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Review Article

Spatial models for context-aware indoor navigation systems: A survey

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Abstract: This paper surveys indoor spatial models developed for research fields ranging from mobile robot mapping, to indoor location-based services (LBS), and most recently to context-aware navigation services applied to indoor environments. Over the past few years, several studies have evaluated the potential of spatial models for robot navigation and ubiquitous computing. In this paper we take a slightly different perspective, considering not only the underlying properties of those spatial models, but also to which degree the notion of context can be taken into account when delivering services in indoor environments. Some preliminary recommendations for the development of indoor spatial models are introduced from a context-aware perspective. A taxonomy of models is then presented and assessed with the aim of providing a flexible spatial data model for navigation purposes, and by taking into account the context dimensions.

Keywords: indoor spatial data models, context-awareness, navigation systems and wayfinding, qualitative spatial representation, quantitative spatial representation, location-dependent queries

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1 Introduction

The notion of context has been recently recognized as a key element in the development of mobile information systems [26]. Contextual information can be defined as any information that is gathered and can be used to enrich the knowledge about the user's state, his or her physical surroundings, and capabilities of his or her mobile device(s) [35,110]. Context varies according to application constraints, taking into account the way users act in the

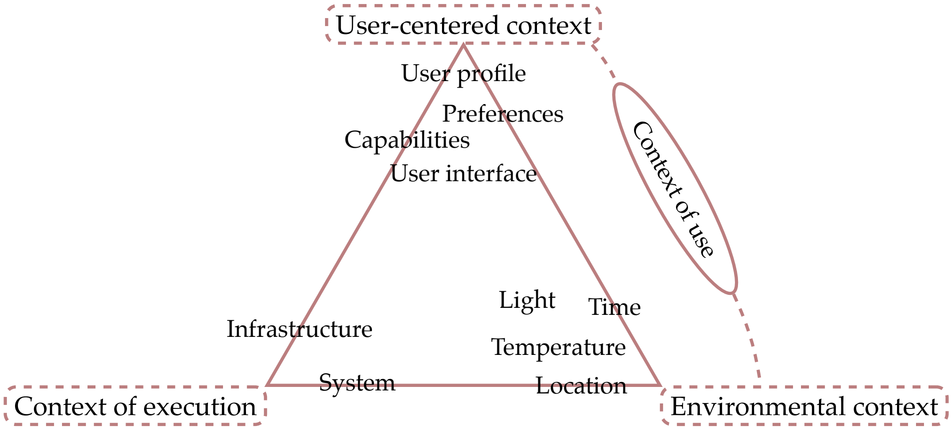

Figure 1: A classification of context dimensions.

environment, as well as the interfaces to interact with. Two generic concepts have been introduced as superclasses that encapsulate contextual dimensions [99]. Figure 1 summarizes those context dimensions.

- The *context of use* includes: (1) user-centered dimensions of context such as the user profile, preferences, and physical/cognitive capability, and the user interface that provides direct interaction with the system (i.e., input data manipulation and output communication operations); and (2) the environmental context which refers to the parameters that influence the user (e.g., location, time, temperature, light).
- The *context of execution* models the behavior of an information system and encompasses: (1) the infrastructure dimension and the topological organization of the system components; and (2) the system dimension that evaluates resource utilization (e.g., memory, processor, and network) of the system components and capabilities of the user's mobile device(s).

An indoor space can be informally defined as a built environment where people usually behave [85] (e.g., houses, commercial malls). Emerging and continuing advances in ubiquitous systems and localization techniques have brought novel opportunities to develop context-aware indoor navigation services. Diverse kinds of services can be provided by enabling real-time integration of context dimensions into the services delivered to the users. Examples of such services include, but are not limited to, human wayfinding and navigation in built environments, evacuation routes for people stuck in a building in case of an emergency, and real-time collaborative activities [10, 30]. Much work has been done on user modeling for developing systems that can adapt to the properties and dimensions of the user [50,53,68]. Other efforts have addressed the issue of information gathering from different kinds of deployed sensors [27]; and systems that support collaborative activities, such as healthcare activities in a pervasive hospital environment [10].

Whether location information should be handled as any other context information or be managed differently is a key issue. Indeed, a better understanding of location information and the relationships that might exist among spatial entities, either acting or located in the environment, should be taken into account. As shown in Figure 2, many components

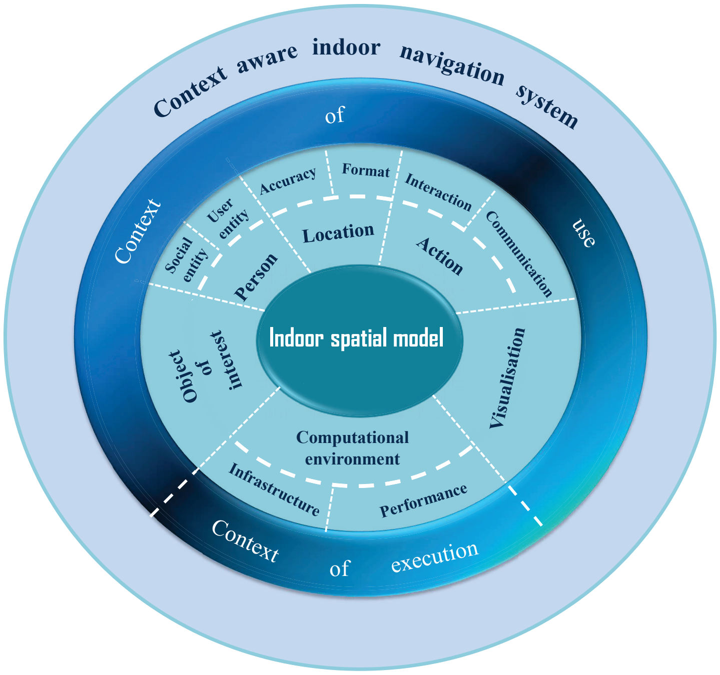

Figure 2: Indoor spatial model to context-aware indoor system.

that contribute to the design of a context-aware system should be reflected by the spatial model underneath. Therefore, the integration of an indoor spatial model into a context-aware system implies a consideration of the environment as a dynamic system that should represent:

1. the features that populate the environment: a feature can refer to either a *person* (i.e., mobile users and other social entities/human beings that are located in the vicinity and are of interest) or an *object of interest*[1].
2. their spatial properties, i.e., *locations* of the objects of interest and the spatial relationships that relate them.
3. the *actions* that emerge from them (i.e., physical interactions and communications).

Moreover, specific properties of the spatial data model retained for the representation of an indoor space influence the manipulation, visualization, and computational capabilities of the system. Those characteristics will serve as basis for the development of our study.

This survey firstly discusses context-aware services and queries in indoor environments in order (1) to reconsider current indoor spatial models from a context-aware systems perspective so that recommendations for the development of a reference spatial model can thereafter be proposed; (2) to take into consideration dynamic properties and activity-

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[1] An object of interest (OOI) may be either communicating or not, mobile or static, physical or virtual, attractive or repellent. Examples of such OOIs are sensors, exits, and so forth.

oriented interactions of moving objects with their physical surroundings; and (3) to examine the role played by smart devices and ubiquitous positioning sensors.

The remainder of the paper is organized as follows. Section 2 provides a review of current location-dependent queries and services. Section 3 introduces a methodological framework for the design of indoor spatial models. Section 4 applies this framework to the assessment of current indoor spatial models. Variants of hybrid spatial models are discussed in Section 5. Finally, Section 6 concludes the paper and draws some perspectives.

2 Indoor location-aware navigation-related services

A wide range of location-aware services can be applied to indoor environments. The main goal of these services is to provide users with the ability to interact with their physical surroundings in order to achieve some objectives. Location-aware, user-centered services can be distinguished according to two modes of data access: *pull* mode and *push* mode [109], which are defined as follows:

- Pull-based location-aware services comprise requests triggered by the user with the aim of pulling some location-dependent information from the service provider [55, 136].
- Conversely, push-based services are initiated by the service provider without having been requested by the user. The service provider takes into account location information of subscribed users to trigger alerts or contextual advertising, and push them to the user's device [47, 96].

Location-dependent queries are typical examples of pull-based services needed in any context-aware navigation system [55, 136]. Queries are location-dependent, meaning that any change of the locations of objects that are involved in the query may significantly affect the answer. For example, if a user wants to find friends within a range of 100m while navigating a shopping center, this answer will depend on the user's current position as well as on the location of the nearest friends. Location-dependent queries have been surveyed in [55]; some particularly relevant queries in indoor contexts are briefly described as follows:

- *Position queries* return the locations of mobile and static objects, and are processed according to either a geometric or a symbolic model of space. This is an essential kind of query since other location-dependent queries cannot be carried out without up-to-date information about the locations of objects of interest [13].
- *Navigation queries* encompass all queries that directly help the users to find and reach some points of interest by providing them with navigational information, while optimizing some criteria such as total traversed distance or travel time. Examples of such queries are: (1) discovering *optimal* paths to a nearest point of interest (e.g., a landmark or a place), (2) planning a path to a destination.
- *Range queries* are used to find and retrieve information on objects of interest or places within a user-specified range or area [130, 135]. They support navigation by continuously updating relevant details according to users' movements. Ranges may be characterized by a circular or rectangular-shaped window in which objects of interest must be located. In addition, range queries may be static or dynamic according to

whether or not the query point is in a static location. Similarly, a range query can be applied on static or dynamic data, depending on whether target objects are moving or not.

- *k nearest neighbor (kNN) queries* search for the k closest qualifying objects to a moving user with respect to his or her current location [116,136]. As opposed to range queries, kNN queries are range-independent, except in the case of *constrained nearest neighbor queries* [42], where the search is constrained to a given region. The user triggers a request by specifying some properties of the objects of interest, so that the k closest objects whose specifications meet these characteristics are retrieved (e.g., the closest available color printer or the k nearest friends).

Efficient management of static and dynamic data is a key issue for processing these queries, since the result of a query is valid only for a particular location of the query issuer and the objects of interest. Therefore, continuously updating queries implies a communication overhead and additional processing cost at the server side. A concept of validity region is introduced in [136] to lessen this problem by determining a safe area around the initial user position in which the result of the query is always valid. Many variants of these queries are summarized in [55]. Most work on location-dependent query processing has been developed with an outdoor environment in mind (cf. [55] for a recent survey). However, indoor environments bring some special features and constraints that should be considered during query processing (i.e., the constraints that emerge from the architectural layout of space). More realistic approaches based on network and/or temporal distances are generally preferred.

Recent works have studied location-dependent queries in indoor environments [133–135]. Graph data models that represent indoor spaces have been designed, thus allowing processing of network-based queries on top of the spatial model. In [135], the authors present an approach that supports range queries based on a virtual cell-based network generated for each query. Besides, this approach also proposes a technique to continuously process range queries whenever the query point moves. However, this technique addresses only one kind of query (i.e., range queries), and is only applied to static points of interest. Other solutions for continuous range query processing, as well as k nearest neighbor query processing over moving objects have been provided in [133] and [134], respectively. Those methods are developed on top of a graph data model. The former deploys a set of sensors to continuously monitor users' movements, thus maintaining query results up-to-date; the latter uses a probabilistic estimation mechanism to prune unqualified candidates from the candidate set, so that the most probable k nearest neighbors are retrieved. However, the model underneath is based on sensor range-based positioning techniques, which are not perfectly suitable for navigation queries that may require fine-grained location information.

Several other location-based, real-time services that deliver valuable information and allow for communication have been reviewed in [70, 78, 96]. This includes, for instance, location-based instant messaging in which outgoing messages are not just stamped by the local time-zone of the sender but also by the sender's current location [21, 47]. Similarly, a user can instead manually specify a certain location specification so that other users whose specifications meet those given by the sender will receive the message [52]. Other kinds of services are push-based, and that implement principles of *geocast* messaging [11, 96], and include location-based advertisements and alerts. Geocast messaging can be described as a location-based multicast where messages are delivered to users located in a specific area instead of those subscribed to a given group.

In particular, location-based alerts are not necessarily time-related and are generally used in the case of an emergency to warn people to avoid a dangerous zone. It might also be useful, for example, to remind a user navigating a shopping center to buy some groceries when he or she is located next to a supermarket. On the other hand, location-based advertisements [1] (also called proximity-triggered advertisements) generally target nearby consumers to provide them with information about stores' offers, discount coupons, etc. These kinds of push-based services should provide users with a subscription-based mechanism that allows for relevant and non-intrusive advertising.

Although many research studies have discussed location-dependent queries and location-based services, a few works have addressed the issue of incorporating context dimensions into the query processing, particularly those related to *user-centric* and *environmental contexts*. These issues hare highlighted in [91], which discusses some of the challenges to be considered in order to carry out context-aware queries and services. Some of these challenges include (1) designing a user model, (2) supporting multi-objective and possibly contradictory queries, and (3) analyzing efficiency and scalability when dealing with context-aware continuous queries. The following section discusses these issues and propose some preliminary recommendations for the development of an indoor spatial model that meets the requirements of such context-aware applications.

3 Requirements for context-dependent spatial models

Indoor spatial models have been studied and developed in many areas ranging from mobile robot mapping to GIS and ubiquitous computing [13, 94, 119]. This section classifies the requirements needed to design a context-dependent spatial model into two categories: *service-oriented* and *efficiency-related* requirements. The first group supports real-time and delayed services, and includes: (1) localization, (2) navigation, (3) location-aware communication, (4) activity-oriented interaction, and (5) simulation and behavioral analyses. The second group examines efficiency issues and includes: (1) modeling effort, (2) flexibility, and (3) performance and scalability. Those are generic and application-independent requirements for the development of a reference spatial data model, and are hereafter used to assess existing approaches.

3.1 Service-oriented requirements

A context-dependent spatial model should locate objects of interest appropriately and with additional semantic description so that advanced services can be provided. It also needs to support the navigational services of interest to a user. Potential communication between located entities should also be supplied. Moreover, users navigating an indoor space should be able to interact with their physical surroundings. Other deferred services can also be offered by the model, thus enabling a better understanding of users' behaviors.

3.1.1 Localization

Recently, several studies have been performed in order to design and build positioning systems in GPS-less indoor environments [70]. Indeed, indoor spaces are constrained by the architectural components such as doors, floors, corridors, and walls. On the one hand, this constrained environment helps providing meaningful location information at the logical and topological levels; on the other hand, the task of achieving accurate localization is not always straightforward. Two different structures of location information can be delivered according to either a geometric or symbolic representation of space:

- *Geometric information* gives a quantitative representation of moving objects in the form of coordinates (e.g., Cartesian or latitude, longitude, altitude) referenced to a given coordinate system. Whereas systems like Global Positioning System (GPS), used outdoors, provides geometric coordinates with respect to a *global reference system*, others such as the Active Bat system [127] and MIT Cricket [101] use ultrasonic technology and provide three-dimensional positions with respect to *local coordinate systems*. Those are developed based on a set of local landmarks (e.g., beacons) that are distributed in an indoor space. Topological relationships like "overlap," "inside," "intersect," and "disjoint" can be inferred, thus enabling an interpretation at a higher level of abstraction. As an example of overlapping relationships, floors can be shared between several wings within a building. In such a situation, floors overlap with wings, while a room may belong to a floor and a wing.
- *Symbolic information* provides qualitative human-readable descriptions about moving objects based on structural entities and/or points of interest (e.g., room or floor identifier, building name). For instance, the Active Badge system handles values that represent the symbolic identifiers of fixed IR sensors [126]. In contrast to geometric information, symbolic descriptions allow topological relations (e.g., spatial containment) between entities in the environment to be explicitly modeled. This can be done by means of symbolic spatial models such as set-based or graph-based models. Symbolic descriptions enable spatial and semantic reasoning at an abstract level, thus supporting interaction between spatial entities and within the indoor space.

Nowadays, techniques currently available for *indoor positioning* range from radio-based technologies (WLAN, RFID, and Bluetooth) to non-radio technologies (infrared and ultrasound) to inertial navigation systems (INS) [70]. Moreover, hybrid approaches appear to be promising solutions to providing reliable, continuous, and accurate location information [105]. These approaches highlight the fact that location information is often acquired by different sensor types. Therefore, appropriate multi-sensor data fusion techniques and map matching algorithms need to be used in the filtering process [102]. Consequently, a spatial model should be capable of representing the coordinate system by which the location information is expressed and, when necessary, transforming that location information in order to get all sensor data in a common format.

3.1.2 Context-aware, adaptive navigation

Navigation in the environment can be defined as a scheduled and goal-oriented movement made by humans or robots [92]. While navigating, a user may be technically assisted by sensory devices embedded in the environment that provide relevant information to maintain orientation, and other suggestions to encourage the user to interact within the environment.

As an extension of typical navigation tasks, context dimensions need to be integrated into querying tasks, thus offering opportunities to develop advanced services. A context-aware navigation task is carried out in two phases [24]: the static phase, which is generally known as "path planning," encompasses a multi-criteria path selection process that generates an unbroken path from the current location to the destination. This process is context-sensitive as it aggregates multiple criteria (e.g., user preferences and capabilities, distance, time) passed as function parameters to evaluate the cost value of each step and then to adopt the most appropriate path—that is, the *optimal* path that allows, for instance, to reach a destination while avoiding threats [36]. The dynamic phase lies in a dynamic framework that implements event-triggered controllers needed to monitor the user's progression in order to avoid deviations from the planned path. Although few works have discussed the integration of such a dynamic framework, researchers agree on some general requirements [33]. First, this framework should include a next-step selection algorithm that keeps continuous track of the user's position and tries to recover from deviations by providing additional information. Secondly, the framework should adapt the predetermined path if it detects any significant event that may affect the user's movement. In such a situation, a path to the nearest emergency exit should, for instance, be recomputed. Recent studies have proposed algorithms for shortest and/or fastest path searches with improved tracking strategies [18, 115, 132]. The main focus of these algorithms is to keep real-time tracking of moving objects. However, each of them deals with either time or distance constraints without incorporating other elements such as user preferences or events that may significantly influence the answer.

3.1.3 Location-aware communication

In contrast to internet telecommunications, which enable communication between computing devices based on IP or MAC addresses, communication among objects in smart environments is often based on their location [17]. Location-aware communication models in distributed systems can be classified according to who initiates information exchange and how information is then forwarded to the specified receiver [5]. One can make a distinction between direct (i.e., point-to-point) and indirect communications [9]. As an example of indirect communication, a provider can disseminate information about events to invoke *remote callback methods* from potential subscribers. Similarly, a consumer can request information from a known (i.e., direct message exchange) or anonymous (i.e., indirect message exchange) provider. Moreover, collaborative activities can take place between communicating objects working together to achieve some common goals.

Although spatial models do not affect users' physical abilities to communicate, the adoption of a specific spatial model has a direct effect on the quality and format of data exchanged between users and other entities located in space. Moreover, the way a user perceives its ability to communicate with other entities may be significantly disturbed due to inadequate representation of space. For instance, a fined-grained model can represent a sensor range more accurately than a coarse representation of space. Thus, the user can be aware of the exact communication range for a given sensor.

A dynamic, symbolic location model that supports location-aware communication among rigid entities (i.e., sensors and users) in smart spaces has been suggested in [108], which gives an example of what can be achieved. Rigid entities and places are represented as components in a hierarchy of symbolic labels (i.e., user/room/floor/building hierarchy) based on the containment relationship. Each component in the hierarchy can act as a service provider, a service consumer, or both. Different types of communication can then be established between these components depending on their location in the hierarchy.

3.1.4 Activity-oriented interactions

A context-dependent model should also support human activities aimed at achieving some objectives. An activity can be defined as a collection of goal-oriented and context-dependent actions an entity can perform [69, 131]. Actions comprise a sequence of location movements, interactions with other neighboring entities and artifacts, and requests for some services in order to achieve a predefined goal. An activity can also be made of a set of primitive activities or be part of a larger collective activity [30]. Activity theory has focused attention on the usefulness of spatial models in the design process to enrich consciousness and interaction within space [65, 95].

Indeed, the number of artifacts has increased and been distributed into ubiquitous environments. Artifacts can be physical (e.g., chair, door, heating) or virtual (e.g., 2D/3D image of a physical artifact, digital user interface, recommendation/information) [98]. Physical artifacts can also be augmented with various kinds of sensors or tags (e.g., RFID) so that they can perceive the environment and provide additional information [106]. Those are referred to as *digital* or *sentient* artifacts [17, 66]. Spatial representations serve as a mediator to relay relevant information to humans about artifacts in their surrounding. This allows users engaged in a certain activity to both collect knowledge and understand their physical surroundings. Furthermore, it supports reconfiguring and manipulating physical/virtual artifacts to anticipate or produce changes in the environment. Consequently, embodied interaction, defined by [37], can take place by means of spatial reconfigurations that may influence the context by affecting existing activities and/or initiating new ones. A main challenge that designers face is to efficiently represent artifacts of interest located in the environment. Unfortunately, most existing spatial models are not designed for that purpose and thus do not supply interaction with these artifacts and the tasks they might participate in.

3.1.5 Spatial and behavioral analyses

An essential issue in the development of analyses and simulations lies in identifying an appropriate spatial representation with respect to the phenomenon or behavior being explored. Several typical scenarios for planning purposes are introduced in [86]. These scenarios present application-dependent constraints, so each of them needs an appropriate level of granularity. Some examples of spatial analyses and scenarios applied on a fine-grained spatial model are [86]:

- Route analysis scenarios that aim to find shortest paths between two given locations or all pairs shortest paths applied on a given floor architecture and with a given data structure [128, 137].
- Diffusion analysis defined as a dynamic process where the spatiotemporal evolution and extent of a phenomenon within an indoor space are explored [12].
- Centrality measures that characterize the architectural design and the spatial distribution of objects of interest in a built environment [20], and are largely applied by space syntax studies [60, 67, 71].

Indeed, granularity is an important aspect of these analyses that enables the exploration and understanding of spatial data. A fine granularity can certainly reflect the indoor space in detail. Fine granularity is especially needed when simulating a physical process or when considering fine-grained tracking of human mobility to get accurate understanding of the environment. In contrast, topological analyses often require a coarser granularity to support adjacency and connectivity relations between spatial units (e.g., room), and thus deriving a more abstract view of the topology of a complex indoor space. In particular, topological analyses have been largely developed and applied by space syntax studies to evaluate human-environment interactions and to examine different spatial and structural configurations [59, 122].

Behavioral analyses are, on the other hand, of special interest in context-aware computing, and have been recently developed in numerous fields for activity-recognition purposes [6]. Activity-recognition systems can support different application scenarios in many areas including safety control, medical healthcare, and other monitoring activities in virtual environments that aim to customize the system to end-users' situations or contexts [10, 30]. This helps, for instance, to reduce the occurrence of hazardous situations by monitoring and correcting human error during the execution of critical tasks (e.g., administering medication in healthcare, ensuring proper execution of tasks in safety applications) or to exploit user interactions with an application (e.g., mouse clicks) to infer the user's activities as suggested in [7]. Moreover, knowing the locations and preferences of the users in an indoor context-aware navigation system can lead to improving knowledge of the user's behavior in the considered scenario (e.g., inferring the most bought products in a supermarket by loyal users) [100]. Activity monitoring combined with the delivery of behavior-related context-aware reminders for elderly persons have been also discussed in [137].

3.2 Efficiency-related requirements

An offline requirement regarding the modeling effort needs to be considered in the evaluation process. A spatial model should also be flexible as much as possible so that a wide range of applications can be applied. Efficiency is closely related to the performance and scalability of the system being developed. Those requirements are discussed in the following subsections.

3.2.1 Modeling effort

The modeling effort can be evaluated by the cost and complexity of the model design effort. Some modeling techniques are sophisticated and take considerable effort [119]. Some others are closely dependent on objects within space and need to be periodically maintained or even to be rebuilt from scratch if these objects change their position or shape. Recently, some authors have discussed methods for automated construction that minimize manual intervention by designers during the modeling phase [114].

3.2.2 Flexibility

A flexible spatial model should support a wide spectrum of applications that can be developed at different levels of abstraction, as well as different kinds of positioning sensors that might coexist to achieve better accuracy. This enables human reasoning about space, robot-based activities, and even sensor-based and object-oriented interactions within the environment. In brief: can a simple unmixed spatial model assist with diverse intelligent navigation tasks efficiently? As will be shown later (cf. Section 5), it might be difficult to find a single solution that meets these seemingly contradictory requirements. Consequently, we propose to assess current models based on the range of queries and services that can be supported.

3.2.3 Performance and scalability

A context-aware indoor navigation system must efficiently execute users' queries, such as shortest paths between two given locations, k nearest neighbors, or all accessible locations starting from their current positions [88]. Time complexity for query processing is given by the amount of CPU time spent per sampling unit. In addition, when considering contextual information, performance is no longer restricted to simply deriving position queries or distance functions, but some other features are required, thus leading to a significant increase in workload.

Furthermore, dynamic updates of the spatial data model stored on mobile devices should be periodically performed in order to maintain accuracy and quality of the stored data. For instance, one challenge facing spatial model designers is the cost of updating the location of every moving object continuously in the database. Existing approaches try to overcome this problem by performing periodic, deferred (i.e., demand-based) or immediate (i.e., event-driven) update queries to keep an incremental view maintenance of the database [56]. A related approach focuses on real-time map updates on mobile devices by considering the use of a spatial model with different levels of detail [64]. Updates in this approach are handled at the basic level on the server side, and then an update propagation process through the other levels of the spatial model is continuously performed at the client side.

The scalability requirement denotes the ability of a spatial model to scale up to a large indoor environment while keeping tolerable resource consumption, which mainly affects the memory storage capacity and the behavior of processing workloads. In context-aware applications, heterogeneous mobile devices as well as a huge number of embedded sensors have to be handled in an efficient and scalable way. Therefore, there is a need to establish a mechanism that eliminates superfluous information to reduce processing and communication costs, so that the system can handle a higher number of real-time queries.

4 A taxonomy of indoor spatial models

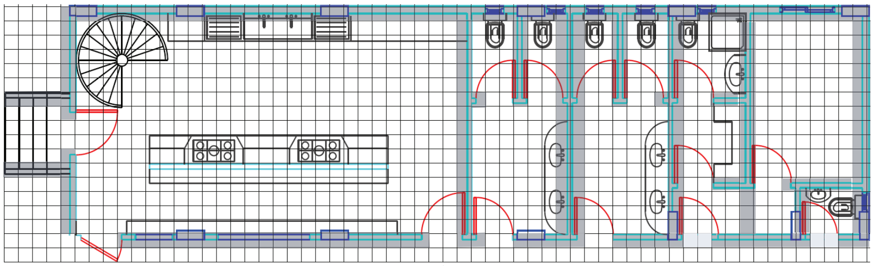
In order to deliver navigation-oriented context-aware services applied to indoor spaces, the system requires an appropriate data model that is capable of representing the locations of objects either situated or active within the environment. Regarding modeling approaches, two main classes are inferred: symbolic and geometric spatial models. In the following section, the strengths and weaknesses of both classes of models are assessed by describing and evaluating different spatial representations.

4.1 Geometric-based approaches

Geometric spatial models (otherwise referred to as metric or coordinate-based approaches) consider space as continuous or discrete, and mainly comprise cell-based and boundary-based geometrical representations. Table 1 presents an assessment of geometric models according to the requirements previously defined.

4.1.1 Cell-based models

The *cell-based* approach tessellates the physical space into a finite number of non-overlapping areas, thus building a partition that covers the entire space. This approach provides an implicit modeling ability to capture adjacency between neighboring cells. Two main types of tessellations can be distinguished [77, 90, 111]: regular tessellations decompose space into cells that have the exact same shape and size (e.g., primarily square- and hexagonal-shaped cells as illustrated in Figure 3). Irregular tessellations aim at providing an adaptive decomposition of space that is suitable to exactly represent the complexity of the environment being studied (e.g., to accurately represent obstacles). The cells forming the irregular partition of space can have different shapes and sizes (i.e., arbitrary polygons in 2D or polyhedrons in 3D).


(a) Square-shaped grid

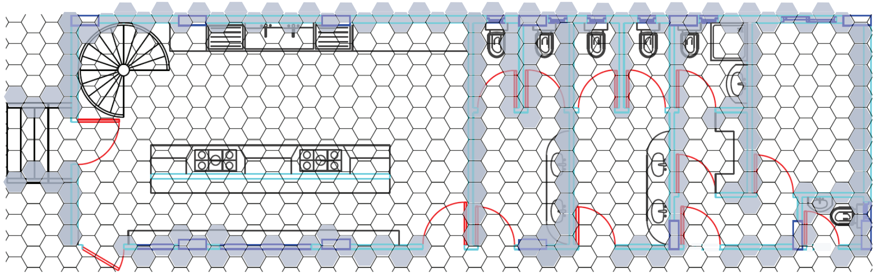

(b) Hexagonal grid

Figure 3: Grid tessellation of a floor plan based on either (a) square or (b) hexagonal cells.

Regular tessellations A well-known regular tessellation is the grid-based model. Indeed, grid-based techniques are trivially implemented and can simply represent navigable and impassable regions in space by associating different cell states. In particular, the *occupancy-grid* approach provides a probabilistic-based regular tessellation representation, which was firstly introduced in [40,93], to address mobile robot mapping issues. In an occupancy grid, a high probability value is assigned to cells within accessible space, while a low probability is assigned to cells occupied partially or completely by objects or obstacles.

Grid-based approaches provide spatial models with continuous geometric properties, supporting different kinds of geometric-based queries as well as cell-level interactions. The extent and the level of granularity are two mandatory parameters that have to be determined a priori for the derivation of the grid. So, the accuracy of the resulting grid depends on the cell resolution. Hence, a first trade-off arises between the precision of information retrieval and the consumption of limited computational resources, especially when dealing with large environments. A fine-grained grid provides accurate location data, but could introduce heavy processing workloads.

Dealing with a huge number of cells may exponentially increase query processing time (e.g., shortest path queries, real-time updates), thus leading to performance and scalability problems. Moreover, regular tessellation techniques do not precisely represent objects with arbitrary shapes. Hence, object boundaries are jagged, and it is possible for narrow pathways to be missed in the modeling process, especially in areas burdened by spatial objects.

The aforementioned inefficiency has motivated the development of hierarchically-organized grid-based structures known as *quadtrees* for two-dimensional spaces [107]. For instance, the *region quadtree* (also referred to as *PR quadtree*) structure is commonly used when less detail is required for some paths of the represented space. This also allows missed pathways to be recovered by repeatedly creating smaller squares to capture more detail when necessary. However, the key disadvantage of this approach lies in its lack of flexibility, especially when dealing with a highly dynamic environment. Whenever the distribution of objects, such as moving users, sensors, and transient obstacles, changes, a significant update may affect the whole quadtree. Moreover, a quadtree model delivers quadrant-based location data so that accuracy is closely related to the size of the quadrant being identified. Localization in free areas, where the size of the quadrant can be excessively large, is therefore significantly disturbed and may not be sufficiently accurate for navigational purposes. A large quadrant representing a part of free space may also disturb the perception of communication ability of the user. A quadtree variant called *skip quadtree* is proposed in [41], which allows dynamic insertion and deletion of points, and search operations in logarithmic time.

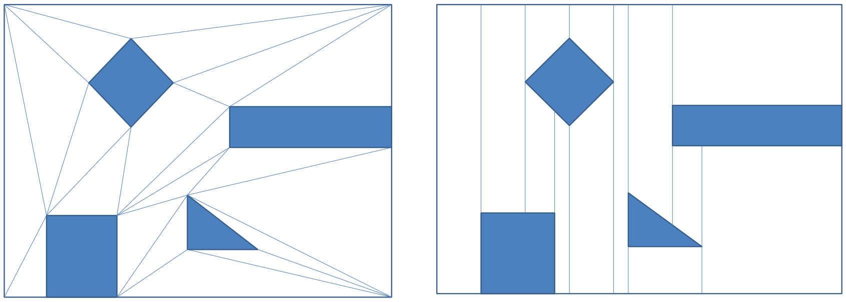
Irregular tessellations Given a set of polygonal obstacles described as line segments, two main techniques have been proposed to irregularly tessellate a space:

- *free-space tessellations* that take into account obstacles and decompose free areas into convex polygonal cells (e.g., triangles, trapezoids) [34, 90].
- *Voronoi tessellations* subdivide space into a set of special cells called *Voronoi cells* [8,29].

Free-space tessellations

Two kinds of decomposition can be described in this category: *trapezoidal-* and *triangulation-based* tessellations. Both spatial models are constructed based on the endpoints of the line segments that compose the boundaries of the obstacles. Trapezoidal decomposition is built by projecting a vertical line from each end-point through the free space until it hits another barrier, thus forming trapezoidal cells of different thicknesses (Figure 4b). The resulting cells tend to be long and thick, which is not suitable for localization. Navigation is performed by finding the intermediate cells that form a route to destination.

Triangulation-based tessellations can be generated by injecting edges between boundaries' endpoints without any edge crossings until no more edges can be inserted [34]. This technique supports path finding by hopping between triangles. Still, it may result in thin triangles. Another technique known as *Delaunay triangulation* overcomes the shortcomings of the last mentioned approach. A Delaunay triangulation of the set of endpoints is the set



(a) Triangulation tessellation (b) Trapezoidal-based tessellation

Figure 4: Examples of free-space tessellation techniques.

of triangles that decompose space such that no endpoint is inside the *circumscribed circle* of any triangle of the Delaunay triangulation.

Free-space tessellation methods support object-oriented analysis and allows for object-oriented interactions within space. However, they suffer from multiple paths between a source and a destination inside the chosen channel (i.e., the set of qualifying polygons), because accurate location information within each polygon cell is unavailable. Moreover, dynamic insertion and deletion of objects is rather difficult.

Voronoi tessellation

The *Voronoi diagram* (VD) of a set of k points is another approach that represents a built environment as a network of one-dimensional curves which concisely exhibit pathways across these points thus forming an irregular tessellation of space [8]. The VD can also be applied to convex objects such as line segments or obstacles rather than points. This extended approach, called the *generalized Voronoi diagram* (GVD), uses a function to measure the distance from a point in space to the closest point on the geometric object (Figure 5). Choset et al. [28, 29] have formally discussed how to incrementally construct the GVD by operating with line-of-sight sensors so that they can derive a *generalized Voronoi graph* (GVG) used for motion planning as described in Section 4.2.

GVDs represent a fundamental data structure for spatial modeling and have been widely used in many research areas, such as robotic motion planning, computational geometry, computer graphics, and GIS. As for other irregular tessellations, with a restricted number of objects Voronoi tessellations can be more compact than grid-based approaches. However, the construction and maintenance of GVDs is still not straightforward. Additionally, localization is often mentioned as a real problem since Voronoi diagrams force mobile users' positions to be shifted along Voronoi edges which may yield to suboptimal trajectories. As a result, GVDs cannot directly fulfill our requirements with respect to context-aware navigational services, but lend themselves perfectly to extract the GVGs that, per se, can be used as operational route-based graphs suitable for many uses.

Irregular tessellation techniques generally offer several advantages over regular techniques including smooth modeling of arbitrary objects, recognition of narrow valid paths, and the fact that it can be markedly compact in unburdened environments. However, most

		Service-oriented requirements				Efficiency-related requirements			
		Localization	**Navigation**	**Location-aware communication**	**Activity-oriented interaction**	**Spatial & behavioral analyses**	**Modeling effort**	**Performance & scalability**	**Flexibility**
Geometric approaches	**Grid-based** [40, 93]	⊕ accurate location data	⊕ suitable for navigation ⊖ no symbolic instructions	⊕ geometric-based data exchange ⊕ high quality data	⊕ cell-level interactions ⊖ no object-based interactions	⊕ continuous analysis ⊖ no object-oriented analysis	⊕ easy to design and maintain	⊖ consumes high memory and processor time in large spaces	⊕ good for navigation queries as geometric information is accurate
	Quadtree [107]	⊕ quadrant-based location data ⊖ constrained by its structure and the size of quadrants	⊕ optimizes navigable space ⊖ no symbolic instructions	⊕ geometric data exchange ⊖ disturb the perception of communication ability[a]	⊕ quadrant-based interactions	⊕ quadrant-based analysis ⊖ no object-oriented analysis	⊕ medium effort to build the tree ⊖ dynamic insertion and deletion of objects is difficult	⊕ more compact ⊖ poor in highly dynamic environments	⊕ good for navigation queries ⊖ not flexible in dynamic environments
	Free-space tessellation [34, 90]	⊕ location data based on an irregular tessellation ⊖ not always suitable for localization	⊖ paths might be not optimal	⊕ geometric data exchange ⊖ disturb the perception of communication ability	⊕ object-oriented interactions	⊕ object-oriented or empty space related analysis	⊕ easy to tessellate space ⊖ dynamic insertion and deletion of objects is not straightforward	⊕ efficient because more compact ⊖ poor in highly dynamic environments	⊕ basic navigation services
	Generalized Voronoi diagram [8, 29]	⊕ location data based on an irregular tessellation ⊖ no accurate location information	⊖ paths might be not optimal	⊕ geometric data exchange ⊕ ability to communicate about objects	⊕ interactions with objects within cells	⊕ analysis of objects within Voronoi cells	⊖ dynamic insertion and deletion of objects is not straightforward	⊕ efficient because more compact ⊖ poor in highly dynamic environments	⊕ basic navigation services
	Boundary-based [25, 31]	⊕ geometric location data	⊖ very limited	⊕ geometric data exchange	⊕ boundary-based interactions	⊕ basic analysis	⊕ easy to design and maintain a CAD model ⊖ model matching can be costly in robotic applications	⊕ efficient with basic operations	⊖ do not support navigation services

Table 1: Assessment of geometric-based approaches.

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[a] A large quadrant may be partially covered by a sensor, but this covered zone can not be perceived by the user, thus weakening its ability to communicate

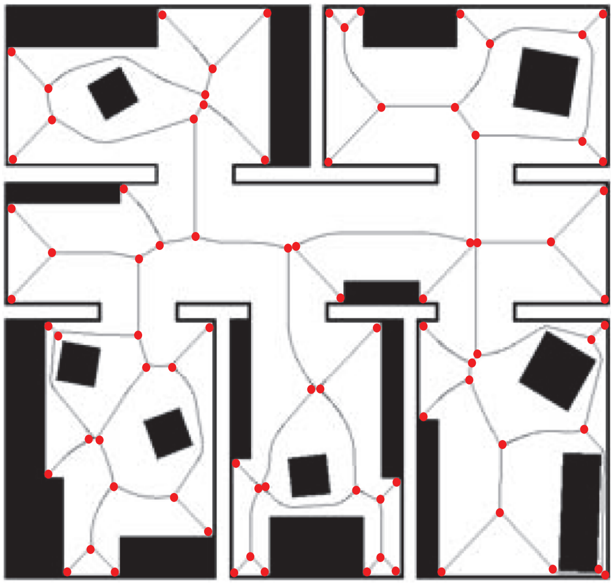


Figure 5: A generalized Voronoi diagram of an indoor space [124].

of these techniques do not support highly accurate localization of mobile objects within the polygonal cells.

4.1.2 Boundary-based models

Boundary-based models represent the obstacles' boundaries of an indoor space with sequences of primitive geometries, such as points, lines, curves. In most cases, a boundary-based map is constructed by concatenating a set of lines segments either extracted from sensor data and representing obstacles as polygons [25, 31, 117], or designed using a CAD system (Figure 6). In many robotic applications that assume no prior knowledge of the environment, sensor data is obtained and the resulting extracted objects are matched to a geometric map. However, model matching can be computationally expensive [117]. Indeed, the line extraction sensors need to be extremely accurate so that lines representing walls, for instance, can be properly positioned at the right location and the right angle on the map. On the other hand, a geometric floor plan can be designed using a CAD system so that various spatial entities (e.g., doors, windows, rooms) are represented as sequences primitive geometries.

In contrast to cell-based approaches, boundary-based geometric models form the most direct way to represent an indoor space and can be highly compact. However, such an approach lacks the capability to incorporate additional object-based semantics so that a deeper knowledge of the represented spatial entities can be achieved. Moreover, boundary-based models are less suitable for navigational services, like path planning, or for communication because they do not lend themselves to applying standard techniques and algorithms for spatial search, and similar services.

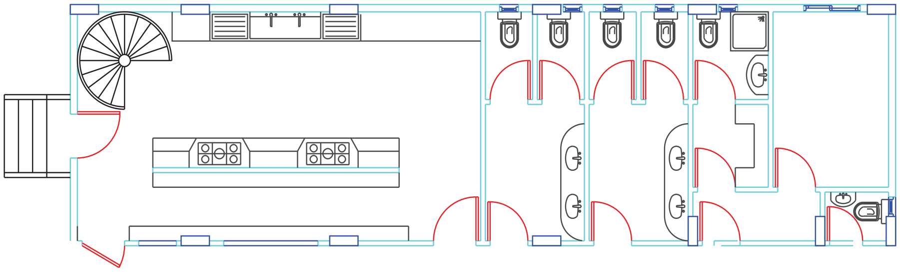


Figure 6: Example of a floor plan designed using a CAD system.

4.2 Symbolic-based approaches

Symbolic approaches have frequently attempted to model indoor environments using topological-based structures [39, 54]; graphs by capturing the connectivity and reachability between spatial units [46, 58, 123]; and hierarchies [15, 29, 113]. The main advantage of these approaches is that object location is provided semantically using human-readable descriptions (e.g., room identifier), and topological relationships are also represented. Depending on their nature, symbolic location models can reveal *containment*, *connectedness*, *closeness*, and *overlapping* relationships [39, 54, 58]. Using the containment relationship, for instance, one can derive a hierarchical structure of the indoor space in order to take into account application constraints and properties. The accuracy of location information in symbolic space depends on the level of abstraction of the indoor data model. For instance, a place-based symbolic model can provide location information at the structural-entity level. However, symbolic models are often unable to support a highly accurate indoor positioning system, and are less suitable for determining the Euclidean distances between spatial entities. Moreover, a symbolic model depends on the application domain and needs to be created and managed accordingly. Hence, managing a very large number of location symbols requires an important modeling effort.

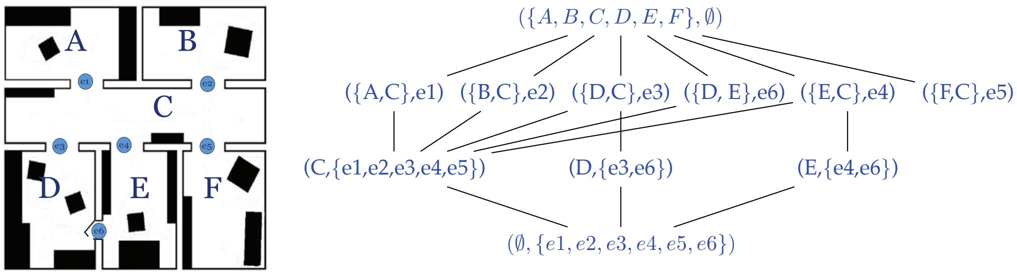
Symbolic models are classified into two categories: set-based models and graph-based models. The set-based approach gathers object or place identifiers into sets and subsets; these are used to define spatial relations between elements of a set or, for instance, the intersection between two subsets. [13, 19]. These sets can be further hierarchically organized to form a tree- or lattice-based structure [39, 54, 84]. Graph-based approaches represent a space as a topological graph. Nodes in the graph symbolize predefined landmarks (e.g., place, gate, sensor range, object) extracted either manually or automatically from the environment. Edges stand for the connections that make it possible to move through these landmarks [29, 103, 104, 128]. These two categories will be discussed further as follows.

4.2.1 Set-based symbolic models

Set-based models identify places or objects of interest within an indoor space, and then gather these symbolic identifiers into sets. Two kinds of set-based models are distinguished: *place-based* and *object-oriented* models. The former considers a set of place identifiers based on the architectural properties of an indoor space [13, 83], while the latter deals with all entities that may contribute to build a smart environment [19]. Indeed, the major difference between these two approaches is the level of abstraction. Place-based models deal with places and build a hierarchy based on the containment relationship; object-oriented models consider not only places, but all other objects of interest (e.g., walls, doors, sensors) in order to build the hierarchy.

Place-based sets Current place-based approaches model an indoor space by creating sets and subsets of place identifiers based on the architectural properties of space [39, 62]. A typical example considers places of a building such that each floor is contained within a building, and each room is contained within at most one floor. A superset is likely to be defined as the set of floor numbers, and at a lower level, a subset related to each floor that aggregates all room numbers has to be created. Such a model is hierarchically organized and can be viewed as a tree structure in which location information is represented at different levels of abstraction. Moreover, when considering places and their neighbors, one can reflect adjacency relations between them as well as some qualitative notions of distance, i.e., one can infer that the distance between two neighboring rooms is smaller than the distance between two distant rooms [13].

Place-based sets models deliver room-level location data, and allow for place-based data exchange as well as for interactions with places. However, the main shortcoming of those approaches is their inability to model connectivity between places as, for instance, two neighboring rooms may or may not be interconnected. Also, it is often unable to determine quantitative distance efficiently. Furthermore, such a tree-based structure is built with respect to the containment relationship, and it does not allow for an element to inherit from multiple parents; this means that a place cannot be contained within two overlapping subsets. This is the case where floors are shared between several wings within a building. In such a situation, a room may belong to a floor and a wing at the same time. This problem has been dealt with by using a lattice structure instead of a conventional tree [83].



(a) An exit-location area in a building

(b) The corresponding lattice-based model

Figure 7: Example of a place-based set model.

As defined in [62], a fine-element lattice is a partially ordered set in which every subset can have a least upper bound and a greatest lower bound. These characteristics of lattices are then applied on a set of places along with the containment relationship $\leq$ (i.e., $p_1 \leq p_2$ means p_2 spatially contains p_1) in order to construct the model. This model overcomes the last mentioned problem regarding overlapping subsets by allowing for multiple inheritance, and it is appropriate for range queries as used in [39] to send *geocast* messages.

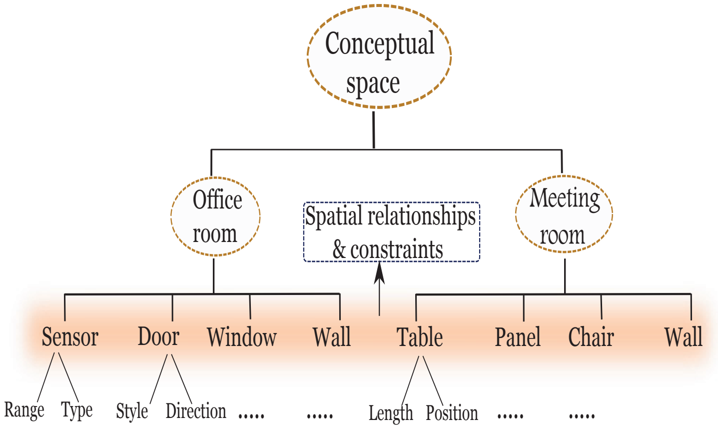


Figure 8: Example of an object-oriented model of an indoor space.

However, this model does not lend itself to other tasks like navigation, because it still does not represent connectedness between places. Another lattice-based semantic model has been presented in [83], that uses the exit-location concept. The exit-location approach models a given space with two types of entities: a location described as a bounded geometric area bordered by one or more exits, and an exit as a boundary gate that allows moving in or out of a location [54, 78]. The hierarchical structure of the lattice is mainly based on the containment relationship between locations (see Figure 7). This model is, for instance, applied to find optimal paths based on nearest neighbor relations.

Object-oriented model An object-oriented model of an indoor space introduces an approach that annotates objects of interest with semantic information according to the properties of the environment. Entities are thus represented as objects, and are characterized by specific attributes and relations. For instance, the *Industry Foundation Classes* (IFC) provide a specification of an object-oriented data model, which serves as a data exchange format reflecting building information [48, 87]. In contrast to geometric plans (e.g., 2D or 3D CAD drawings), IFC represent all entities of space (e.g., walls, windows) as objects. IFC-based models are used in planning and management processes to improve quality of data exchanged and to perform complex management-oriented analysis (e.g., electronic checking, energy effort)

An object-oriented model based on the IFC specification has been proposed in [19]. The indoor space is then defined as the combination of three complementary layers:

- A conceptual layer models terminological and functional characteristics on the architectural entities (e.g., sensor, sliding door, meeting room, computer science laboratory) regardless of how and where they will be used.
- A quality module gives qualitative descriptions about spatial dependencies and relationships with other entities. For instance, the authors use relations as provided by the spatial calculus RCC [51] (e.g., proper part of, partially overlaps, and so forth)
- Finally, architectural entities are quantitatively described in the quantity module.

The advantage of this approach is that it (spatially) qualifies the different roles played by the objects in the environment. Such a conceptual space, illustrated in Figure 8, models all entities of interest along with quantitative and qualitative properties attached to them, as well as spatial relationships and constraints between represented entities.

Object-oriented data models provide symbolic location data at the object level, and allow for semantically-enriched data exchange about objects of interest. Moreover, object-oriented spatial and behavioral analyses can be performed. Nevertheless, object-oriented approaches are not directly suitable for navigational tasks, since geometric details about represented objects as well as connectivity and adjacency relationships are not directly supported.

4.2.2 Graph-based models

Graph-based approaches represent an indoor space as a graph where nodes model predefined locations (e.g., place, gate, point of interest) extracted either manually or automatically from the environment, and edges stand for the connections that make it possible to move through these locations [29, 103, 104, 128]. For instance, a topological graph that directly reflects the architecture of a floor plan represents rooms as nodes and doorways as edges; this can simply express connectedness relationship between the architectural entities [46]. In this category, two main modeling concepts are discerned: *layout-based* and *layout-independent* models. The difference between these two categories is shown as follows.

The layout-based representations rely on graphs where nodes are derived or extracted from the structure of space. This can be exhibited by a basic graph model that can be referred to as a *place graph*, as well as by *visibility graphs*. *Voronoi-based graphs* are also constructed by extracting meet points and boundary points directly from space as described earlier. These points refer to the nodes of the generalized Voronoi graph. *Fine-grained graphs* preserve indirectly structural properties of the environment since nodes are evenly distributed over the entire space. In contrast, some other approaches have adopted graph models that are layout-independent [14, 58]. Nodes are then not directly derived from the structure, but instead are extracted by means of a sensor deployment strategy within space.

Place graphs

In their simplest form, place graphs clearly materialize topological properties of space. In this approach, nodes stand for places such as rooms and/or hallways, and doorways that connect these places appear as edges (Figure 9). Besides the connectivity relationship, other variants of topological relations between structural entities can be inferred, such as adjacency and containment properties by annotating nodes and edges and/or supporting a graph with multiple levels of granularity. So far, this modeling concept has been widely used since it provides for efficient navigation between places, planning routes to destinations, and nearest neighbor queries. In addition, it supports symbolic data exchange and interactions with places. Nevertheless, this approach still does not consider interacting objects. It also has a less accurate location information that does not meet specific application requirements. Geometric properties of space disappear, and it is still difficult to model a semantic distance function which helps, for instance, determining the shortest path.

A semantic exit-location model has been presented by [54]. The aim of this modeling approach is not only to preserve the advantages of the classic place graph model, but also

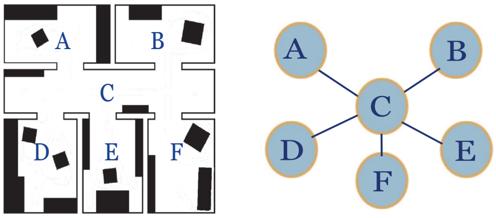


Figure 9: An place graph representing structural entities of an indoor space.

to integrate geometric information, such as a distance model, to overcome some of the aforementioned problems. The exit-location approach models the space with two types of entities: a location described as a bounded geometric area bordered by one or more exits, and an exit as a boundary gate that allows movement in or out of a location. The authors have introduced a series of algorithms for automatically constructing the location and exit hierarchies to derive the symbolic location model. Moreover, this symbolic model is built on some geometric information that maintains distance semantics to support services such as nearest neighbor search, shortest path, and location-aware navigation. Although this approach has dealt with many critical problems, other advanced contextual queries were still not addressed because the model cannot fully support object movement and can provide only basic types of services.

Visibility graphs

Based on a triangulation, one can derive a visibility graph that materializes edges between mutually visible endpoints representing specific locations and obstacles [32]. Visibility graphs are useful for some behavioral and spatial analyses [46, 121]. However, the disadvantages of triangulations remain; accuracy of location information, optimality of path queries, interaction, and flexibility are not dealt with. Furthermore, dynamic insertion and deletion of objects may lead to changes in the graph topology, i.e., the locations and number of nodes can change, and additional edges could be drawn.

Generalized Voronoi graph (GVG)

The GVD is an appealing approach that represents a built environment as a network of curves, which concisely represent pathways suitable for navigational purposes. A route-based graph can be extracted from the GVD as previously described. Such a route graph is referred to as the *generalized Voronoi graph* (GVG), which directly reflects pathways through obstacles [29]. Voronoi-based approaches are suitable for navigation services, such as finding a collision-free path towards a destination. In addition, a GVG inherits all the advantages of graph-based representations. For instance, its nodes can be annotated with additional information for location-aware communication and object-oriented interactions. Specific techniques have been suggested to further prune and remove irrelevant nodes and edges so that the whole graph can be more compact [124, 125]. However, an indoor space, such as an office building, can be populated with a huge number of objects of interest, which may significantly increase the number of nodes and edges that constitute the graph. Furthermore, the location accuracy problem is raised in specific situations when moving in

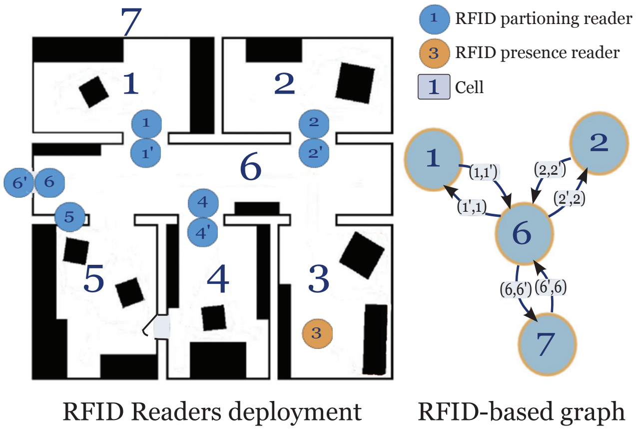


Figure 10: Example of a sensor-based graph.

free-areas, which means that the model does not lend itself to completely support ubiquitous positioning sensors.

Fine-grained graphs

Although previous approaches consider an indoor space at a more abstract level and so have a more compact representation, they appear to be badly-suited to context-aware navigation services since interactions at a fine level within space are increasingly needed. In a companion paper [86], the authors have presented a graph-based model at a fine level of granularity that retains continuous and structural-based properties of space. Nodes in this model represent cells within an occupancy grid, while connections between cells are materialized by edges (Figure 11). Nodes and edges are labeled according to their belonging to a given spatial unit, such as a room or a connecting space. One advantage of this modeling approach is that it achieves a maximum coverage of space so that accurate positioning sensors used for indoor navigation can be supported. Indeed, the geometrical properties are implicitly represented by the continuous layout of the graph and reflect indirectly the shapes of places being considered. This approach allows for high quality data exchange, and for fine-grained and continuous analysis. However, a major difficulty that still needs to be confronted is efficiency-related criteria, especially when considering performance and scalability issues. A large indoor space could comprise thousands of nodes and edges so that managing and executing real-time queries could be an excessive time- and memory-consuming process.

Sensor-based graphs

Many approaches have adopted a sensor-oriented point of view where the objective is mostly oriented to the tracking and monitoring of mobile objects [14, 58]. For instance, the model presented in [14] describes space as a set of layers, the topographic space and the sensor space, and establishes connections between layers based on the sensor coverage. Deployment graphs have been proposed in [58] by using different types of positioning sensors in order to improve indoor tracking accuracy (see Figure 10). A classification of posi-

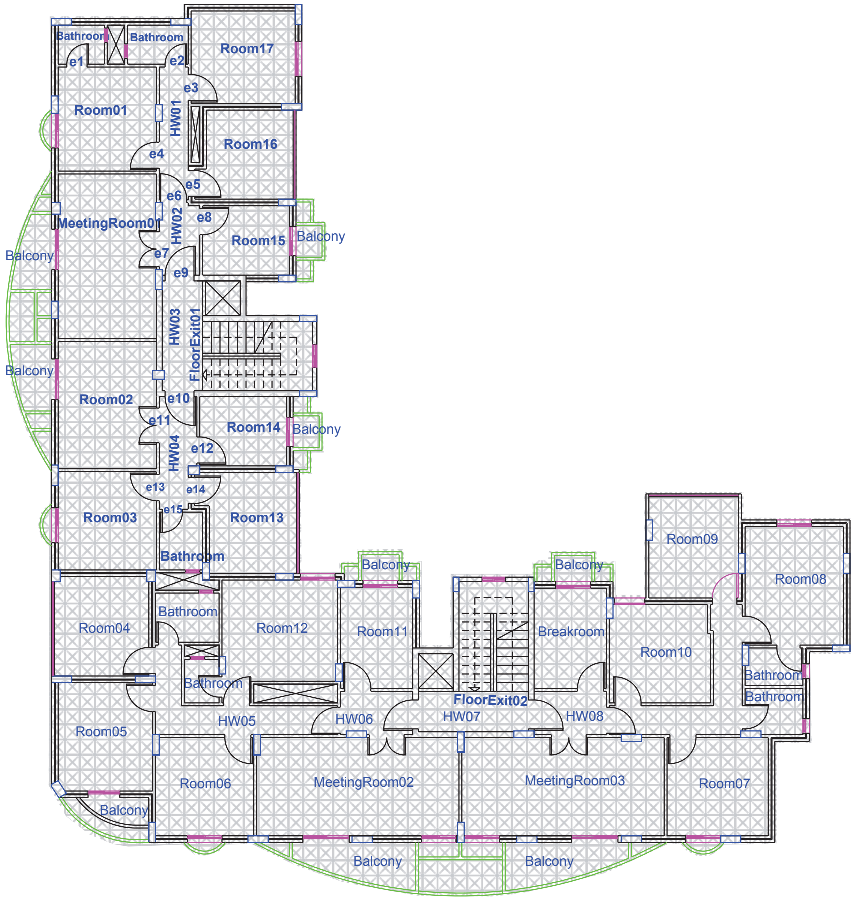


Figure 11: Example of a fine-grained graph of a floor plan.

tioning sensors in indoor space into presence sensors and partitioning sensors can be found in [57]. Navigation between cells representing ranges of the deployed sensors is supported, which also allows for range-based analysis. However, accuracy of location information in such techniques is relatively low since it depends on the sensor range. Object-oriented interaction is also not supported since objects are not directly represented. Furthermore, an optimized deployment strategy of the sensors is needed so that a more compact and more efficient graph can be created. A more detail discussion on sensor-based graphs along with a method for an optimized deployment of sensors can be found in [63].

4.3 Discussion

The taxonomy presented in this section relies upon the nature of location information being delivered. Other classifications of indoor models have been proposed in [13, 129]. The distinction between geometric and symbolic (also referred to as *topological* in [129]) spatial models is similarly emphasized in both classifications as explained earlier in this section.

		Service-oriented requirements				Efficiency-related requirements			
		Localization	Navigation	Location-aware communication	Activity-oriented interaction	Spatial & behavioral analyses	Modeling effort	Performance & scalability	Flexibility
Symbolic approaches	**Place-based set** [13, 39, 83]	⊕ location data at room & connection level	⊖ no information about connectivity between places ⊖ not suitable for metric functions	⊕ symbolic-based data exchange ⊖ no geometric data exchange	⊕ place-based interactions ⊖ no object-oriented interaction	⊕ room-level analysis	⊕ easy to design and maintain	⊕ efficient and scalable due to the hierarchical structure	⊕ suitable for range queries ⊖ no support for navigation services
	Object-oriented set [19]	⊕ location data at object level (e.g., sensor, ...)	⊖ needs information about adjacency and connectivity between places ⊖ not directly suitable for navigational tasks	⊕ symbolic-based data exchange ⊕ object-oriented communication ⊖ no geometric data exchange	⊕ object- and place-based interactions	⊕ semantic & object-oriented analysis	⊖ medium effort as the number of objects to manage is high	⊕ scalable due to the hierarchical structure	⊕ semantic-based applications ⊖ navigation services are limited
	Place-based graph [54, 84]	⊕ graph-based, room & connection level	⊕ suitable for navigation as connections between places are materialized ⊖ no support for metric functions	⊕ symbolic data exchange ⊖ no geometric data exchange	⊕ place-based interactions ⊖ no object-oriented interaction	⊕ room-level analysis	⊕ easy to design and maintain	⊕ efficient due to its compactness	⊕ navigation services
	Visibility graph [32]	⊕ graph-based (accuracy depends on the number and location of nodes)	⊕ suitable but for basic navigational tasks	⊕ symbolic data exchange ⊕ object-oriented communication	⊕ object-based interactions	⊕ visibility and spatial analyses	⊕ easy to design ⊖ dynamic insertion and deletion of objects is not straightforward	⊕ efficient because more compact ⊖ poor in highly dynamic environments	⊕ applications for spatial cognition and human reasoning
	Generalized Voronoi graph [29, 124]	⊕ graph-based (accuracy depends on the number and location of objects)	⊕ suitable but for basic navigation services	⊕ symbolic data exchange ⊕ object-oriented communication	⊕ object-based interactions	⊕ navigation-based analysis	⊖ sophisticated, takes considerable time	⊕ efficient because more compact ⊖ poor in highly dynamic environments	⊕ navigation services
	Fine-grained graph [86]	⊕ graph-based (accurate location data)	⊕ suitable for navigation	⊕ symbolic-based data ⊕ high quality data exchange	⊖ no object-oriented interaction	⊕ fine-grained and continuous analyses	⊕ easy to design and maintain	⊖ consumes high memory and processor time ⊖ not scalable	⊕ navigation services
	Sensor-based graph [14, 58]	⊕ graph-based (accuracy depends on sensor range)	⊕ range-based navigation	⊕ symbolic & range-based data exchange	⊖ no object-oriented interactions	⊕ range-based analysis	⊕ medium effort to design the graph ⊖ optimized deployment strategy of sensors is needed	⊕ efficient due to its compactness	⊕ tracking services

Table 2: Assessment of symbolic approaches.

A distinction is also made between spatial and semantic models since the latter kind of models is object-oriented and not necessarily spatially-dependent [129]. However, neither of these proposals has reviewed and assessed different modeling approaches from the particular perspective of context-aware indoor navigation systems. A summary of different modeling approaches is given below, along with a discussion of their use from an application perspective.

4.3.1 Geometric-based approaches

Grid-based models can efficiently integrate metric properties, thus allowing precise locations, direction information, and distances (cf. Table 1). Quadtrees are hierarchically-organized grid-based structures that allow for space optimization, but lack flexibility in dynamic environments. Free-space tessellations and Voronoi-based diagrams are less suitable for localization, but they are more compact. Boundary-based models are less suitable for navigational services but provide accurate location data. In addition, geometric models require an integration of semantic annotations to achieve a higher degree of location- and context-awareness.

4.3.2 Symbolic approaches

As shown in Table 2, symbolic models are generally less accurate, but context-awareness is easier to achieve as symbolic models support human-recognizable descriptions. Owing to their hierarchical structure, set-based models achieve a good level of efficiency and flexibility, but lack topological relationships, such as connectedness. Graph-based models are widely used in applications at a coarse-grained level of abstraction due to their richness and variety. The major shortcoming of symbolic models is the lack of geometric details on entities and places represented in space.

4.3.3 Application perspective

Symbolic-based approaches are often preferred, from an application perspective, over conventional geometric-based approaches. Symbolic-based approaches have been recently used in several application scenarios [13], because they can capture the semantics of entities and places represented in an indoor space. In particular, graph-based and semantic models constitute the most common approaches used, so far, in many application areas ranging from emergency management and safety control in micro-scale environments [76,79,80,97] to indoor context-aware navigation services, and especially those adapted to users with special needs [14, 23, 38, 45, 72, 120]. Applications that aim to support intelligent emergency response mainly employ simple place graphs, which capture topological relations between structural entities, because these applications are more concerned with network-based models that allow the discovery of nearest or best exits [76, 79]. In contrast, applications that support contextual elements, such as user preferences and capabilities, tend to favor semantically-enriched data models. These applications operate either by designing an ontology-based model, or by employing a hybrid model that combines a graph-based with a semantic model of space [23, 38, 72, 120] (as discussed in Section 5).

5 Towards hybrid spatial models

Numerous spatial data models have been presented in different research fields (e.g., robotics, GIS, ubiquitous computing) with the aim of combining the advantages of geometric and symbolic approaches [22, 61, 81, 118, 124]. Those approaches have complementary strengths and weaknesses. Geometric models can efficiently integrate metric properties to provide highly accurate location and distance information—necessary elements in most of context-aware applications. Symbolic models maintain a more abstract view of space by providing users with easily-recognizable information and by materializing more complex relationships between entities. Neither approach is, therefore, directly suitable for fulfilling all requirements of context-aware services. Clearly, integration of geometrical and topological representations implies considering qualitative and quantitative points of view, as suggested by the spatial semantic hierarchy (SSH) introduced in [73]. This enables human reasoning and human- or robot-centered activities, and even sensor-based interactions within the environment.

Accordingly, the idea of integrating different coexistent models of space appeared as a promising alternative. Hybrid spatial models can be produced in different manners by applying various kinds of organization [13, 22, 124]: (1) parallel models (also referred to as overlays) aim at using different spatial models (usually a combination of geometric and symbolic models) that cover the entire space [14, 86, 112, 118, 124]; (2) patchwork-based approaches represent a space with several local, usually geometrical, models that are linked together to form a global, usually symbolic, model of space [73]; and (3) hierarchical models that embed different layers with different levels of abstraction [43, 44, 61].

Recent studies on mobile robot navigation have focused on how to extract a topological graph from a basic geometric map, such as a grid-based map or a Voronoi diagram. The resulting graph is then pruned by applying some algorithms that select the more relevant nodes. This implicitly provides a hierarchical representation as those encompass knowledge of the environment at different levels of abstraction [118, 124]. Earlier, the SSH model has been presented [73, 74], and further extended in [16, 75]. The SSH model consists of a hierarchy of representations that are interdependent. This hierarchy is constructed from local geometrical maps that correspond to the human or robot's sensory horizon, and are merged together based on topological relationships which, in turn, are derived from causal state-action-state schemata.

A relevant example of a hybrid spatial model designed to handle location-dependent queries is presented in [61]. This model is a combination of a hierarchical, set-based representation of space and a geometric representation of places, sensor ranges, and objects of interest. These geometric annotations are attached to the corresponding elements in the symbolic set. The model achieves a good trade-off between geometrical and symbolic approaches by combining the benefits from both sides. Although this model handles some relevant location-dependent queries such as "find the nearest object of interest," it lacks a clear process description of how to acquire an accurate location of the mobile user continuously. In addition, queries are handled based only on the distance parameter. Most context-aware applications require integration of context dimensions that aim to find the best solution, not only the nearest one. In [112], a physical space was symbolized with a set of layers that corresponded to different location models designed to meet various activities performed by the users. At the basic layer, the model embeds a quadtree by considering some points of interest. On top of this layer, various topological models were added depending on users' activities. The lattice model has been used together with a simple graph model, extracted to materialize connections, and to perform relevant location-dependent queries such as position, range, and path queries.

The annotated hierarchical graph model (AH-graph), presented in [43, 44], constitutes a comprehensive framework for efficient mobile navigation. The AH-graph consists of multiple topological layers defined at different levels of abstraction and linked together based on abstraction functions developed for nodes and arcs. An annotation function is also defined at each level so that information can be attached to nodes and arcs. This allows basic queries (e.g., path searching) to be performed hierarchically, thus achieving better scalability. An extension of the model was then presented by adding multiple hierarchies produced based on several scenarios specified at the application level, thus supporting a large spectrum of applications and achieving a high level of flexibility. The model has been further used in [103] to implement the SSH at the topological level due to its efficiency and flexibility. In [49], the AH-graph hierarchy was appended to a semantic hierarchy to further improve human-robot communication.

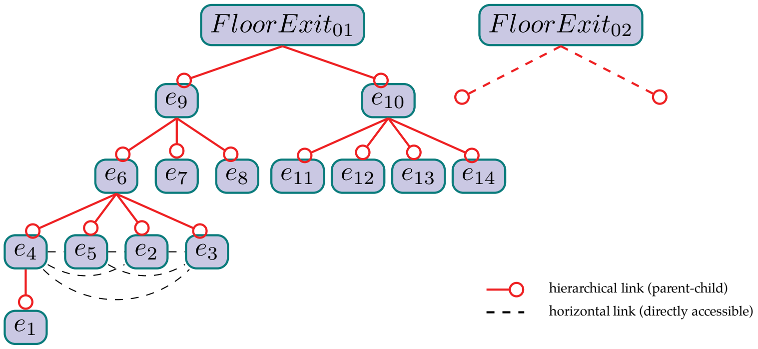


Figure 12: Part of an exit hierarchy derived from a fine-grained graph (Floor-01, Building-1 of Figure 11).

Generally, parallel models that combine, for instance, a graph-based model with a geometrical model underneath, tend not to scale well to large environments since they could not avoid the weaknesses of geometric models with respect to efficiency and scalability. Hierarchical models, by contrast, scale very well to large environments because queries, such as path search, are performed hierarchically, switching between finer and coarser levels. In addition, a specific level of granularity can be used in specific situations with respect to application constraints and users' preferences. Approaches that integrate hierarchical organization require, however, the maintenance of connections between levels and the integration of a fine-grained geometric model that guarantees accurate localization for specific navigational purposes.

Our objective in ongoing work, [2–4], is to develop a context-dependent multi-granular indoor data model that can provide a flexible representation of an indoor space, taking into account the objects located and acting in the environment. This modeling approach integrates across different levels of granularity, and considers context dimensions beyond the location of the involved entities, such as time and user profiles (Figures 11, 12, 13). This indoor data model allows a large spectrum of applications to be developed at different levels of abstraction, while alleviating performance and scalability issues in

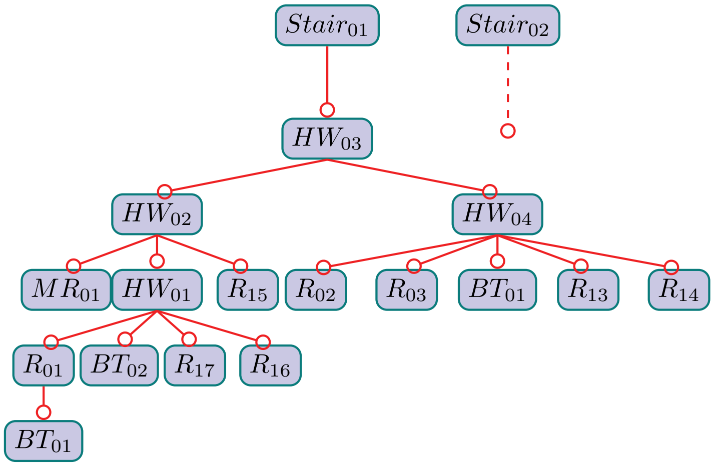


Figure 13: Part of a location hierarchy derived from a fine-grained graph of Figure 11.

location-dependent query processing. Moreover, this model supports different categories of location-dependent queries, either in continuous or discrete modes, as well as algorithms for continuous processing of navigation and range queries [2]. Future work will be oriented towards (1) taking advantage of this proposal to deal with the continuous processing behind other relevant location-dependent queries in indoor contexts; (2) integrating an extended context model with a semantic reasoning in real time, mainly to deal with real-time event management; and (3) generalizing the hierarchical data model to higher levels of abstraction (floor and building levels), thus building a nested-graph model similar to the hypernode/master-node data model described in [82] and [89], respectively.

6 Conclusion

Location information is an unavoidable dimension to be considered in the design of context-aware information systems. Context-aware navigation systems require the use and integration of an appropriate indoor spatial model that satisfies application and structural constraints, and takes into consideration dynamic properties and interactions of moving objects with their physical surroundings. This paper introduced some typical examples of location-aware services, and then presented several service- and efficiency-related requirements with the aim of comparing and contrasting existing spatial models from a context-aware systems perspective. A taxonomy of indoor spatial models has been presented and assessed based on these requirements. Two classes of models are distinguished: symbolic and geometric spatial models. Whereas geometric models can efficiently integrate metric properties to provide highly accurate location and distance information that are necessary elements in most of context-aware applications, symbolic models maintain a more abstract view of space by providing users with easily-recognizable information and by materializing more complex relationships between entities. Hybrid spatial models are then presented as an intermediate approach that can fulfill context-aware application requirements. We believe that a hierarchical organization of location information, which materializes containment and connectedness relationships between entities, coupled with a fine-grained geometrical model can guarantee flexibility, efficiency, and accuracy so that a large range of context-aware queries and services can be provided.

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