				
RTR/TP2R-tree [26]	R-tree	Indoor range query	Low	Low
DR-tree [27]	R-tree	Indoor trajectory query	Low	Low
ACII [28]	R-tree and hash	Full temporal moving objects query	High	High

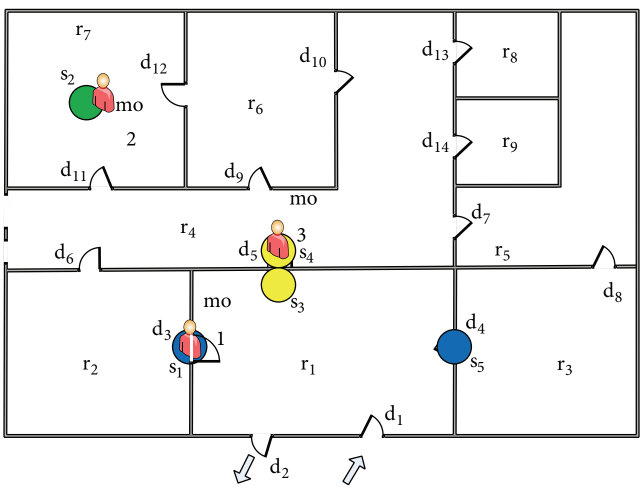


Figure 2: An example of indoor space.

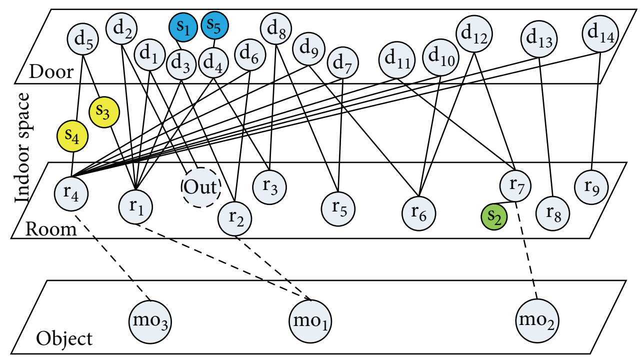


Figure 3: Conceptual structure of the LayeredModel.

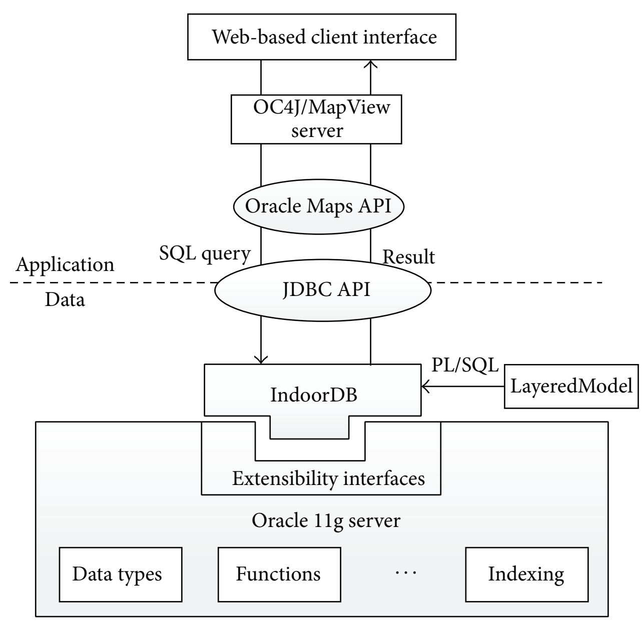


Figure 4: Architecture of IndoorDB.

3. Implementing an Indoor Mobile Information System

In this section, we present an indoor mobile information system called IndoorDB that integrates many indoor-space-based designs.

3.1. Data Model of IndoorDB. IndoorDB is implemented on the basis of an indoor moving object data model named LayeredModel [74], which is a symbolic and semantic model for indoor space as well as indoor moving objects. Formally, LayeredModel is represented as a set of 5-tuple, as shown in formula (1). Consider

$$\text{LayeredModel} = (\text{DL}, \text{RL}, \text{OL}, \text{CE}, \text{LE})\,. \tag{1}$$

Here, DL is a set of doors, RL is a set of rooms, OL is a set of objects, CE is a set of connection edges between doors and rooms, and LE is a set of location edges between objects and rooms.

Figure 2 shows an example of indoor space and Figure 3 shows the conceptual structure of the LayeredModel. Compared with common symbolic models for indoor space, LayeredModel supports richer semantics. For example, it can support navigation queries given like "*Go to Room 7 from Room 3 without passing through Room 1 and Door 11.*"

3.2. Implementation of IndoorDB. IndoorDB is a LayeredModel based indoor moving object management system. It is an extension of Oracle 11g DBMS. Figure 4 shows the architecture of IndoorDB.

There are two main components of IndoorDB divided by the dashed line in the figure. The lower part is the data storage and management part; LayeredModel has been implemented

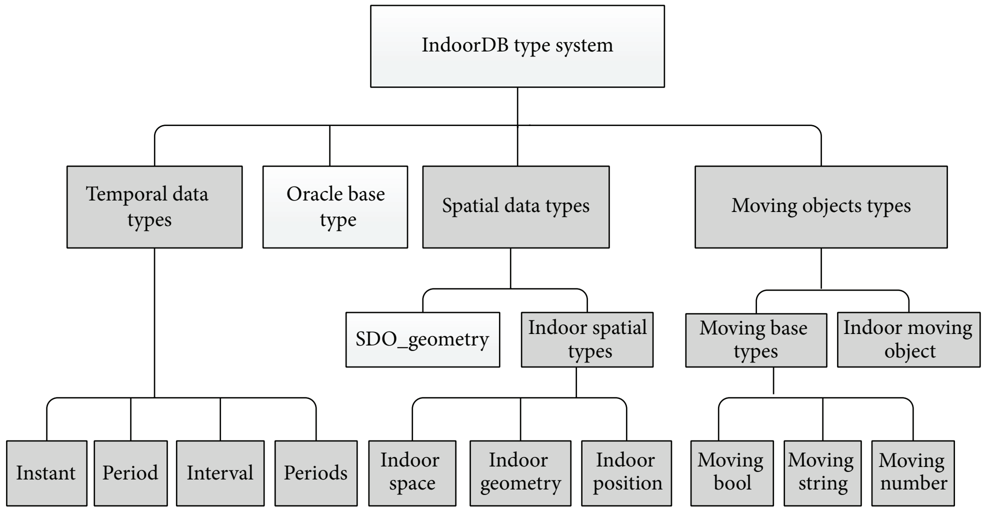
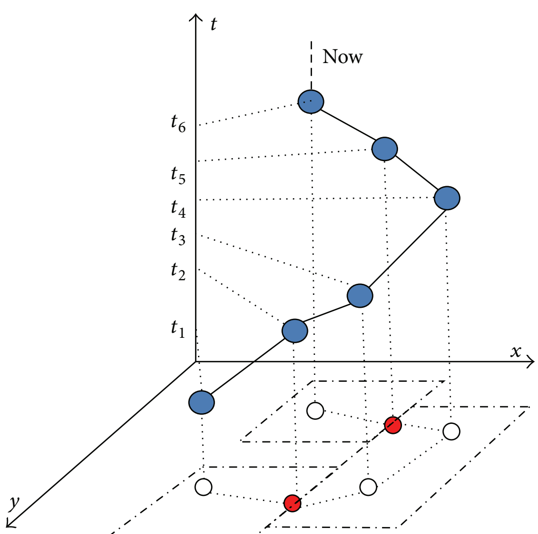


Figure 5: Type system of IndoorDB.



(a) Indoor moving object

```
CREATE OR REPLACE TYPE MObjU AS OBJECT -- Moving Unit
(       posIndoor IndoorPos4MO,
        cRX NUMBER, --changeRateofX
        cRY NUMBER, --changeRateofY
        cRZ NUMBER, --changeRateofZ
        period T_period
);
--Table for Moving Units
CREATE OR REPLACE TYPE MObjT IS VARRAY (102400) OF MObjU;
CREATE OR REPLACE TYPE MObj AS OBJECT -- Indoor Moving Object
(       MObjUnits MObjT,
        Trajectory IndoorPosArray
);
```

(b) Defining *indoor moving object* type using PL/SQL

Figure 6: Defining the *indoor moving object* type in IndoorDB.

as the underlying indoor model of IndoorDB. The ability of IndoorDB is depending on this underlying model. Also a series of type systems and operation functions is developed to enrich LayeredModel so that the system can store and manage the data of indoor moving object. The upper part is the part for application and interaction. Oracle Maps API accesses JDBC API to get the indoor map data, and after drawing the map, Map Viewer service presents it to the user interface.

IndoorDB extends three categories of new data types into Oracle, namely, *temporal data types*, *spatial data types*, and *moving objects types* (as shown in Figure 5). The *moving objects types* contain moving base types and an indoor moving object type. The former refers to the numeric, Boolean, or string values changing with time, whereas the latter refers to the indoor moving objects as well as their trajectories. All the new data types are implemented by PL/SQL using the CREATE TYPE statement. Figure 6 shows an example of indoor moving objects and the definition of indoor moving object type in IndoorDB.

IndoorDB implements ten types of spatiotemporal operations, which are (1) object data management operations, (2) object attribute operations, (3) temporal dimension project operations, (4) value dimension project operations, (5) temporal selection operations, (6) quantification operations, (7) moving Boolean operations, (8) temporal relation operations, (9) object relation operations, and (10) distance operations. All the operations are implemented by PL/SQL and as member functions of extended data types, as shown in Figure 2. For the space limitation, we will not discuss the details about each data operation. However, in the demonstration process, we will show how to use those operations to answer different spatiotemporal queries.

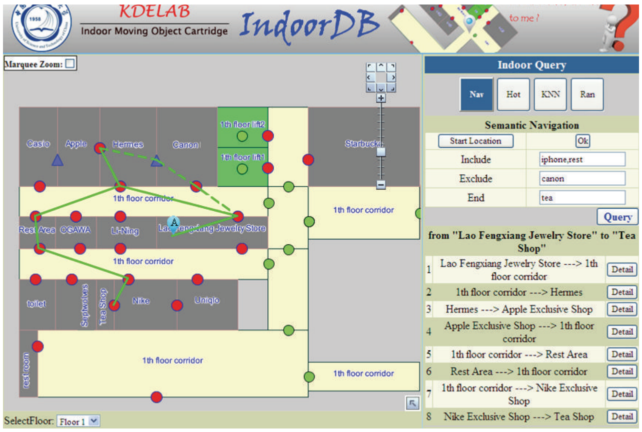


Figure 7: An example of indoor semantic navigation queries in IndoorDB.

The web-based client with an interactive interface is shown in Figure 7. Figure 7 also shows an instance of indoor semantic navigation query. The semantic information of each room in Figure 5 is shown in Table 2. And the semantic navigation query can be seen in the right side of Figure 7: "Include: iPhone, rest; Exclude: canon; End: tea." The result is shown in the map as well as the lower right corner. As it can be seen, the system satisfies the constraints and returns a shortest path.

Table 2: Semantic information of rooms in Figure 7.

Room name	Room semantics
Rest room	{rest}
Starbucks	{coffee, starbucks}
Uniqlo	{uniqlo, clothes, trousers}
Nike Exclusive Shop	{nike, sneaker, sport suit, clothes, trousers}
Tea Shop	{drink, milky, tea, water}
Septwolves	{clothes, trousers, luggage, suit, leather, shoes}
1st floor toilet	{toilet}
Casio	{wrist watch, casio}
Apple Exclusive Shop	{iphone, ipad, ipod, itouch, apple, cellphone, pad}
Hermes	{luggage, hermes}
Canon Exclusive Shop	{canon, camera, lens, DV}
Rest Area	{rest, seat, relax}
OGAWA	{ogawa, massage armchair}
Li-Ning Exclusive Shop	{Li-Ning, sneaker, sport suit, clothes, trousers}
Lao Feng-Xiang Jewelry Store	{jewelry, silver}
1st floor lift 1	{lift}
1st floor lift 2	{lift}
1st floor corridor	{corridor}

4. Future Research Topics

4.1. Privacy Protection in Indoor Space. With the development of indoor positioning systems and indoor location-based services (LBSs), privacy risks have been a threat to the user of indoor mobile information systems, especially the enthusiasts of LBSs. According to [75], two sources of information have a great privacy risk. One is location privacy, because the large amount of location traces generated by indoor positioning devices may be exposed to the untrusted LBS provider; thus, it leads to location privacy threats to the user. The other one is the content privacy. The untrusted service provider may find users' interests or interpersonal relationship by understanding the information requested by the mobile clients. The leakage of either location information or personal information may cause serious problems. So it is necessary for the research on privacy protection in indoor space.

A typical method of location privacy protection is spatial-cloaking-based technique [76]. The principle of this method is to add uncertainty to the location information which is exposed to the location service, and the spatial-cloaked region is constructed to ensure that there are several users who are located in the same region.

There was a concern about location privacy protection for several years in the outdoor space, so there have been already a large number of solutions for location information preserving. However, content privacy protection is a new subject growing up with the development of LBSs. So maybe it will be an issue worth of research in the future.

4.2. Indoor Trajectory Analysis. So far, there are few researches on indoor history trajectory analysis. Mining the history trajectory data can help managers or administrators have a better understanding about the indoor space they manage. For instance, moving objects density analysis can identify the hotspots in indoor space [77]; the fire escape near these hotspots should be kept clear in case of emergency occurs. A frequent movement pattern analysis can find customers' trend and interest, and this analysis can be used for personalized recommendation.

A simple method to identify the hotspots can work like this: given a time period T_p, a velocity threshold V_0, and a density threshold D_0, a shop can be regarded as a hotspot when it has a higher costumer density than D_0 whereas the costumers have a lower moving speed than V_0 during time T_p.

Also with hotspots detection, indoor density query is another way of analysis of indoor trajectory. Finding the dense locations in large indoor spaces is very useful for getting overloaded locations, security, crowd management, indoor navigation, and guidance. Recently, there have been some researches on this topic such as [78, 79].

4.3. Integration of Indoor and Outdoor Data Management. The techniques of spatial-temporal data management in outdoor space have been already very mature at present. There are many available systems for positioning, navigation, and so on. On the other hand, indoor data management is just in the primary stage; many issues are waiting for solution. However, it is predictable that indoor and outdoor systems will undergo integration in the future.

One of the most challenging tasks is to switch seamlessly between indoor and outdoor environment. The location return from GPS positioning system is in a form of latitude and longitude coordinates, called absolute coordinates. Database should record the absolute coordinate just before entering indoor space and keep modifying the recorded coordinate when an object moves in indoor space, so that when object switches indoor space into outdoor space, the latitude and longitude coordinates will be the proper value.

5. Conclusions

Indoor moving objects data management has been a hot research topic due to the rapid development of indoor positioning technologies and location-based services. In this paper, we first analyze the special features of indoor spaces and indoor location-based services. Then, we summarize the main research issues of indoor mobile information systems. These issues include indoor positioning technologies, modeling of indoor spaces, indoor-space-based queries, and indexes for indoor spaces and moving objects. For each research issue, we discuss the significance of the issue and further give a detailed description on the research problems involved in the issue. In addition, we present the recent works and advances on each direction.

After a review on key issues and existing work on indoor mobile information systems, we briefly introduce IndoorDB, which is an indoor mobile information system that was proposed and implemented by our previous studies. IndoorDB is an integration of several indoor-based technologies such as indoor-space models, indoor data storage, indoor query processing, and indoor map interfaces. After describing the data model of IndoorDB, we explain the implementation techniques of IndoorDB, including its architecture on an object-relational DBMS, the data type system, and the user interface to demonstrate its support to indoor queries.

Further, we propose a few future research directions for indoor mobile information systems, including privacy protection in indoor spaces, indoor trajectory analysis, and integration of indoor and outdoor spaces. There are also some other interesting topics related to indoor mobile information system but we believe that these are of the most importance in future studies.

In summary, this paper offers a systematic review on indoor mobile information systems, which is helpful to researchers in indoor moving object databases and other related areas. To the best of our knowledge, the proposed IndoorDB system is the first prototype in indoor-space-related information systems. Presently, IndoorDB has some limitations on performance and functionality. In the future, we will concentrate on optimizing IndoorDB. For example, we will consider automatically importing indoor maps with CAD formats [80] and integrating indoor-space-based indexes into IndoorDB to improve query performance.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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