



NAVI-GRAPH: A SEMANTICS-BASED NETWORK FOR INDOOR PATHFINDING

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Abstract

The traditional methods for constructing indoor networks for pathfinding primarily rely on geometric processing. The generated networks are geometric networks that lack semantics, which have limited their use. This study introduces a novel semantics-driven method for constructing navigable indoor networks by leveraging the rich semantic data embedded in Industry Foundation Classes (IFC), represented through the IFC-Graph. The proposed approach was validated using a real-world building model, and the result shows that 1) the semantic-based indoor network is easier to establish from IFC-Graph; 2) the proposed approach can enable semantics-driven pathfinding, which can provide more possibilities in pathfinding applications.

Introduction

Efficient indoor pathfinding is crucial for enhancing the experience of built environment users, such as residents, visitors, and facility managers, given that people spend approximately 90% of their time indoors (Lee, et al. 2017). Indoor pathfinding remains challenging because of the lack of indoor navigation maps, or the network of routes, which are mainly modelled manually from two-dimensional (2D) architecture models from computer-aided design (CAD) (Teo and Cho 2016, Zhou, et al. 2020).

The indoor navigation maps showing the connectivity of spaces are fundamental to indoor pathfinding, which are also referred to as navigation network graph (Fichtner, et al. 2018), indoor graph network (Teo and Cho 2016), route graph (Wallgrün 2005), geometric network model (GNM) (Lee 2004), or indoor spatial model (Li, et al. 2018, Lin and Lin 2018), depending on how these models are created. Despite the difference in name, connectivity is the common feature among them.

The automatic generation of connectivity graphs has been explored in the area of automation and computer science by using geometric information, such as 2D floor plans (Wallgrün 2005). Various methods have been developed to extract navigation graphs from 2D floor plans, including visibility graphs, straight skeletons, and generalized Voronoi diagrams. These techniques

primarily rely on geometric information and computational geometry, making the process resource-intensive and time-consuming (Liu 2017, Zhou, et al. 2020). According to Teo and Cho (Teo and Cho 2016), constructing a Geometric Network Model (GNM) can be complex and time-consuming, particularly when network nodes require additional semantic information. Moreover, these methods were primarily designed for robotics-focused applications such as autonomous navigation and mapping (Wallgrün 2005), which is different from human-oriented indoor pathfinding.

To deal with the problems in the geometry-based approach, the importance of semantic information in constructing indoor navigation network has been acknowledged (Mortari, et al. 2014, Teo and Cho 2016), and with the advancement of Building Information Modeling (BIM) technology in the Architecture, Engineering, and Construction (AEC) industry, the use of semantic building information has gained increasing attention in recent research. (Fichtner, et al. 2018) claimed that pathfinding can benefit from the enhanced semantic understanding of its environment. BIM models in the Industry Foundation Classes (IFC) format offer not only detailed geometric representations of the built environment but also a wealth of non-geometric semantic information, including attributes, properties, and relationships, which can greatly facilitate the construction of indoor navigation graph. Some studies have explored the use of semantic information from IFC in the construction of indoor navigation network, such as (Zhou, et al. 2020), (Lin and Lin 2018), (Xu, et al. 2017), (Zhao, et al. 2022) and (Teo and Cho 2016). A variant is using semantic information from IFC-based ontology, e.g., BOT ontology (Bonduel, et al. 2018), such as in the study by (de Koning, et al. 2021).

However, the range of semantic information utilized in these studies remains quite limited, with most still relying primarily on geometric data, such as 2D floor plans, to generate indoor navigation graphs (Zhou, et al. 2020). Most of these studies use only basic semantic information, such as entity types (e.g., doors and walls) and a few attributes of building elements, for example, the 'IsLocked' attribute to indicate door status, even though IFC defines a much broader and richer set of semantic

data (Zhu, et al. 2025b). For example, IFC4 has defined 776 entities (buildingSMART 2017). In short, the majority of the semantic information in IFC has not been sufficiently explored for the use in indoor pathfinding, especially the relationship information.

Given that geometry-based approaches to indoor pathfinding are computationally intensive and time-consuming, and that semantics-based methods remain underdeveloped, this study aims to incorporate semantic building information, particularly relational data, into the construction of indoor navigation networks. The remainder of this paper is structured as follows: Section 2 introduces the proposed semantics-based indoor navigation graph. Section 3 details the validation of the proposed method. Section 4 presents the discussion, and Section 5 concludes the paper.

Method

Given the issues identified in literature and the latest advances in building information technology such as IFC-Graph (Zhu, et al. 2023), this study seeks to investigate semantics-driven indoor pathfinding through the development of a connectivity graph based on semantic information. This approach has four steps: 1) constructing graph-based building information (i.e., IFC-Graph) from text-based IFC data, e.g., IFC-SPF (STEP Physical File), 2) extracting horizontal connectivity graph from IFC-Graph by using graph query, 3) establishing vertical connectivity graph by using location information from vertical connecting elements, such as stairs and lifts, and 4) merging the horizontal and vertical connectivity graphs to form a comprehensive building-wide connectivity graph.

IFC-based Indoor Navigation Data Model and IFC-Graph

An indoor navigation data model provides an abstract representation of the indoor environment to support navigation tasks. While general models like CityGML and IFC (Park, et al. 2020) can represent indoor environments, they are not specifically designed for indoor pathfinding. Previous studies have proposed navigation-specific models for geometric networks, such as the BIM-Oriented Indoor Data Model (BO-IDM) (Isikdag, et al. 2013) and the Indoor Navigation Space Model (INSM) (Liu and Zlatanova 2012). This study introduces a new data model tailored to a semantics-driven approach, built upon the IFC data model. The proposed navigation model incorporates both horizontal and vertical connectivity: horizontal connectivity describes relationships between elements and spaces on the same storey, while vertical connectivity accounts for connections between different storeys.

To implement the indoor navigation data model and construct the connectivity graph, relevant information is extracted from IFC data. To streamline this process, the study employs IFC-Graph, a graph-based representation of IFC data using a labelled property graph (LPG) structure, which facilitates efficient access to and querying of interconnected building information (Zhu, et

al. 2022, Zhu, et al. 2025a, Zhu, et al. 2023). Pattern-based graph queries enable efficient retrieval and exploration of building information. In this study, the IFC-Graph was generated from IFC-SPF files using the method proposed by (Zhu, et al. 2023).

Generating Horizontal Connectivity Graph for Individual Storeys

Previous studies have typically derived horizontal connectivity from geometric information, overlooking the fact that such relationships are already explicitly defined in IFC through entities like `IfcRelSpaceBoundary`. This entity links spaces (e.g., rooms, corridors) to their physical or virtual boundaries. These boundaries are commonly physical building elements, such as walls, slabs, doors, windows, and columns, or virtual separators like space/room dividers. Together, `IfcSpace` (space entities), `IfcRelSpaceBoundary` (boundary relationships), and `IfcElement` (boundary elements) provide the foundation for constructing the horizontal connectivity graph. In this study, elements capable of connecting different spaces, such as doors, windows, and openings, are referred to as connecting elements.

Using IFC-Graph, the horizontal connectivity graph for each storey can be efficiently generated through a graph query language (GQL) (ISO 2024), such as Cypher (Neo4j Inc. 2024a) or its open-source counterpart, openCypher (Neo4j Inc. 2024b). Cypher graph patterns enable the representation of human knowledge about indoor spaces (Zhu, et al. 2025a) and support building information querying and knowledge discovery. For instance, it is commonly understood that spaces are connected via doors or virtual elements that denote ‘notional’ boundaries. This type of knowledge can be encoded using the graph pattern shown in Listing 1, which is then applied to construct the horizontal connectivity graph.

Listing 1: Constructing horizontal connectivity graph using graph query for individual storeys.

```
match p=(:IfcSpace)--(:IfcRelSpaceBoundary)--(n)
where n.name in ['IfcDoor','IfcVirtualElement']
return p
```

Establishing Vertical Connections for Building-wide Connectivity Graph

While `IfcRelSpaceBoundary` enables the construction of horizontal connectivity graphs, a key limitation exists in the vertical dimension, namely, IFC does not define explicit relationships for vertical connections between storeys (Chen, et al. 2022, Liu and Zlatanova 2012, Teo and Cho 2016). This absence hinders the development of a comprehensive building-wide connectivity graph. To address this gap, this study introduces a new relationship entity, `IfcRelConnectsSpace`, which connects vertical circulation elements (e.g., stairs) to spaces across different storeys. In this study, vertical connectivity was manually established using this newly defined relationship.

Once vertical connectivity between storeys is established, it can be used to generate a vertical connection subgraph.

Combined with the horizontal connectivity graph, this subgraph enables the construction of a complete building-wide connectivity graph. The proposed approach ensures that all connected and accessible indoor spaces are accurately represented within the final graph.

Indoor Pathfinding and Navigation Guidance

The building-wide connectivity graph enables indoor pathfinding through the application of standard pathfinding algorithms. In this study, paths were computed using graph queries executed on a graph database employing Dijkstra’s algorithm. Path length was defined by the number of elements involved, with the shortest path, termed the least-element path, aligned with the minimum navigable unit criterion described by (Liu 2017). While the resulting paths indicate the sequence of spaces or connecting elements (e.g., doors and stairs) to follow, this alone is insufficient for practical indoor navigation. Visual guidance is also essential. To this end, the study incorporates the 3D body geometry of the involved elements for path visualization. This approach differs from previous methods that relied on abstract points and lines as visual cues. Rather than directing users along a ‘line’, it intuitively highlights which spaces to enter next, enhancing user comprehension. The geometric data were extracted from IFC-SPF files using techniques outlined in (Zhu, et al. 2018, Zhu, et al. 2019, Zhu and Wu 2021a, Zhu and Wu 2021b).

Results

Building Model and IFC-Graph

The Institute model (Figure 1(a)) from KIT (Karlsruhe Institute of Technology) was used for validation of the proposed method. IFC-Graph for the Institute model was generated and is shown in Figure 1(b). The Institute model was used because it is well modelled, while other publicly available models may have problems in geometry or semantics. An overview of the institute model and the IFC-Graph is presented in Table 1. The Institute model consists of five storeys: basement (-1), ground floor (0), first floor (1), second floor (2), and third floor (3). Each storey features an I-shaped floor plan, and all storeys are connected by four vertical circulation elements, i.e., stairs. The following software tools were employed in this study: IfcOpenShell for parsing IFC-SPF, Neo4j graph database for storing the generated IFC-Graph and connectivity graphs, and py2neo for interacting with the Neo4j database. The experiments were conducted on a computer equipped with an Intel i7-13700K CPU, 32 GB of RAM, and an NVIDIA GeForce RTX 3060 Ti graphics card.

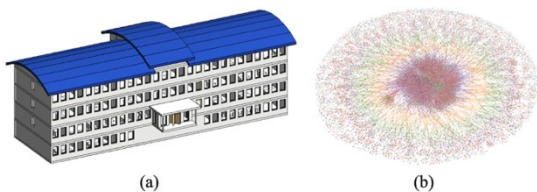


Figure 1: (a) the Institute building, (b) IFC-Graph for the Institute building.

Table 1: Overview of building models used in this study.

Model	IFC-SPF	IFC-Graph	
	Entities/Instances	Nodes	Edges
Institute	189/147712	194845	285504

Establishing Horizontal Connectivity Graph for Individual Floors

The horizontal connectivity graphs for each individual floor were generated using the graph query shown in Listing 1, which identifies all spaces connected either by a door or a virtual boundary via the IfcRelSpaceBoundary relationship. The query execution time was 2,430 milliseconds. Figure 2 illustrates the horizontal connectivity graphs for all floors. As shown, the graphs exhibit a simple tree-like structure, where there is exactly one unique path between any two nodes.

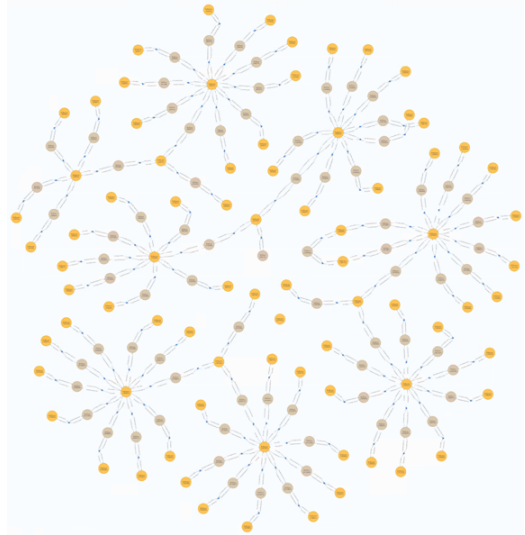


Figure 2: Horizontal connectivity graph for all floors.

Establishing Vertical Connectivity Graph

Vertical connections were manually identified from the Institute model, and a corresponding graph was created to represent these links, as shown in Figure 3. In this graph, the blue nodes represent the newly defined IfcRelConnectsSpace instances. The complete building-wide connectivity graph, referred to as the Navi-Graph, was then constructed by integrating the horizontal and vertical connectivity graphs (see Figure 4).

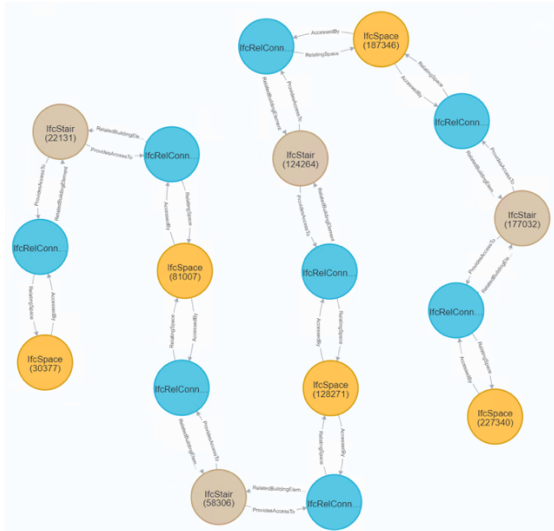


Figure 3: Vertical connectivity graph of Institute.

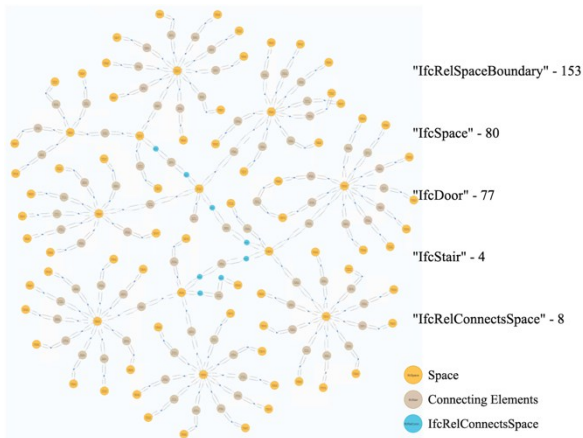


Figure 4: Building-wide Navi-Graph for Institute.

Indoor Pathfinding using the Navi-Graph

The building-wide Navi-Graph serves as the foundation for indoor pathfinding. To identify the shortest path between any two objects, a graph query such as ‘match p=shortestPath((n1{id:id1})-[*]-(n2{id:id2})) return p’ can be executed. This query returns a subgraph representing the shortest route. Using the unique identifiers embedded within the returned nodes, the geometric shapes of the corresponding elements can be extracted from the IFC-SPF file to reconstruct the physical path, i.e., the actual navigable route that users can follow to reach their destination. This physical path preserves key landmarks such as doors and stairs, thereby supporting intuitive indoor wayfinding for users. To demonstrate the effectiveness of the semantics-driven pathfinding approach, two scenarios were tested: space-to-space navigation and space-to-exit navigation.

Space-to-Space Pathfinding

Two spaces, i.e., space (186482) and space (26145), were randomly selected for this purpose and the query was completed in 31.2 ms. The returned graph path is presented in Figure 5, and the sequence and IDs of the involved elements are [186482, 209557, 186903, 218941, 187346, 124264, 128271, 58306, 81007, 22131, 30377,

57992, 29934, 55844, 26145], the physical path is presented in Figure 6.

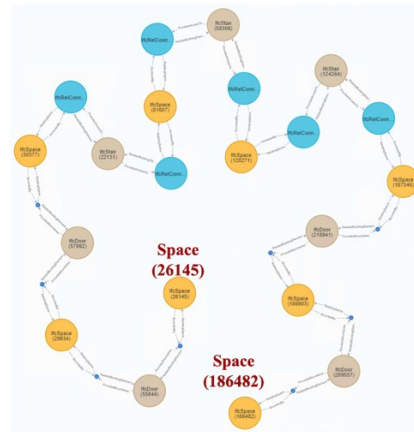


Figure 5: The graph route between space (186482) and space (26145).

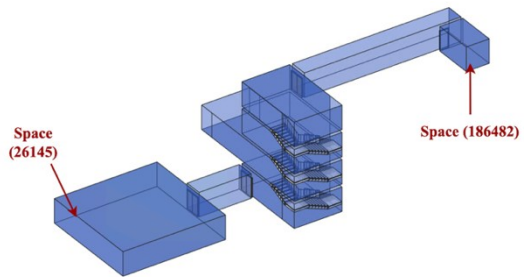


Figure 6: The physical route between space (186482) and space (26145).

Space-to-Exit Pathfinding

Space (186482) and exit (90012) were used for this purpose, and the query was completed in 15.6 ms. The returned graph path is presented in Figure 7, and the sequence and IDs of the involved elements are [186482, 209557, 186903, 218941, 187346, 124264, 128271, 58306, 81007, 90012], the physical path is presented in Figure 8.

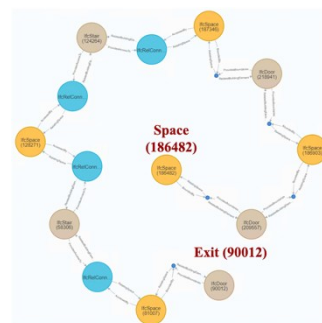


Figure 7: The graph route between space (186482) and exit (90012)

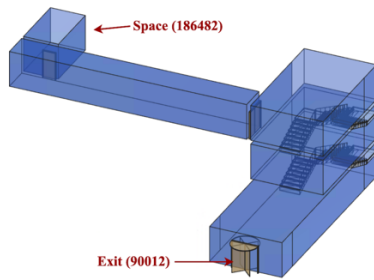


Figure 8: The physical route between space (186482) and exit (90012)

Discussion

This study proposes a new semantics-driven approach for indoor pathfinding by constructing a semantics-based indoor network. The proposed approach is different from previous studies, which is easier to construct and can enable semantics-driven pathfinding, rather than using geometric network.

The semantics-based connectivity graphs facilitate object-to-object pathfinding by leveraging the rich semantic information embedded in IFC models. Unlike traditional methods that focus on identifying geometric points along a route, this approach identifies meaningful building elements. As demonstrated, the connectivity graph supports navigation between any two nodes, such as from one space to another. This contrasts with conventional coordinate-based, point-to-point pathfinding, which relies heavily on geometric data and demands high-precision indoor positioning systems. In contrast, semantics-driven object-to-object pathfinding requires only room-level accuracy, making it more suitable for indoor navigation scenarios where precise positioning is unavailable or impractical. Since the approach only needs to determine which space (e.g., room) the user occupies, it can operate effectively even with limited positional resolution.

This approach aligns well with Digital Twin (DT) technology, which integrates modeling, indoor positioning systems, the Internet of Things (IoT), sensor networks, and augmented reality (AR). A Wi-Fi-based indoor positioning system can estimate a user's approximate location within a building and return rough coordinate data. These coordinates can then be used to identify the user's current space, which serves as the starting node for pathfinding. Once the destination is identified through semantic search, a path can be retrieved from the connectivity graph, and navigation can begin via AR. During navigation, the user's real-time location is continuously tracked and updated within the system and compared against the graph structure. Based on this comparison, the current and upcoming spaces along the path are highlighted as visual cues, guiding the user step by step from one space to the next.

In addition, this new approach is also flexible enough to include additional semantic information to support additional use case. This is enabled by the use of graph structure and graph database. The navigation model is easily extensible to accommodate additional needs. For instance, to support pathfinding between spaces and

specific facilities, such as fire extinguishers, relevant information can be extracted from the IFC-SPF file and integrated into the existing connectivity graph.

Although the proposed approach shows significant potential, several limitations should be addressed in future work. 1) This study focuses on constructing a connectivity graph for indoor pathfinding without incorporating physical distance. Future research should explore methods for embedding distance into the semantics-based graph, such as assigning weight attributes to nodes or appropriately subdividing indoor spaces (Liu 2017), or using virtual boundary (Yang and Worboys 2015). 2) The current model is designed primarily for human pedestrian navigation. Future extensions should include additional navigation modes, such as aerial movement for drones or rolling mobility for wheeled robots. 3) The efficiency of the proposed method should be compared with other methods, such as those geometry-based. 4) A more efficient way is required to create vertical connectivity. 5) Indoor/outdoor integrated pathfinding should be explored by integrating BIM and geographic information system (GIS) (Zhu and Wu 2022).

Conclusions

This study proposed a new semantics-driven approach for indoor pathfinding by constructing connectivity graph using IFC-Graph. This approach is different from previous studies that mainly used geometric information from either CAD or BIM. This new approach tries to avoid the use of computing-intensive geometry processing and instead uses the rich semantic information in IFC data. The proposed methods were validated using a real-world building model. The main findings and contributions of this study are as follows: (1) This study demonstrates the feasibility of constructing a semantics-based indoor network from IFC data for indoor pathfinding. The proposed approach effectively supports navigation tasks within built environments. (2) Unlike traditional geometry-driven methods, the semantics-driven approach offers a distinct process for constructing the navigable connectivity graph. By leveraging graph-based IFC data, the semantic network is more straightforward to establish. (3) The semantics-driven approach mainly uses semantic information from IFC, rather than geometric information, which provides more possibilities in applications like emergency response. While the semantics-based connectivity graph has shown strong potential and flexibility for indoor pathfinding, further research is needed to enhance its robustness and broaden its applicability. Future work should include validation using more complex building models and support for additional navigation modes, such as flying (for drones) and rolling (for robotic platforms). Overall, the semantics-driven approach aligns well with Digital Twin technology and augmented reality systems.

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