An indoor spatial accessible area generation approach considering distance constraints

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1. Introduction

Accessible area generation in indoor space is of important realistic significance for spatial analysis. It can be used to generate the area that people or robots can reach, which is helpful for further spatial analysis in indoor space, such as route planning, navigation and facility deployment (Coenen and Steinbuch 2012; Liu and Zlatanova 2015).

Currently, accessible area generation in indoor space is usually carried out from two perspectives. One is spatial perspective, from which accessible area can be generated by analysing indoor spatial obstruction and occupation. Hard barriers (such as walls and slabs), a kind of common spatial constraint, divide indoor space into multiple discrete sub-spaces (such as rooms and corridors); people can only move from one sub-space to another through connecting elements (such as doors, exits and stairs) and cannot go across these hard barriers (Lee et al. 2014; Li 2008; Yang et al. 2017). A sub-space, such as flues, is not accessible if no connecting element is located on its boundaries. Meanwhile, in furnished indoor environment, the spaces occupied by furniture are often treated as inaccessible areas that need to be circumvented (Yang et al. 2018). Besides, in some specific application, such as robots’ indoor motion planning (Berg et al. 2008) and indoor navigation for a person manipulating a machine whose size cannot be ignored (Liu and Zlatanova 2015), the accessible area is usually defined as the space that moving objects can fit.

Another perspective is the attribute perspective, from which the indoor space ownership can also be considered while generating accessible areas. For example, Alattas et al. (2017) define the spatial accessibility of indoor environment for different users according to the ownership and/or usage right by utilizing IndoorGML (Lee et al. 2014) and Land Administration Domain Model (LADM). Based on the spatial accessibility, the new generated accessible and inaccessible area spaces can be used for indoor navigation route planning.

Though the above-mentioned methods for generating accessible areas can be effective for indoor spatial analysis, it can still be found that the spatial distance restriction, such as walking distances of people and service radius of facility, is seldom considered. The accessible areas for indoor objectives within a predefined distance are essential for many...
indoor spatial analysis applications. For example, while evaluating the spatial coverage of indoor facilities, it is necessary to predefine a maximal service distance and calculate the areas that people can reach within such distance. This kind of accessible area generation with a distance constraint is an important foundation for further spatial analysis, such as facilities’ spatial layout analysis and deployment optimization. Lacking the consideration of distance constraints cannot satisfy the requirements of these applications.

To the best of our knowledge, few studies concerning indoor accessible area generation considering distance constraints have been conducted. But in outdoor space, many studies have been carried out. In general, there are two main approaches. The first approach is spatial buffer analysis. It obtains the accessible area of spatial objects by buffering a certain distance around the objects, which has been wildly used in the area of spatial analysis and decision making for many years (Chakraborty and Armstrong 1997; Hsueh and Tseng 2013; Lovett et al. 2002; Ringrose, Vanderpost, and Matheson 1996; Thornton 2011; Zhu and Cheng 2011). However, the precondition while using this approach to generate accessible area is that the experimental region is continuous and can be travelled by people freely. However, in indoor environment, because of the existence of complex hard barriers that people cannot go across, directly and simply utilizing buffer approach to get objects’ accessible areas will lead to wrong analysis results.

The second kind of approach is road network-based analysis (Gupta et al. 2016; Oh and Jeong 2007; Upchurch et al. 2004; Yang, Goerge, and Mullner 2006; Zhu and Cheng 2011). According to a predefined distance value, route search algorithm is used to traverse the road network to return a subset of connected line features. And then, by putting the geometry of these obtained lines into a triangulated irregular network (TIN) data structure, polygons surrounding these lines, the spatial objects’ accessible area, can be generated. By restricting people’s travel to a specified road network, it can effectively eliminate the influence of hard barriers, but the quality of accessible areas generated is highly relied on the correctness and completeness of road network. In fact, in indoor space that people can walk freely, it is hard to construct a line-featured road network to wholly cover the area-featured spaces in a fine scale. Thus, the accessible area generation based on a road network is not applicable in indoor space.

Since the two approaches with distance constraints mentioned above are not suitable for indoor accessible area generation, it is necessary to propose an approach that is suitable for indoor space. In this paper, an improved approach considering distance constraints and indoor spatial connectivity is proposed based on traditional spatial buffer zone generation. In this approach, the accessible distance is treated as the initial buffer distance. The buffer zone generation is first executed around the indoor objects within their located subspace. And then, based on the indoor spatial connectivity, the buffer zone generation around exit points is successively executed in its next connected subspace until the buffer distance decreases to zero.

The remaining part of the paper is organized as follows. Section 2 illustrates the methodology in detail, including how to construct the indoor spatial data model, and how to generate the spatial accessible area based on the data model. In Section 3, experiments are carried out to validate the accuracy and efficiency of the proposed approach. Section 4 discusses the potential use, limitation and contribution of the approach. A conclusion is given in Section 5.

2. Methodology

2.1. Construction of indoor spatial data model

Nowadays, the representation of indoor space mainly contains two models, geometric model and symbolic model (Becker and Dürr 2005; Leonhardt 1998; Li and Lee 2008). Geometric model uses the coordinate information in Euclidean space to express the position of spatial objects. Based on the coordinates, the distances among objects can be calculated accurately. But the relationship among them, such as connectivity and adjacency, cannot be represented by geometric model (Lee et al. 2014; Teo and Cho 2016).

Symbolic model abstracts spatial objects as symbols without accurate spatial positions, and uses certain names to specify these objects (Li and Lee 2008). In this model, graphs, trees or lattice can be used to represent the relationship among objects (Hu and Lee 2004; Kainz, Egenhofer, and Greasley 2007; Karlsen 2006). For example, Jensen, Lu, and Yang (2009) take indoor partitions, such as rooms and corridors, as nodes, and doors as edges to construct the indoor connectivity graph model. However, because that symbolic model cannot describe the accurate position of spatial objects, the distances among them could not be obtained.

Since the two models have their own advantages, this paper combines geometric model and symbolic model to support indoor accessible area generation, shown in Figure 1. In geometric model, the indoor subspaces, which maintain specific geometric boundaries and one or more exits, such as rooms and corridors, are represented by polygons; and concave subspace needs to be divided into a series of discrete convex polygons by
adding some virtual lines (the red dotted line in Figure 1(b, d)) to ensure Euclidean distance method can be used rationally in indoor space. According to OGC IndoorGML (Lee et al. 2014), exits in indoor environment, only through which a moving object located in a subspace go to another connected subspace, are usually presented as navigable edges in topographic space (the green dotted line in Figure 1(b)). But in our model, in order to simplify the calculation of distance $d_{ij}$ between any two objects ($i$ and $j$) located in different subspaces, exits in indoor space are abstracted as points on these navigable edges (The red and yellow points in Figure 1(d)); and $d_{ij}$ equals to the polyline distance between these objects and corresponding exits. Meanwhile, in order to simulate the navigable potentiality of any positions on virtual lines, one or multiple virtual exits on these new convex polygons’ edges need to be added to ensure the precision of distance calculation. It is suggested that the longer a virtual line is, the more virtual exits (virtual points) are needed.

Based on geometric model, symbolic model can be established, which mainly contains two components, subspaces and exits (Hu and Lee 2004; Li and Lee 2008). As shown in Figure 1(c,e), subspaces in symbolic model are usually represented by points, and exits by lines. Because multiple virtual points are allowed to add in one navigable edge, more connections between two subspace nodes may exist in our model than in IndoorGML model (the parts of geometric model highlighted by ovals with purple dotted edges in Figure 1(c,e)).

2.2. Generation of indoor accessible area

2.2.1. Overall flow work

Based on the symbolic and geometric hybrid spatial data model, the flow work of indoor accessible area generation can be described in detail as follows.

First, get the subspace $L_{O}$ where object $O$ is located by spatial geometric model. Calculate the minimal Euclidean distance $\{d_{Oi}\}$ between each exit $\{e_{Oi}\}$ of $L_{O}$ to object $O$. According to simple buffer zone generation method that takes Euclidean distances of straight lines as buffer distances, an initial buffer zone $B_{O}$ of indoor object $O$ with distance $R_{O}$ is generated, and then the accessible area $A_{O}$ in subspace $L_{O}$ is obtained by intersecting the area of $L_{O}$ with buffer zone $B_{O}$. But in fact, because the time used for buffer zone generation and spatial intersection is much longer than writing a piece of data record, instead of executing these spatial operations (buffer and intersection) promptly, a self-defined relationship $Q_{0}$: subspace $L_{O}$ ~ object $O$ ~ distance $R_{O}$, is used to record the operation.
Then, for each exit located in the boundaries of subspace \( L_0 \), let \( e = e_{oi}, R = R_0 - d_{oi} \). Execute the depth-first search algorithm (IndoorAccessibleAreas_DepthSearch) or breadth-first search algorithm (IndoorAccessibleAreas_BreadthSearch) proposed in Section 2.2.2 to generate relationship \( Q \). The records in \( Q \) which are a series of operations that create multiple buffer polygons around different exits \( \{e\} \) to specific distances \( \{R\} \) in their connected subspaces \( \{L\} \), will be performed later.

Finally, based on record \( Q \cup Q_0 \), spatial buffer and overlay operations are executed, and the intersection areas are merged to form the indoor accessible area of object \( O \) in indoor position \( L_0 \) with distance of \( R_0 \).

### 2.2.2. Spatial search strategies

While successively generating the buffer zones around the exits of connected subspaces, two kinds of generation strategies, depth-first search algorithm and breadth-first search algorithm, are proposed in this section, which can be described as the flow works shown in Tables 1 and 2.

To better illustrate the two strategies while generating accessible areas in indoor environment, a two-floor building is used as an example to visually demonstrate the flow works in detail, which can be seen in Figure 2. From the illustration, it can be found that the final results of accessible area generated by these two strategies are the same. The only difference lies in the sequence of relationship record saved in record set \( Q \).

#### 2.2.3. Remarks

It is worth noting that the subspace connectivity in indoor space usually has a loop phenomenon, namely, it is possible for an object to return to the initial subspace but not repeatedly travel through the same subspace. For example, in Figure 3, the object located in position \( L1 \) can move through the positions \( L2 \rightarrow L7 \rightarrow L5 \rightarrow L4 \rightarrow L6 \rightarrow L8 \rightarrow L3 \) and then return to position \( L1 \), shown as the red dotted line. Because of such a loop phenomenon, it is possible that multiple buffer zones are generated at the same exit of the same subspace for several times. As shown in Figure 3, treating the purple triangle in the first floor as the object for accessible area generation, if the accessible distance is long, after generating the buffer zone at the exit \( e_3 \) in subspace \( L1 \) for the first time, and after generating buffer zones in subspaces of \( L2, L7, L5, L4, L6, L8, L3 \), it is possible to generate a smaller buffer zone at the exit \( e_2 \) in subspace \( L1 \) for the second time.

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**Table 1. The description of depth-first search algorithm.**

| Algorithm                  | IndoorAccessibleAreas_DepthSearch |
|----------------------------|-----------------------------------|
| **Input**                  | An indoor subspace \( L \), an exit \( e \) located on the boundaries of the subspace \( L \), the accessible distance \( R \) at exit \( e \) |
| **Output**                 | Relationship record \( Q \): subspace \( L \) \( \sim \) exit \( e \) \( \sim \) distance \( R \) |
| **Steps**                  | 1. If \( R > 0 \), obtain the connected subspaces of subspace \( L \) that share the same exit, \( \{L_j | L_j \neq L\} \); otherwise, stop the algorithm.  
2. For each subspace \( L_j \)  
2.1 Generate relationship \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R'\} \).  
2.2 If a record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) \( \in \) record set \( Q \); if \( R' \geq R \), return to step 2.1 to process the next subspace in \( \{L_j | L_j \neq L\} \). else if \( R' < R \), rewrite record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) in \( Q \) as \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \). Otherwise, put record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) into \( Q \).  
2.3 Get the other exits \( \{e_k | e_k \neq e\} \) locating on the boundaries of current subspace, and calculate the distance \( \{d_{ek}\} \) between \( e \) to \( \{e_k\} \).  
2.4 For each exit \( e_k \)  
   i. Let \( L = L_j \), \( e = e_k \), and \( R = R - d_{ek} \).  
   ii. Execute the algorithm IndoorAccessibleAreas_DepthSearch. |

**Table 2. The description of breadth-first search algorithm.**

| Algorithm                  | IndoorAccessibleAreas_BreadthSearch |
|----------------------------|-------------------------------------|
| **Input**                  | An indoor subspace \( L_0 \), exits \( \{e = e_{oi}\} \) located on the boundaries of subspace \( L_0 \), the accessible distance \( R = R_0 - d_{oi} \) at these exits. |
| **Output**                 | Record set \( Q \) that records the relationship \( \{\text{subspace} L \sim \text{exit} e \sim \text{distance} R'\} \) at these exits. |
| **Steps**                  | 1. Initialize queue \( Q = \emptyset \) and \( n = 1 \).  
2. For each element \( \{e\} \), judge \( R > 0 \) or not. If it is, the connected subspaces \( \{L_j | L_j \neq L\} \) will be obtained. If \( \{L_j | L_j \neq L\} = \emptyset \), for each subspace \( L_j \), put its relationship \( \{L_j \sim \text{exit} e \sim \text{distance} R' \} \) into set \( Q \).  
3. Do  
   3.1 For the nth record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) \( \in \) \( Q \), get the other exits \( E = \{e_k | e_k \neq e\} \) of subspace \( L_j \), and calculate the distance \( \{d_{ek}\} \) between \( e \) and \( \{e_k\} \).  
   3.2 If \( E = \emptyset \), for each element in \( E \) (exit \( e_{nk} \)), execute the following steps 3.2.1-3.2.3.  
   3.2.1 Let \( L = L_j \), \( e = e_{nk} \), and \( R = R - d_{ek} \).  
   3.2.2 If \( R > 0 \), get its connected subspace \( \{L_j | L_j \neq L\} \) according to symbolic model. If \( \{L_j | L_j \neq L\} = \emptyset \), for each subspace \( L_j \), get the record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \).  
   3.2.3 If a record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) \( \in \) record set \( Q \); if \( R' > R \), execute step 3.3; else if \( R' < R \), rewrite record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) in \( Q \) as \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \). Otherwise, put record \( \{\text{subspace} L_j \sim \text{exit} e \sim \text{distance} R' \} \) into \( Q \).  
3.3 \( n = n + 1 \)  
Until the quantity of elements in \( Q \) is smaller than \( n (|Q| < n) \).  
4 Export record set \( Q \). |
The existing loop phenomenon brings complexity while generating indoor accessible areas. Different search strategies, depth-first and breadth-first, have different frequencies of manipulating recording set \( Q \), thus resulting in different computational efficiency, which is further analysed in experiment section.

3. Experiment

In this experiment, the proposed indoor accessible area generation algorithm is coded in Visual Studio 2013 software and implemented on a Personal Computer with an Intel(R) Core(TM) i7-4558U CPU @ 2.80 GHz and 4 GB RAM using the Windows 7 64-bit operating system.

3.1. Experiment design

A case study is carried out in an office building of five floors with three elevators and three staircases. Assuming that the connected cost (travel distance) of each elevator and each staircase is 3 m and 5 m,
respectively. The distances within the same floor are measured by actual Euclidean distance. The experiment data used in this paper are shown in Figure 4. For better visualization, elevators and staircases are represented by lines.

Based on the experiment data above, two sets of experiments are designed. The first one is to generate the accessible areas based on indoor objects of point, polyline and polygon, to visually demonstrate the similarity of the two algorithm mechanisms for these three different objects. The second one takes point objects as examples to compare the two algorithms based on depth-first search and breadth-first search and validate their correctness.

### 3.2. Results and analysis

#### 3.2.1. Experiment 1

Letting the accessible distance is 5 m; accessible areas of three different spatial features, point (the red feature in Figure 5), polyline (the blue feature in Figure 5) and polygon (the green feature in Figure 5), can be obtained, which are shown as the areas covered by the oblique lines in their corresponding feature colour. It can be found that these three accessible areas have similarity in their spatial shapes, which are formed by multiple buffer zones in different indoor subspaces. Besides, all the buffer zones in subspaces without indoor objects are the overlapping areas of the exits’ point buffer areas and their corresponding subspaces. It can be concluded that the accessible area generation of points, polylines and polygons are similar in the algorithm mechanism. Therefore, in the following experiments, accessible area generation based on points is chosen for further analysis.

#### 3.2.2. Experiment 2

In this experiment, the algorithms of depth-first search and breadth-first search are employed for the accessible areas generation based on the point in Figure 5 with distances of 10, 20, 30 and 40 m, respectively, to test their efficiency. Moreover, three criteria, shape index of accessible area ($C_{\text{shape}}$), frequency of manipulating record set $Q$ ($C_{\text{frequency}}$), and average calculating time ($C_{\text{time}}$, measured by millisecond) are imported to evaluate the results, which are shown in Table 3.

The shape index of accessible area $C_{\text{shape}}$ is the ratio of polygon’s area and perimeter after merging multiple buffer zones together. It can be expressed as:

$$C_{\text{shape}} = \frac{\text{Area}}{\text{Perimeter}_b},$$

in which, $\text{Area}$ is the area of accessible area, and $\text{Perimeter}_b$ is its perimeter. Table 3 shows that the shape index values of accessible areas obtained by depth-first and breadth-first algorithms are the same, which proves that the accessible areas generated by these two algorithms are the same to a certain extent. The results corresponding to four different accessible distances can be visually displayed in Figure 6.

Even though the accessible areas generated by depth-first and breadth-first search are the same, their frequencies of manipulating recording set $Q$, $C_{\text{frequency}}$, which mainly refers to the manipulation of adding new records to $Q$ and rewriting the existing records, are totally different. Therefore, counting the operation time of manipulating $Q$ is helpful for evaluating computational efficiency of the algorithms. It can be found from Table 3 that when accessible distance is relatively short (e.g. 10 m), the record set is relatively simple, the two algorithms maintain the same manipulation frequency to $Q$. But with the increase of accessible distance, the record set becomes

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**Figure 4.** Experiment data in this study.
more and more complicated and the loop phenomenon mentioned in section 2.2.3 appears more and more frequently. Increasing loop phenomenon can result in the growing gap of frequency between the two algorithms while manipulating $Q$. Obviously, while the accessible distance reaches 40 m, the manipulation frequency to $Q$...
of depth-first search algorithm is 4.49 times that of the breadth-first search algorithm, which demonstrates that operations to buffer relationship record set of breadth-first search are much less than that of depth-first search algorithm if the accessible area generation happens in a complex indoor environment.

After 100 repeated computations, the average calculating time $C_{time}$ of the two algorithms can be obtained, which clearly demonstrates their computational efficiency. It can be seen from Table 3 that if the accessible distance is small and the two algorithms maintain the same $C_{frequency}$, the breadth-first algorithm will take a longer time than the depth-first algorithm. However, with the increase of accessible distance, the calculating time of breadth-first algorithm is shorter than that of the depth-first algorithm, which shows higher calculating efficiency.

4. Discussion

4.1. Main contribution

Accessible area generation considering distance constraints is essential for advanced GIS spatial analysis, which has been playing an important role in the spatial analysis at global, regional and city scale. With the development of indoor GIS applications, accessible area generation in indoor space needs to be enriched and perfected simultaneously.

According to the characteristics of indoor environment that the indoor space is divided into discrete and connected planar area due to the presence of hard barrier, this paper proposes an accessible area generation approach, based on the traditional buffer analysis method and a hybrid indoor spatial data model, with a view to consider the constraints of spatial distance and connectivity. This approach could be a useful complement to indoor GIS spatial analysis, and could provide technical means in typical indoor applications.

4.2. Potential use of the approach

Indoor accessible area generation can provide rich adjacent information in indoor environment and can be used in many applications. For example, it can provide indoor spatial elements for users within a predefined travel distance in the application of LBS (location-based service), and can also be used to quantitatively analyse the service coverage of indoor facilities if the service cannot get through hard barriers.

Taking the indoor spatial allocation of fire extinguishers as example, the potential use of indoor accessible area generation can be demonstrated.

Assume that the indoor spatial allocation of extinguishers should meet the criterion that people located in any place of the building can reach an extinguisher within 10 m travel distance. Then, we can use the algorithms proposed in this paper to generate the accessible area by taking extinguishers as indoor objects for analysis and setting the accessible distance as 10 m. The generated accessible area is shown in Figure 7. From the figure, it can be seen that the areas not covered by the generated accessible area still exist, which means that people located in these areas cannot reach a fire extinguisher within 10 m’ travel distance. Therefore, it can be inferred...
that there is a lack of rationality of the indoor spatial allocation of fire extinguishers.

4.3. Potential limitations of the approach

The approach proposed in this paper is based on a hybrid indoor spatial data of geometric model and symbolic model, which can be effective for the generation of accessible area. However, its potential limitations are also worth noting.

This paper uses symbolic model to simplify the indoor spatial relationship by recording the connectivity between subspaces and exits. In order to ensure the distance between any two points in a subspace equals the Euclidean distance of a straight line, it is necessary to split concave indoor subspaces into several convex polygons by some virtual lines. These virtual lines (the dotted line in Figure 8) are not real boundaries and can be passed through; thus, adding virtual exit points on these lines can be effective to retain the spatial connectivity. The quantity of these virtual exits is crucial for the precision of distance measurement. For any two points located in different subspaces, for example, the blue points in Figure 8, their connectivity distance in the indoor data model adopted in this paper must be measured along the polyline through virtual exits (red points in Figure 8) rather than other points on the virtual line (the green points in Figure 8). Obviously, it brings some errors while calculating connectivity distance.

In order to avoid this kind of problem, it is suggested that multiple virtual exit points are added. For example, these points can be densified at an interval of 1 m. The more the virtual exit points added, the more precise the distance is, but the more computation cost is required. How to improve the calculating efficiency while maintaining spatial evaluation precision still needs further exploration.

5. Conclusion

This paper first analyses the limitations of traditional accessible area generation method in dealing with the problem in indoor environment which is usually divided by multiple hard barriers into discrete and connected planar areas. Then, an indoor accessible area generation method based on a symbolic and spatial hybrid indoor spatial data model is proposed from two algorithmic perspectives, breadth-first search and depth-first search. Through a series of experiments, the two algorithms’ result computation efficiency are quantitatively analysed. Experiments show that the breadth-first search algorithm could be more efficient if the indoor environment is complicated.

The accessible area generation method in indoor environment can not only be a useful complement for traditional GIS analysis, but also helpful for indoor spatial analysis in many practical applications. However, it cannot be denied that the proposed method still has limitations, such as how to improve the algorithm efficiency while maintaining the precision of spatial distance measurement, which are worthy of further studies in the future.

Disclosure statement

No potential conflict of interest was reported by the authors.

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