Indoor Space Dimensional Model Supporting the Barrier-free Path-finding

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***Abstract*—In total, about 65 million people have to move by wheelchairs. However, the spatial location service for wheelchair users is one of the scarce aspects in the current geographic information industry. Especially in the poorly-visible indoor spaces, the absence of distributive information for barrier-free facilities will make their movement hard. Therefore, it is of great value to provide indoor location services that support the barrier-free path-finding.**

The indoor location service is the hotpot in the field of spatial information research at present, and the indoor space model is the basis of the indoor location service which is also the key. In recent years, a variety of indoor space models have been propose,d and they can be divided into semantic models, topological models, geometric models and hybrid models connected in parallel stitching or dimensional ways. It is difficult for users to understand the indoor space merely described by the semantic model. The semantic model is usually used to assist in constructing other types of indoor space models. The grid model has been commonly used, although it can accurately display the position information, it increases the data volume and complexity of the model and reduces the efficiency of the analysis. The topology model is most widely used in indoor path finding, but its lack of location information needs to be complemented with the geometric model. Therefore, the paper proposed a three-layer indoor space dimensional model, it contains geometric information, topological information and semantic information based on several traditional indoor space models. First geometric information, topological information and semantic information were extracted from the source data. Then the general semantic description of the indoor space and the topological relations of indoor space components were constructed. According to different scenes, multiple properties of user's behaviors and components' states were specified. The three layers of information were merged into a dimensional model, which was the basis for indoor path planning in different scenes. Finally, a hospital building was taken as an example to construct the indoor space model. The geographic information software was used to plan indoor paths for users in ordinary scene and accessible scene respectively. The experiment shows that the indoor space dimensional model is simple to construct , it can adapt to the indoor routing requirements in different scenes and is easy to update.

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I. Introduction

Currently, 90% of human activities are concentrated indoors, and the average indoor activity time in China is up to 20 hours per day [1]. The generation, interaction and storage of indoor information are more complex and intensive than outdoor activities. Therefore, indoor space modeling has shown great development prospect in such a situation. It can reconstruct the indoor environment in a virtual way [2], and visualize the indoor map in 3D [3]. It can also provide indoor positioning and navigation service [4], it can improve efficiency of indoor activities by analyzing data, and it can enhance the effective sharing of information. Therefore, how to establish a simple and efficient indoor space model has become a hot issue in current research. Through data analysis in the indoor space model, indoor environment of living and working can be improved, the efficiency of indoor activities can be improved, and the transmission and sharing of effective information can be strengthened. Therefore, how to establish a simple and efficient indoor space model has become a hot issue.

As the extension and supplement of outdoor space models, the indoor space models have inherited the accuracy, immediacy and query function, navigation function and visualization of outdoor space models. Compared with outdoor space models, indoor space models have their particularity, which are mainly manifested in particle size [5], path selection [6][7], platform support [8], information type, sharing update and so on. For example, indoor space is microscopic in size relative to outdoor space. People have different perception, understanding and expression of different granularity of space. The outdoor space has a clear road network. And there is no road network in the interior space, which needs to be rebuilt. In addition, existing indoor data sources are widely available, but they are lack of unified data standards and formats. Modeling methods of indoor models are mostly for specific indoor scenes, and there is no general indoor space model applicable for most scenarios. Therefore, the modeling of interior space cannot directly follow modeling methods of outdoor space. It needs to construct a set of technical methods including data processing, model construction and scene application, according to the particularity and complexity of interior space.

At present, different indoor spatial data models are proposed for different indoor space applications, which can be divided into geometric model, grid model, topological model and semantic model [9]. The geometric model describes the interior space structure and components through geometric elements with precise coordinates such as points, lines, planes, and bodies. And it conforms to the characteristics of the space entity. It has compact structure and precise coordinate position, which is obvious to users. However, during the construction of geometric model, the extraction of boundary lines is more complicated. And lacking of semantic information, it can not support indoor path planning and navigation services. The geometric model is mainly used as data sources or modeling bases for other models. The grid model is established by the finite non-overlapping grid division of indoor space [10]. If the number of grids is too small, the accuracy of the model will be reduced and the information of indoor space will be lost. If the number of grid is too large, the data volume and complexity of the model will be increased, and the efficiency of query and analysis will be affected. Therefore, it is very important to select different grid shapes and sizes according to different indoor environment. Topological model represents the topological relation which between indoor objects in the form of graphs, tables and sets. The topology model reveals the adjacency relation, including relation, intersecting relation and connection relation of indoor space, so it can support range query, nearest query, path navigation and other location services. However, this qualitative description makes the topological model lack of quantitative information such as location coordinates and relative distance, which can not meet the requirements of high-precision location query and path navigation. Therefore, the topology model is usually combined with other models. The semantic model distinguishes and describes the identification, properties, functions and interrelationships of different types of indoor space objects. Different scenarios result in different classifications, resulting in different semantic models. The typical semantic models used in previous studies include the semantic space model used to construct the topological world [11], the spatial semantic reasoning model used in environmental design [12], and the four ontology models used for studying indoor and outdoor seamless navigation [13]. These semantic models have their applicable scenarios.

Geometric models, grid models, topological models and semantic models have advantages and disadvantages, and are difficult to achieve both in terms of usability and efficiency. Therefore, in order to compensate for the limitation of the single model, various hybrid models are proposed to improve the equilibrium of the model. For example, Stevens et al. conducted path analysis by establishing three-dimensional lattice topological relations for two-dimensional planar data [14]. Li proposed an interior model based on concept lattice that shows the connection of indoor space through the connection diagram between location and exit [15]. Becker et al. divided the interior space into a number of different levels of information, and established a multi-level model, in which the topological layer expresses the topological relations between the interior elements [16]. According to the analysis of the characteristics of real estate data, Wen et al. used the ‘path’ and ‘node’ as the key elements to express the spatial relationship and the topological structure of the building and apply it to the construction of emergency evacuation buildings [17]. Yang and Worboys proposed a formal model based on combinatorial graphs to enhance the geometric and semantic information, and automatically calculate the indoor space navigation map [18]. Tashakkori et al. studied the IFC (Industry Foundation Classes) -based indoor emergency space model (IESM). This model combines the 3D interior architectural semantic information needed by the rescuers at the time of an indoor disaster with the indoor and outdoor geographic information to improve situational awareness of the interaction between the rescuers and the indoor and outdoor components, so as to realize the emergency response and management [19]. Teo and Cho proposed a BIM (Building Information Modeling)-based multipurpose geometric network model (MGNM). The model can automatically generate and connect from the BIM indoor and outdoor network, and achieves pedestrian path planning. Compared with the traditional indoor network model, the model gives significantly lower actual error [20].

Hybrid models can be divided into parallel model, splicing model and dimensional model. The parallel model use several different sub-models simultaneously to describe the entire interior. Each sub-model in the parallel model can be detailed, but the links between them are weak. The splicing model connects several local geometric models through the global topological model, which is suitable for spatial description and query of large-scale and continuous scenes. However, it is lack of spatial analysis function. The dimensional model builds multiple layers of indoor space at the same time in a model. These independent layers represent the geometric, semantic and topological information of indoor space, and the connection between each layer is very compact, and the number of layers in the model is also extensible. The dimensional model can realize the functions of location query, path planning and spatial analysis. When the indoor scene and mode change, the dimensional model is useful to solve the problem of data synchronization update. The difficulty of building a dimensional model is the construction of each layer and the way they relate to each other. The context-dependent double-layer data model for indoor space is a kind of typical dimensional model. The high-connectivity region in the model is finely divided by Voronoi diagram. Although the accuracy is improved, the data volume also increases, and the structure of the situation ontology is too large[21].

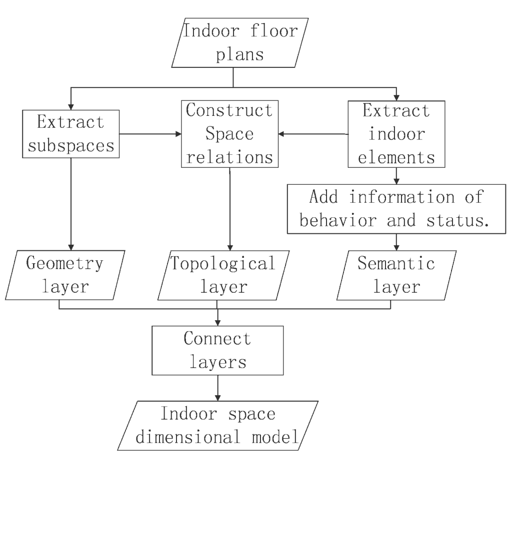
Therefore, this paper studies an indoor space dimensional model supporting the barrier-free path-finding. In this model, the geometry layer, topological and semantic layer are combined closely, this combination can complement the shortcomings of other hybrid models. and is suitable for the floor structure clear, includes barrier-free facilities of public indoor space modeling. This model is applicable to the modeling of public indoor spaces with clear floor structures and accessible facilities.

II. Indoor Space Dimensional Model Supporting The Barrier-free Pathfinding

At present, most public places are provided with barrier-free facilities. The utilization rate of them is not high because of their unclear distribution. The indoor space dimensional model supporting the barrier-free path-finding studied in this paper meets the application needs of most people, it also provides wheelchair users with barrier-free facility inquiries and indoor barrier-free path-findings. In order to realize the personalized location service, this paper constructs user's behavior information and the status information of the indoor space elements into the semantic layer. In the process of modeling, this paper discusses methods of extracting indoor elements, topological subspaces and indoor path networks based on the existing plan, the method of constructing and associating the geometric layer, topological layer and semantic layer and the visualization of cross-floor model. The results of indoor path-findings under different scenes are compared by experiments.

In the dimensional model of this paper, the geometric layer describes the location information of indoor objects and the starting point and the final point of path-findings. The topological layer describes the relation of each object and the topology change caused by the addition of various dynamic information, so as to meet the location service demand of different users. The semantic layer distinguishes the different types of objects and shows the change of attribute values and subordinate relationships of indoor space objects in different scenarios. And the expression of the indoor space under different requirements is satisfied. The single model is difficult to expand in a large area of indoor public space, but the dimensional model can solve this problem. Moreover, features at different granularities, such as indoor location services, route navigation features can be easier. Difficulties in building the indoor space dimensional model supporting the barrier-free path-finding are to integrate the behavioral state attributes into the semantic layer and to establish and maintain the association between layers.

Fig. 1. The process of building the indoor space dimensional model supporting the barrier-free path-finding



In this paper, the process of building the indoor space dimensional model supporting the barrier-free path-finding is shown in Fig. 1. First, the subspaces and indoor components are extracted according to the indoor floor plans and stored as a geometric layer containing information of behavior and status. Then, the subspaces and indoor components are abstracted as nodes whose spatial relationships are abstracted as edges and stored as a topological layer that contains the indoor path network. Finally, the connection between geometric layer, topological layer and semantic layer is established, and the dimensional model of indoor space is obtained.

A. *The geometry layer*

In the construction of the indoor space dimensional model, the semantic information, regional location, topological relation, coordinate and position of indoor objects need to be acquired. In order to clarify the semantic meaning and topological relation of indoor objects, the indoor elements need to be extracted first. On this basis, indoor space should be visualized, and the geometric layer of the indoor space dimensional model has been extracted.

The geometry layer is a collection of vector graphics describing the shape, size and position of indoor elements, usually including points, lines, faces. Points, lines, surfaces are extracted from the indoor floor plan to construct the geometric, semantic, and topological layers in the interior space dimensional model.

B. *The topological layer*

The topological layer is a collection of relations between topological subspaces. Topological subspaces which represent subsets of the indoor space have a specific function, such as rooms, walkways, living rooms. Topology subspace assists the establishment of indoor topological networks and record the spatial connectivity information, which are of great significance for indoor path analysis and query. However, the structure of indoor floor plan is often complicated. The inner and outer wall lines, gate lines and auxiliary lines will interfere with the automatic extraction of subspaces and the result of extraction. Different extracting criteria lead to different topological subspace structures.

In order to ensure the operability of the topological subspace extraction method and the reasonableness of extracting the result, this paper has analyzed cases of indoor space division. Considered architectural design and model application, the following two principles of subspace extraction need to be met.

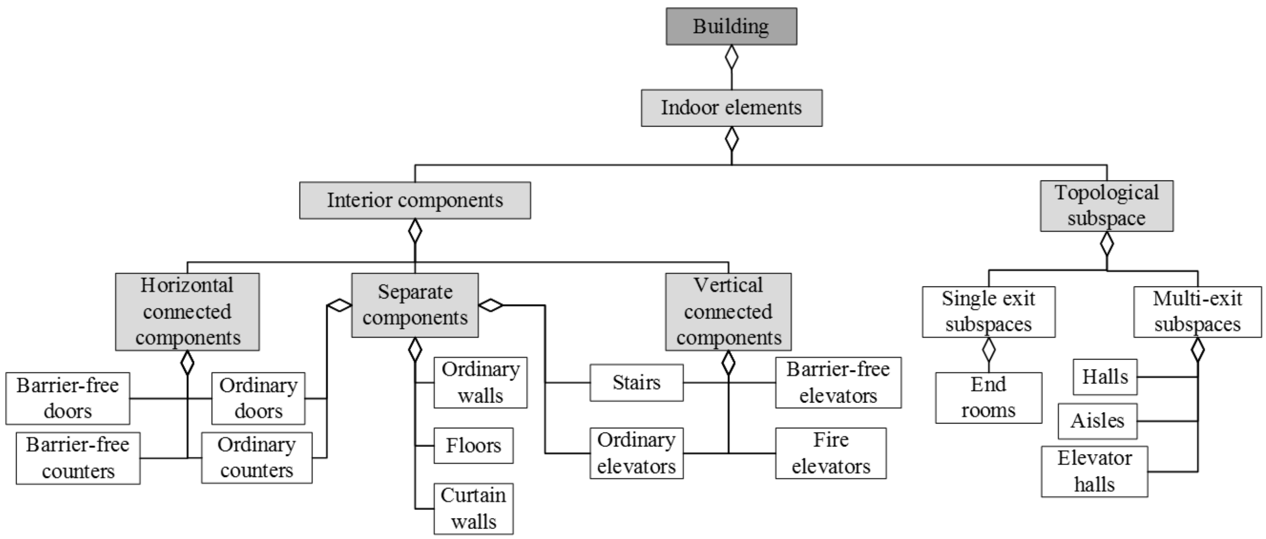
- Extract the enclosed space enclosed by the opening and the wall.
- The extracted subspace can not contain more subspaces.

The topological layer emphasizes the division of indoor functional space and accessibility structures which is based on the ontology feature description of the semantic layer and takes the semantic features of indoor components and indoor subspaces as logical links [22]. There are three types of relationships between topology subspaces and indoor components, including the containment, the association, and the connectivity. The containment exists between the indoor component and the topological subspace. The association exists between indoor components, and the relation exists between topological subspaces. As shown in Fig. 2, the black fine line connected to each node represents the horizontal connectivity of the topological subspace, and the green dotted line represents the vertical connectivity between topological subspaces of the two floors.

Fig. 2. The connection between topological subspaces

Based on the semantic classification for the dynamic evacuation of indoor fires [23], this paper expands the semantic description of indoor spaces for barrier-free access.

The connected component refers to the indoor component that plays the role of transportation in the process of human indoor movement. And the indoor path network can be built horizontally and vertically. Horizontal connected components include doors and windows. Vertical connected components include stairs and elevators. Connected components can be

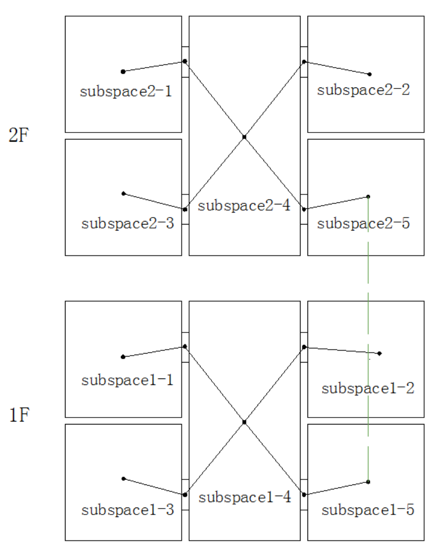


C. *The semantic layer*

The semantic layer is a collection of various attributes of indoor components. Attributes provide information about indoor components, such as name, use, permission, time limit, access conditions, etc.

The semantic layer constructed in this paper is a comprehensive expression of the semantic ontology and its logical relations for barrier-free access, as shown in Fig. 3.

Fig. 3. The semantic description of indoor space for the barrier-free path-finding



divided into ordinary connected components and barrier-free connected components. The separate component refers to the indoor component that divides indoor space into several topological subspaces, include walls, floors, and curtain walls. When wheelchair users move, ordinary doors and ordinary windows used as connection components are converted into separate components.

In the semantic layer, the information of behavior and status is added to describe the user's capacity, speed of movement and the open and close state of indoor components in different scenes. The behavior information records the information of different users, including each their behavior ability, traffic speed and access rights. For example, adults, children and wheelchair users can reach different ranges of areas and they travel at different rates. The patient and the medical staff have different access rights in the hospital. The status information records information of different scenarios. For the wheelchair user and the ordinary patient, the ordinary door has different accessibility. The information of behavior and status is the new information that is obtained by Boolean-operation of the behavior value and state value. As shown in TABLE I. , the new information of behavior and status is obtained of wheelchair user’s behavior information and ordinary door’s status information by or-operation. The new information named *Capacity* indicates the general ability of the door, and it shows whether an ordinary door for the wheelchair user is a connected component or a separate component. Moreover, barrier-free components are designed for wheelchair users alone, so these scenarios do not need to be considered, and their values of *Capacity* are always 1.

TABLE I. OR-OPERATION OF CAPACITY

Or-operation		Wheelchair user's behavior information	
		Alone-0	*Together-1*
Ordinary door's status information	***Close-0***	0‖0=0	0‖1=1
	Open-1	1‖0=1	1‖1=1

The following scenarios can be digitized by Boolean operations.

- Multiple user modes.
- Connected status or separate status of indoor components in different scenarios.
- The above two scenarios exist simultaneously.

In a similar way, a variety of user behaviors and indoor component status can be assigned. Similarly, the bidirectional traffic of indoor components named *One-way* can be expressed in four values, as shown in TABLE II. Elevator operation floors, subspace access and opening time, etc., can be expressed through this mechanism.

TABLE II. VALUE INTERPRETATION OF ONE-WAY

Value	interpretation
FT	Only allow one-way traffic along the digitized direction of the edge
TF	Only allow one-way traffic in the opposite digitized direction of the edge
N	No traffic
NULL	Any other value indicates that two-way traffic is allowed.

D. The connection between the geometry layer, the topological layer and the semantic layer

In this paper, the semantic information is given and the indoor topology network is constructed on the basis of the geometric layer of indoor components, thus the three layers are connected. As shown in TABLE III, the connection of layers is made by associating semantic information and status information in various edges of the topology network. The connection can not only expand the single function in the traditional indoor space model, but also help to synchronously update topological information and semantic information in the indoor space dimensional model. The information table can integrate the semantic information and behavioral status information of indoor elements. The information of element type, edge length, accessibility, and one-way traffic is related to geometric information and topological information of indoor topological elements.

TABLE III. THE INFORMATION OF EDGES IN A TOPOLOGY NETWORK

FID	Shape	length	Capacity	One-way	…
0	polyline	0.72	0	TF	…
1	polyline	1.91	1	NULL	…
2	polyline	1.98	1	FT	…
3	polyline	1.88	1	NULL	…
……	……	……	……	……	…

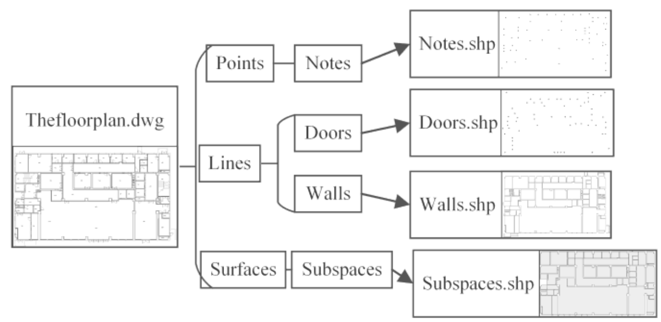
III. MODELING AND EXPERIMENTS

This paper has modeled the indoor space of a hospital according to the modeling process in Fig. 1. The modeling includes the indoor element extraction, the spatial relationship construction, the cross-floor visualization and other processes. The experiments of indoor path-finding are carried out in single-floor and cross-floor models, respectively.

A. Extraction of indoor elements

In this paper, the indoor floor plan of a hospital is selected as the experimental data, and indoor elements of the point, the line and the surface are extracted from the source data, as shown in Fig. 4.

Fig. 4. Extraction of indoor elements

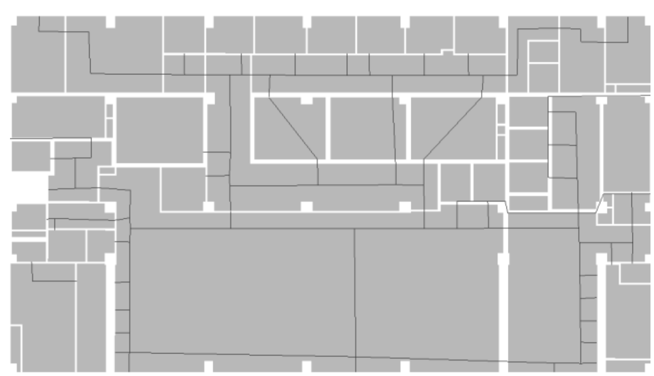


The points and lines are converted into the indoor element containing geometric information and semantic information, such as notes, doors, windows and walls, which are mainly used to construct the semantic layer. The surface is transferred to the subspace used to construct the topological layer. Notes, doors, windows and walls are abstracted into subspaces in the geometry layer. Therefore, their semantic information can be mapped to the topological subspace. And the extraction of indoor elements and the connection of three layers are realized.

B. Extraction of indoor path network

After extracting indoor components and subspaces, the subspaces and their topological relationships are abstracted into the indoor path network, which is to make the topological relation more clear and visible.

Fig. 5. The subspace and the path network of a floor

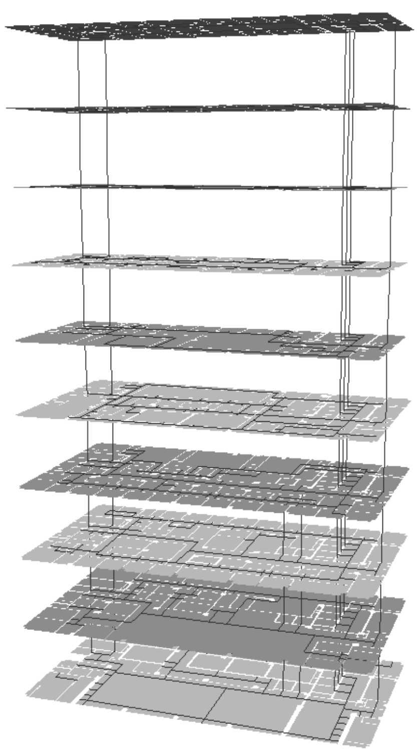


In order to extract the path network, first, corridor paths are generated based on image refinement and feature point extraction algorithms. Then, as shown in Fig. 5, the rooms, stairs, elevators and other nodes are added to the path, and the path network of each floor is generated separately. Finally, the path network of each floor is connected as a whole through the stairs, elevators and other cross-floor components. The status information of the indoor components is also mapped to the indoor path network.

C. *The cross-floor visualization*

In this paper, by giving different heights to floors, the indoor space dimensional model is visualized from 2D to 3D, as shown in Fig. 6. This visualization takes into account the expression of horizontal connection and vertical connection. When expressing the topological relation of vertical connection components, each elevator and stairs do not intersect each other. Therefore, there will be no disorder when cross-floor path-finding.

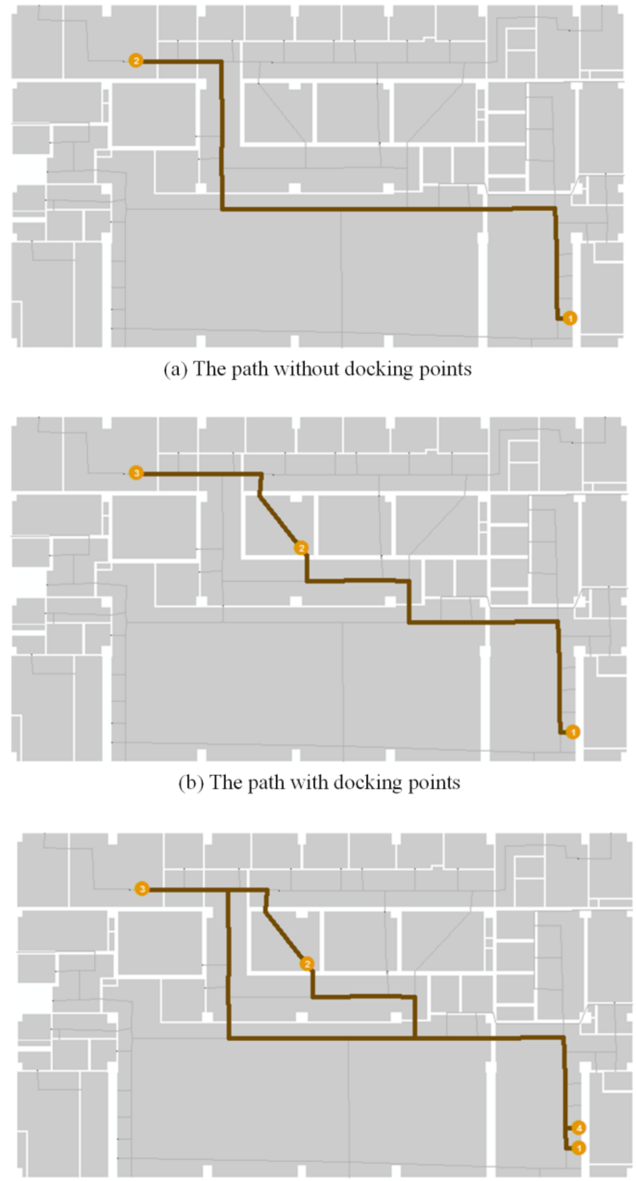
Fig. 6. 3d visualization of the indoor space dimensional model



D. *Experiment I: the indoor single-floor path-finding considering the semantic information*

In order to verify the effect of the semantic information of the indoor space dimensional model in different scenarios, a single-floor model of the hospital was chosen for indoor path-finding. Three typical indoor treatment paths were considered with the same starting point and end point. The path-finding results are shown in Fig. 7, where the brown solid line represents the best path-finding for the ordinary patients. Fig. 7a represents an undocked path, and Fig. 7b represents the path with a docking point, and Fig. 7c represents the roundtrip path.

Fig. 7. Results of the indoor path-finding for the ordinary patient



(a) The path without docking points

(b) The path with docking points

(c) The round trip

This experiment takes into account the semantic information of indoor elements. For example, the X-ray room has special access rules that can only be used one-way, and can only be trafficked if it is designated as the docking point, the starting point or the end point. In Fig. 7b, when point 2 is the docking point, that is, the patient needs to enter the X-ray room represented by point 2 to be treated, and the subspace can be passed. Otherwise, the patient can only follow the path shown in Fig. 7a. As shown in fig.7c, point 2 is not the docking point on the return trip, so the subspace cannot be passed. The experiment results in three shortest paths that meet the requirements of the scene. TABLE IV. lists the straight line distance, the polyline distance, number of subspaces passed and estimated travel time of three indoor paths for the ordinary patient.

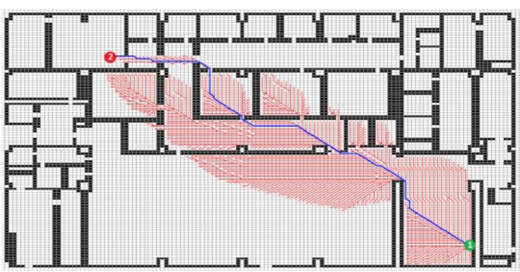
TABLE IV. THREE INDOOR PATHS FOR THE ORDINARY PATIENT

No.	Path	Straight line distance (m)	Polyline distance (m)	Number of subspaces passed	Estimated travel time(min)
1	Without docking points	40.7	55.1	5	1.1
2	With docking points	40.7	43.4	8	0.9
3	Round trip	81.4	107.1	12	2.2

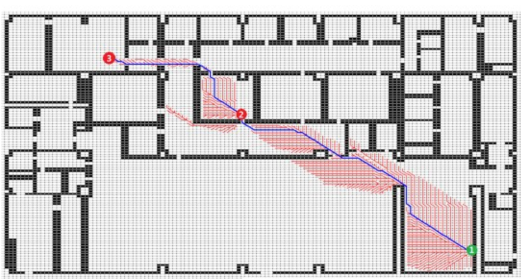
It can be seen from the table that the polyline distance have increased by 35%, 6% and 31% from the straight line distance respectively. In addition to the time of diagnosis and treatment, it takes an average of 12s to pass a subspace. Experiment I shows that the indoor space dimensional model can meet the requirement of semantic information. And the path that meets the hospital's rules has been found for ordinary petients.

We use the grid model and the A* algorithm to repeat the above indoor pathfinding experiment. As shown in Fig. 8a, when there are one starting point and one final point, A* algorithm can ge results in the grid model. In Fig. 8b, when there are two final point in the path, it must be divided into two sections. In Fig. 8c, one-way path cannot be implemented in the grid model.

Fig. 8. The experiment of grid model and A* algorithm



(a) Path 1



(b) Path 2

(c) Path 3

E. *Experiment II: indoor cross-floor path-finding for different kinds of users*

In order to compare the indoor cross-floor path-finding of the indoor space dimensional model for different users, three typical treatment paths are selected. Fig. 9a represents the path of blood sampling, and Fig. 9b represents the path of registration, and Fig. 9c indicates the path of taking drugs after diagnosis. In the three sets of paths of Fig. 9, the left green line represents the best barrier-free path for the wheelchair, and the right brown path represents the best path for the ordinary patient. The path-finding for the wheelchair should try to choose barrier-free components that are suitable for independent use.

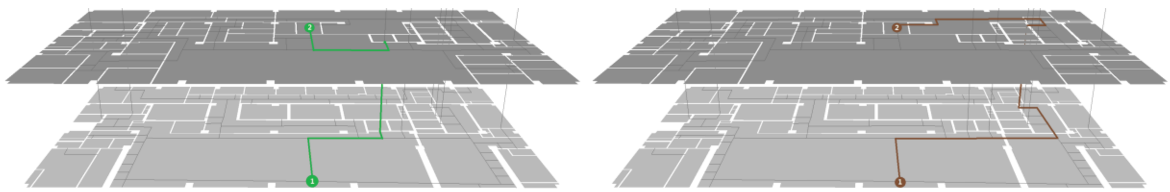
In Fig. 9a, the barrier-free path differs from the ordinary path in the selection of cross-floor components. The former chooses the barrier-free elevator, and the latter chooses the ordinary elevator. In Fig. 9b, the difference between the barrier-free path and the ordinary path is the starting point except the selection of cross-floor components. The former starts from the barrier-free registration window, and the latter starts from the ordinary registration window, which conforms to the behavior information of both types of users. In Fig. 9c, the barrier-free path differs from the ordinary path in the selection of docking points. The former first reaches the barrier-free washroom on the second floor and then through the barrier-free elevator on the other side of the hall to the first-floor barrier-free drug window. The latter first reaches the washroom on the second floor, and then through the same-side stairs to the ordinary drug window of the first floor. Considering that the hospital is a crowded public place, the speed of the wheelchair is 24m/min, and the speed of the ordinary user is 48m/min [24]. TABLE V. lists the distance and the estimated travel time of three indoor paths for the wheelchair and the ordinary patient.

TABLE V. THREE INDOOR PATHS FOR THE WHEELCHAIR AND THE ORDINARY PATIENT

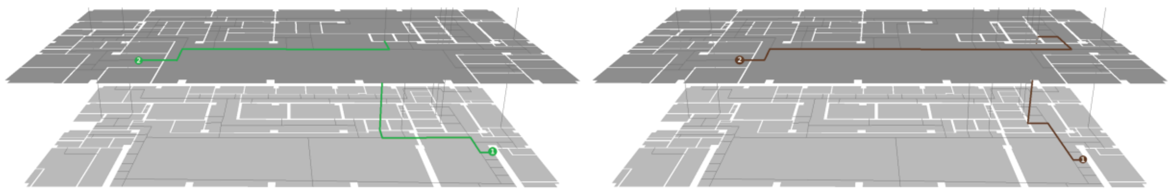
No.	Path	The barrier-free path		The ordinary path	
		Distance (m)	*Time (min)*	*Distance (m)*	*Time (min)*
1	Take a blood sample	71.9	3	44.1	1.8
2	Registration and treatment	76.2	3.2	51.2	1.1
3	Take drugs after diagnosis	119.5	5	92.4	1.9

It can be seen from the table that distances of three barrier-free paths have increased by 63%, 49% and 29% respectively compared to the ordinary path, and estimated travel times have increased by 67%, 191% and 163% respectively. These results are due to the fact that barrier-free components are in specific locations and the speed of the wheelchair is slow. Experiment II proves that the indoor space dimensional model can plan the cross-floor path that the user can pass according to the behavior information of different kinds of users, and give the estimated travelling time.

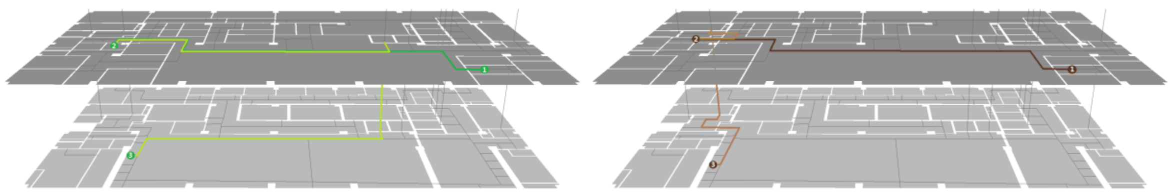
Fig. 9. Results of the indoor cross-floor path-finding for the ordinary patient and the wheelchair



(a) The path of taking a blood sample



(b) The path of Registration and treatment



(c) The path of taking drugs after diagnosis

IV. CONCLUSION

In this paper, we have studied the indoor space dimensional model supporting the barrier-free path-finding. The methods of extracting indoor space elements and indoor space network and 3d visualization have been discussed. The connection of the geometry layer, the topology layer and the semantic layer with the information of behavior and status has been achieved. The model describes the indoor space from multiple layers. It can not only achieve the indoor location query and path-finding for the ordinary patient, but also can support the barrier-free path-finding for the wheelchair. In this pape``r, the information of behavior and status in the semantic layer only considered the ordinary patient and the wheelchair. More types of users such as medical staff and more complex scenes such as evacuation needs to be considered. The focus of the next step is to study the extraction method of the indoor space network with more complicated topological relations.

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REFERENCES

[1] Li K J. Indoor space: a new notion of space[C]// International Symposium on Web and Wireless Geographical Information Systems. Springer-Verlag, 2008:1-3.

[2] Liu Z H, Wang K, Feng J F, Xia Y. Modeling and manufacturing of vector interior maps [J]. Digital Communication,2012(8):77-80. [刘兆宏, 王科, 丰江帆, 夏英. 矢量室内地图建模与制作方法[J]. 数字通信,2012(8):77-80.]

[3] Huang Y P, Du J G, Chen E Y. Automatic generation algorithm of three-dimensional path model [J]. Journal of Beijing Jiaotong University,2010,34(2):79-83. [黄雅平,杜建庚,陈恩义.楼宇三维路径模型的自动生成算法[J].北京交通大学学报,2010,34(2):79-83.]

[4] Umit I, Sisi Z, Jason U. A BIM-Oriented model for supporting indoor navigation requirements[J], Computers ,Environment and Urban Systems,2013,41(3):112-123.

[5] Yan J J, Shang J, Yu F W, Wang X. A method of building 3D building model for indoor positioning [J]. Computer Application and Software,2013,30(10):16-20. [闫金金,尚建嘎,余芳文,王欣.一种面向室内定位的 3D 建筑模型构建方法[J].计算机应用与软件,2013,30(10):16-20.]

[6] Zhao L, Jin P Q, Zhang L L, Wang H S, Yue L H. Layered model: a mobile object data model for interior space [J]. Computer Research and Development, 2011,48（S1）:274-281. [赵磊, 金培权, 张蓝蓝, 王怀帅, 岳丽华. Layered Model:一个面向室内空间的移动对象数据模型[J].计算机研究与发展, 2011,48（S1）:274-281.]

[7] Liu L, Zlatanova S. A "door-to-door" path-finding approach for indoor navigation[J]. International Society for Photogrammetry & Remote Sensing, 2011.

[8] Zhang Y B, Zhang W W, Sun W X. Research on indoor space data model for location based services[J]. Mapping and Spatial Geographic Information, 2014, 37(11): 11-17. [张寅宝,张威巍,孙卫新.面向位置服务的室内空间数据模型研究[J].测绘与空间地理信息, 2014, 37(11): 11-17.]

[9] WORBOYS M.Modeling Indoor Ipace[C]//Proceedings of the 3rd ACMSIGSPATIAL Iternational Workshop on Indoor Spatial Awareness.Chicago:ACM,2011:1-6.

[10] [尚建嘎.室内空间信息及其模型支持下的行人位置感知计算方法[D] 武汉:华中科技大学,2015:1-166.]

[11] Brumitt B, Shafer S. Topological world modeling using semantic spaces[C]//Proceedings of the Workshop on Location Modeling for Ubiquitous Computing. 2001: 55-62.

[12] Bhatt M, Dylla F, Hois J. Spatio-terminological inference for the design of ambient environments[M]//Spatial Information Theory. Springer Berlin Heidelberg, 2009: 371-391.

[13] Yang L, Worboys M. A navigation ontology for outdoor-indoor space:(work-in-progress)[C]//Proceedings of the 3rd ACM SIGSPATIAL international workshop on indoor spatial awareness. ACM, 2011: 31-34.

[14] Stevens M, Choi J.CAD data conversion to a node-rela-tion structure for 3D sub-unit topological representation [J]. Journal of the Korean Geographical Society,2006,41.

[15] Li D, Lee D L. A lattice-based semantic location model for indoor navigation [C]. Proceedings of the Ninth Inter-national Conference on Mobile Data Management, IEEE Computer Society,2008:17-24.

[16] Becker T, Nagel C, Kolbe T H. A multilayered space-event model for navigation in indoor spaces[M]// 3D Geo-Information Sciences. 2009:61-77.

[17] Wen Y N, Zhang H P, Lv G N, Zhang H, Tao H. Estate spatial data based building space modeling for the evacua-tion route[J].Journal of Geo-Information Science,2011,13(6):788-796. [温永宁,张红平,闾国年, 张宏, 陶虹.基于房产空间数据的楼宇空间疏散路径建模研究[J].地球信息科学学报,2011,13(6): 788-796.]

[18] Yang L, Worboys M. Generation of navigation graphs for indoor space[J]. International Journal of Geographical Information Science, 2015, 29(10): 1737-1756.

[19] Tashakkori H, Rajabifard A, Kalantari M. A new 3D indoor/outdoor spatial model for indoor emergency response facilitation[J]. Building & Environment, 2015, 89:170-182.

[20] Teo T A, Cho K H. BIM-oriented indoor network model for indoor and outdoor combined route planning[J]. Advanced Engineering Informatics, 2016, 30(3): 268-282.

[21] Li J W, Liu Y L, Qin X L. The context-dependent double-layer data model for indoor space [J]. Computer science, 2017, 44(8):187-192. [李敬雯, 刘宇雷, 秦小麟. 一个情境相关的双层室内空间数据模型[J]. 计算机科学, 2017, 44(8):187-192.]

[22] Rabiee H R, Kashyap R L, Safavian S R. Multiresolution segmentation-based image coding with hierarchical data structures[C]//Acoustics, Speech, and Signal Processing, 1996. ICASSP-96. Conference Proceedings., 1996 IEEE International Conference on. IEEE, 1996, 4: 1870-1873.

[23] Zhu Q, Hu M Y, Xu W P, Lin X, Du Z Q, Zhang Y T, Zhang F. 3D building information model for facilitating dynamic analysis of indoor fire emergency[J]. Journal of Wuhan University (Information Science Edition),2014,39(7):762-766. [朱庆,胡明远,徐伟平,林珲, 杜志强, 张叶廷, 张帆. 面向火灾动态疏散的三维建筑信息模型[J].武汉大学学报°信息科学版,2014,39(7):762-766.]

[24] Li J, Hu C, Li Y F, Liu S S, Xu P. Influence of crow density on the movement speed on different egress paths[J]. Building Science, 2014, 30(8):122-129. [李俊梅, 胡成, 李炎锋,刘闪闪, 许鹏. 不同类型疏散通道人群密度对行走速度的影响研究[J]. 建筑科学, 2014, 30(8):122-129.]