Space classification for indoor pedestrian navigation with morphological and functional characteristics

Peng Tian,[1,2] Yunjia Wang✉,[1] Yong Wang,[3] and Yuan Yang[4]

[1]*School of Environment Science and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China*

[2]*R&D Department, Xuzhou Survey and Mapping Research Institute Co., Ltd, Xuzhou 221018, China*

[3]*Intelligent Manufacturing College, Jiangsu Vocational Institute of Architectural Technology, Xuzhou 221116, China*

[4]*School of Instrument Science and Engineering, Southeast University, Nanjing 210096, China*

✉Email: wyj4139@cumt.edu.cn

Indoor navigation networks serve as the foundation for indoor pedestrian navigation services. However, current graph-based topological network models cannot easily represent complex indoor structures in a manner consistent with user behaviour and cognitive patterns, and thus cannot support fine-grained indoor navigation analysis services. To enhance the rationality of the model, we considered the influences of morphological and functional characteristics of indoor spaces on pedestrian movement and proposed a method for classifying navigation spaces. This method, based on convex space segmentation, defines morphological and functional characteristic functions, classifying indoor navigation spaces as either corridors or open spaces, which suitable for representing as median axis models or visual graphs, respectively. These categories supported the creation of topological network models for route planning analysis. Indoor map experiments confirmed the effectiveness of our method in identifying various types of corridors and open spaces, that addressing the limitations of width-based parameterseven in complex indoor settings.

Introduction: Indoor navigation models can express geometric, semantic, and topological information about indoor built environments; furthermore they are important tools in indoor facility management, emergency response [1], and pedestrian location and navigation [2]. Existing research on indoor navigation models in indoor settings has predominantly focused on graph-based network models [3–5]. Recently, owing to fineness requirements of indoor pedestrian navigation services, most network models often fail to reasonably express the indoor structure and pedestrian movement characteristics, hence, limiting the ability of the model to express the information on the navigation environment, resulting in a limited degree of accuracy of the model computation and a reduced adaptability of the model to the complex scene.

In indoor pedestrian navigation, a navigation model should represent decision points, corners, distances, etc., as precisely as possible. The median axis model (MAT) [3] visually represents spatial connectivity relationships of the indoor spaces and aligns with the corridor walking habits of pedestrians. However, paths formed by the median axis often exhibit zigzags or detours in complex indoor environments, limiting the accuracy in calculating walking distance and direction with MAT. However, in open spaces, pedestrians tend to select the best path based on the location and visibility of the destination, aiming for conserve time and energy. Utilising a visual graph (VG) [4] to represent the road network aligns more closely with the actual walking routes of pedestrians. The VG connects all visible nodes, enhancing the accuracy of calculated road network distance and angle calculation. However, the method can result in an exponential growth in the number of edges with increasing visible nodes, leading to computational complexity and incomplete representation of node connectivity .

To improve the accuracy of navigation network modelling, the skeleton method [5] can improve the accuracy of MAT but generates detours at intersections in large open spaces. Intra-space connectivity algorithm with inward offsetting of the contour edges [6] can address the detours issue [5]. However, the generated routes do not conform to pedestrian habits of selecting visibility-based routing. Hierarchical management can enhance the computational efficiency of the visibility graph proposed in [7], but it fails to resolve dependent scenario delineation. Constructing a model by combining the advantages of visibility and axial maps also relies on space division and classification. However, current space classification based solely on corridor width has limited applicability and requires further exploration for complex spaces.

To solve the issues of structural illogicality of the navigation network model and the inadequacy of the expressions of environmental information, here, we propose a novel configuration characteristic function to classify various types of indoor navigation spaces. Grounded in research on indoor pedestrian movement habits and indoor space configuration [8], and based on convex segmentation of the indoor navigation space, we defined three morphological and functional characteristic functions of indoor spaces that influence the pattern of human movement. By using this approach, convex spaces are categorised as corridors or open spaces, thereby facilitating the constructions of different network model in a same navigation space, this fully combines the advantages of VG and MAT to enhance the applicability of the model.

Convex space segmentation of a navigation space: A convex space is defined as an enclosing space with internal angles < 180°. Convex segmentation of an indoor navigation space ensures that nodes in subspaces are visible to each other and the common edges of subspaces are visible in both spaces. Passageway gates and intersections with common edges can be used to extract midpoints as decision points, thereby connecting various types of route networks (MAT and VG) and supporting the construction of pedestrian-oriented navigation route networks. Segmentation lines are created by forming s-lines [9], connecting adjacent concave points [10], or establishing plumb lines towards the wall lines [11]. In this study, we combined these methods to create separate segmentation lines, producing the final result according to predefined priorities.

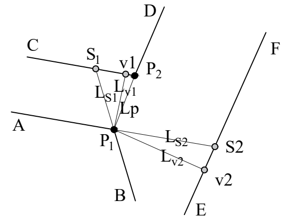

Fig 1 *Segmentation lines generated at the concave point* P_1

As depicted in Figure 1, when the space is segmented at the concave point P_1, five segmentation lines can be generated, namely L_{s1}, L_{s2}, L_{v1}, L_{v2}, and L_p forming a candidate list of segmentation lines. L_{s1} and L_{s2} represent s-lines. L_{v1} and L_{v2} denote segmentation lines perpendicular to the wall lines P_1A and P_1B. L_p represents the line connecting P_1 to the adjacent concave points, which may not exist. The direction of the effective segmentation line lies between $\overrightarrow{P_1S_1}$ and $\overrightarrow{P_1S_2}$. This approach ensures that the concave angle with vertex P_1 is divided into two convex angles. The priority for selecting segmentation lines is as follows: $L_p > \{L_{s1}, L_{s2}\} > \{L_{v1}, L_{v2}\}$. The length of the shortest line in the candidate list is S_{Lmin}, and the length of the final segmentation line is S_L. The threshold r is defined as follows:

$$\frac{S_L}{S_{Lmin}} \geq r \tag{1}$$

The final segmentation line is selected from the candidate list in accordance with the previously defined criteria. The created navigation convex space is then utilised to calculate the configuration characteristics in the subsequent section.

Configuration functions of morphological and functional characteristics of the indoor navigation space: In this section, we analyse the morphological and functional characteristics that affect pedestrian moving routes in indoor navigation spaces. We define three functions related to these characteristics to classify indoor navigation convex spaces as corridors or open spaces. Stairs and rooms are excluded from this study. The characteristic parameters include:

Indoor navigation space aspect ratio AR (C_i)*:* The spatial morphology of a corridor is characterised by its width and length. Wide and longe passing spaces exhibit a linear pattern of pedestrian route choices, also recognised as corridors. For convex space C_i, the aspect ratio $AR\ (C_i)$ is defined as follows:

$$AR\ (C_i) = \frac{L_{smbr}}{W_{smbr}} \quad (2)$$

where, L_{smbr} and W_{smbr} are the length and width of the smallest minimum bounding rectangle(SMBR) [12] of C_i. The larger $AR(C_i)$ value indicates a greater likelihood of being classified as a corridor.

Indoor navigation space openness $OP\ (C_i)$: Openings are passageways with specific functions and shapes in the built environment. This characteristic of space is described as its openness. The function of the corridor is typically to serve open spaces on one or both sides, whereas open spaces function as connectors between different areas. As shown in Figure 2, more openings in a space render it more suitable as a distribution centre [13]. Openness $OP\ (C_i)$ for convex space C_i is calculated as follows:

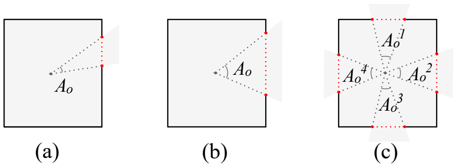

Fig 2 *Different forms of openings. (a) and (b) have different opening ranges and (c) has more openings.*

$$OP\ (C_i) = N_o \times \sum_{n=1}^{N_o} A_o^n \quad (3)$$

where, N_o represents the number of openings, which is the sum of the number of adjacent convex spaces and passage doors in convex space C_i; and A_o is the angle of opening. A higher value of $OP\ (C_i)$ for the area indicates a greater likelihood to become an open space.

Indoor navigation space movement direction variation $MV\ (C_i)$: The positions of openings within a space significantly influences the direction of pedestrian movement. In spaces illustrated in Figure 3a and 3b, pedestrians predominantly move linearly when traversing the area. Conversely, in the space depicted in Figure 3c, pedestrian movement exhibits more variability, indicating a greater likelihood of it being an open space. The space in Figure 3d has more openings but is longer. Therefore, pedestrians likely maintain mostly linear movement pattern along the long axis of the corridor, particularly during long-distance walks.

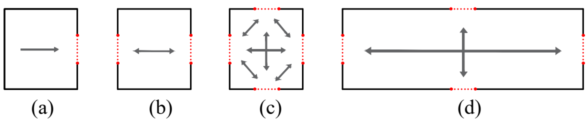

Fig 3 *Convex space openings and pedestrian moving directions*

Figure 4 displays the path of a pedestrian moving between openings in relation to the whole space. $\overrightarrow{dp_i^j}$ and $\overrightarrow{dp_i^k}$ represents two decision points within convex space C_i. These decision points are generated by extracting midpoints of the opening segmentation lines and are mutually visible. When pedestrians move from $\overrightarrow{dp_i^j}$ to $\overrightarrow{dp_i^k}$, the angle between the vector $\overrightarrow{dp_i^j dp_i^k}$ and the long axis of SMBR is denoted as φ_i^{jk}, where φ_i^{jk} is a value within the range [0, 90], $\left|\overrightarrow{dp_i^j dp_i^k}\right|$ defined as $dist_i^{jk}$.

To illustrate the impact of the openings positions on pedestrian movement pattern, the variation of movement direction $MV\ (C_i)$ caused by openings positions is defined as follows:

$$MV\ (C_i) = \sum_{j=1,k=1}^{j=N_o,k=N_o} \varphi_i^{jk} * \frac{dist_i^{jk}}{L_{smbr}} \quad (4)$$

The higher the value of $MV\ (C_i)$, the more pronounced the degree of openness, making it more likely to be classified as an open space.

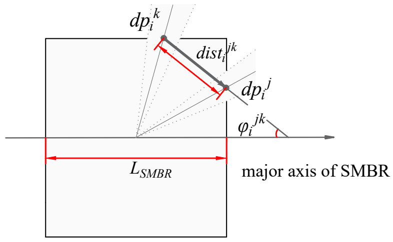

Fig 4 *Movement direction variation in convex space*

Indoor navigation space configuration characteristics $INSC(C_i)$: Based on the characteristic functions related to Aspect ratio, openness, and movement direction variation for the navigation convex space C_i, Equation (5) was utilized to quantitatively characterise the indoor navigation space configuration characteristics ($INSC$):

$$INSC(C_i) = \omega_{AR} * f_{AR}(C_i) + \omega_{OP} * f_{OP}(C_i) + \omega_{MV} * f_{MV}(C_i) \quad (5)$$

where, $f_{AR}(C_i)$, $f_{OP}(C_i)$ and $f_{MV}(C_i)$ represent the characteristic functions for aspect ratio, openness, and movement direction variation, respectively. These characteristics are weighted using ω_{AR}, ω_{OP} and ω_{MV} as their respective weight coefficientsand their proportions are combined using Equation (6) to determine the configuration:

$$\sum \omega_i = 1, \omega_i \in (0, 1), i = (AR, OP, MV) \quad (6)$$

Owing to the differences in dimensions, scales, and influences of these three characteristics, their values are normalised according to the characteristic statistical value of the study area as defined in Equation (7). This normalisation enables the amalgamation of their influence into a single measure($INSC$):

$$f^* = \begin{cases} \dfrac{f^* - f_{min}}{f_{max} - f_{min}}, \text{positive and } f_{min} \neq f_{max} \\ \dfrac{f^* - f_{min}}{f_{max} - f_{min}}, \text{negative and } f_{min} \neq f_{max} \\ 0, f_{min} = f_{max} \end{cases} \quad (7)$$

where, f represents the characteristic value of space configuration, with its maximum and minimum values denoted as f_{max} and f_{min}. Combined with Equation (5), the normalised configuration characteristic function, as shown in Equation (8), is then obtained. Spaces with high $INSC(C_i)$ values are selected as corridor spaces.

$$INSC(C_i) = \omega_{AR} * f^*_{AR}(C_i) + \omega_{OP} * f^*_{OP}(C_i) + \omega_{MV} * f^*_{MV}(C_i) \quad (8)$$

Experimental Setup and results: An experiment was conducted using our teaching building map to evaluate the feasibility and reliability of the characteristic functions. As shown in Figure 5, the navigation area was divided into 18 convex spaces at the intersecting concave points and corridor entrances. Spaces A15, A10, A8, A3, A6, and A4 were designated as open areas, whereas the remaining spaces were classified as corridor spaces. The proposed characteristic function was compared to width characteristics to assess its applicability.

Figure 5 shows the classification results for the navigation area on the standard floor of the teaching building. Optimal results were achieved using experimental measurements of $\omega_{AR} = 0.1$, $\omega_{OP} = 0.6$, $\omega_{MV} = 0.3$, with the $INSC$ threshold set at $\lambda = 0.7$. As shown in Figure 5, the method proposed in this paper effectively distinguished between corridor and open spaces based on defined morphological and functional characteristics. The space with the smallest eigenvalue was A3, connecting four spaces and a passageway gate. The space with the largest eigenvalue was A14, possessing the highest AR value. Spaces A1 and A13 were recognised as corridor areas. Despite having multiple openings linking different directions, their relatively higher AR diminished the influence of the number and position of openings on the linear characteristics of pedestrian movement. Spaces A16 and A4 were also identified as corridor regions due to their status as corners with only one

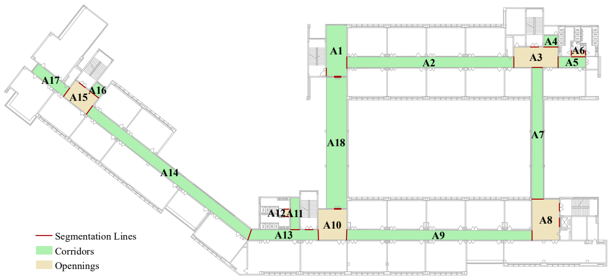

Fig 5 *Teaching building data segmentation results and characteristics value classification results.*

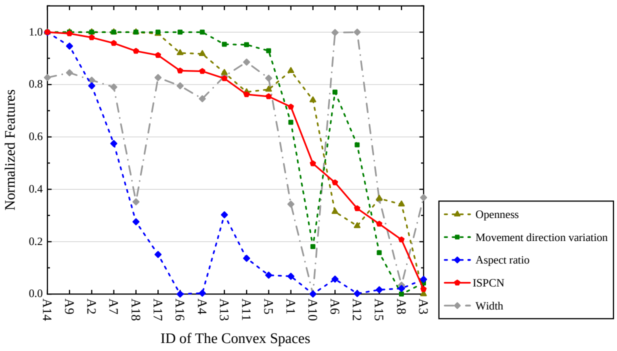

Fig 6 *When recognizing space based on defined datasets, a comparison between single and combined features was used*

entry and exit direction; this resulted in a lower MDV, despite having a smaller AR value.

Figure 6 shows the statistical outcome of various characteristic functions that were consistently ranked based on their contributions to overall configuration characteristics, with higher values indicating an easier recognition as corridor spaces. The impact of each characteristic on the final result is discernible in the statistical plots. The significant effect of enhancing results through the combined use of multiple characteristics is evident. This finding suggests that distinct characteristic functions are vital in achieving accurate recognition across different space types. For example, corridors that connect multiple spaces but possess higher AR (A1, A13), narrow corners with greater OP (A6, A12), and wide spaces with long corridors (A18) illustrate scenarios where the width parameter [11] alone cannot easily distinguish between them. Alternatively, combining all three characteristic functions provides more reliable estimates than relying on a single characteristic, highlighting their effectiveness in elucidating environmental configurations.

Nonetheless, our study shows several limitations. First, the experimental results depend on the underlying database as well as the selected characteristic metrics and metric weights, which require empirical evidence for the weights. Second, the method in this study also requires empirical thresholds for the differentiation of characteristics, which limits the generalisation of the model applicability. A feasible way to implement the evaluation is to apply the proposed method to several maps of different building types (e.g., a shopping mall, a library, a museum, etc.) and analyse the the effect of parameters and weights on the accuracy of the route calculation in order to verify the ability generalise the method.

Conclusion: To enhance existing indoor navigation networks that cannot easily accommodate pedestrian behaviours and can not simultaneously fulfill the fine-grained computational requirements of angles, distances, and spatial relationships, we proposed an indoor space classification scheme based on morphological and functional characteristicswhich supports the construction of mixed network. The method involving leveraging the convex segmentation of indoor spaces defines characteristics of indoor navigation space configuration. Convex segmentation of the spaces and extraction of decision points on the segmentation lines allows connecting different types of navigation networks from corresponding adjacent regions. The eigenfunctions of the convex space reflect the influence of the space on pedestrian movements which can be used to distinguish between corridors and open spaces for the construction of MAT and VG models respectively. Experimental results demonstrated that the proposed method effectively distinguished between various corridors and open spaces, which addressed the limitations of width-based parameters. Consequently, the method is adaptable to increasingly complex indoor scenarios.

Author contributions: Peng Tian: Conceptualization, Methodology, Software, Visualization, Writing - original draft. Yunjia Wang: Funding acquisition, Conceptualization, Writing - review & editing. Yong Wang: Visualization, Validation. Yuan Yang: Funding acquisition, Conceptualization, Review & editing.

Conflicts of interest statement: The authors declare no conflicts of interest.

Data availability statement: Data available on request from the authors.

Acknowledgments: This research was supported by the National Key Research and Development Program of China (Grant Number: 2016YFB0502102). This research was also supported by the Aeronautical Science Foundation of China (Grant Number: 20185869009).

Received: ** ** **** *Accepted:* ** ** ****
doi: 10.1049/****

References

1. Wang, J., et al.: Study on intelligent algorithm of guide partition for emergency evacuation of a subway station. IET Intelligent Transport Systems 14(11), 1440–1446 (2020)
2. Oh, Y., Noh, H.M., Shin, W.: C-cnnloc: Constrained cnn for robust indoor localization with building boundary. Electronics Letters 57(10), 422–425 (2021)
3. Bilgili, A., Sen, A., Basaraner, M.: Evaluation of indoor paths based on indoor navigation network models and space syntax measures. Geodetski vestnik. 67(1), 11–39 (2023)
4. Arnaoot, H.M.E.I.: Hexagon path planning algorithm. IET Radar Sonar Navigation 16(12), 1895–1911 (2022)
5. Fu, M., et al.: Generating straight skeleton-based navigation networks with industry foundation classes for indoor way-finding. Automation in construction 112, 103057 (2020)
6. Mortari, F., et al.: An indoor navigation model and its network extraction. Applied Geomatics 11(4), 413–427 (2019)
7. Zhou, Z., et al.: Hivg: A hierarchical indoor visibility-based graph for navigation guidance in multi-storey buildings. Computers, environment and urban systems 93, 101751 (2022)
8. Sharmin, S., Kamruzzaman, M.: Meta-analysis of the relationships between space syntax measures and pedestrian movement. Transport reviews 38(4), 524–550 (2018)
9. Peponis, J., et al.: On the description of shape and spatial configuration inside buildings: convex partitions and their local properties. Environment and Planning B: Planning and Design 24(5), 761–781 (1997)
10. Jeong, S.K., Ban, Y.U.: Developing a topological information extraction model for space syntax analysis. Building and Environment 46(12), 2442–2453 (2011)
11. Han, L., Zhou, L., Cheng, G.: An indoor navigation network considering walking habits and its generation algorithm. Acta Geodaetica et Cartographica Sinica 51(5), 729–738 (2022)
12. Duchêne, C., et al.: Quantitative and qualitative description of building orientation. In: 7th ICA Workshop on Progress in Automated Map Generalization, Fifth Workshop on Progressin Automated Map Generalization (2003)
13. Hillier, B., et al.: Natural movement: Or, configuration and attraction in urban pedestrian movement. Environment and Planning B: Planning and Design 20(1), 29–66 (1993)