# AUTOMATIC GENERATION OF ROUTING GRAPHS FOR INDOOR-OUTDOOR TRANSITIONAL SPACE TO SUPPORT SEAMLESS NAVIGATION

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**ABSTRACT:**

With the fast development of urbanization, the complexity of built environments has dramatically increased, driving a need for assistance in seamless indoor-outdoor navigation. This requires integration of spatial information of indoor and outdoor environments from heterogeneous data sources. While outdoor road network data is largely available from many sources (such as OpenStreetMap), indoor spatial information is either inexistent or is inconsistently represented using several different standards. Among these standards, IndoorGML is a well-developed standard with the focus on indoor location-based services. This standard has already been accepted by Open Geospatial Consortium (OGC) and is now under active development. Although in IndoorGML some mechanisms have been defined to enable integration of indoor and outdoor networks, there is still a lack of concrete guidelines for determination of indoor-outdoor connections. It also lacks solid scientific foundations and efficient tools to extract the connecting nodes and edges that link indoor and outdoor spaces. To address this gap, in this study we focus on the connection of indoor and outdoor spaces and aim to provide a tool, which can automatically construct navigation graphs of the indoor-outdoor transitional space to support seamless integration of indoor-outdoor navigation. To this end, voxel-based modeling approaches are used to model the connecting space between indoor and outdoor environments. Based on Python, we develop the intended tool, which can generate voxel models from point clouds, identify navigable space by taking into account the characteristics of agents (such as pedestrians, wheelchairs, and vehicles), and automatically build navigation graphs linking IndoorGML networks with outdoor street networks. It is expected that the methodology and tools developed from this project will benefit the IndoorGML ecosystem and greatly advance the capability of IndoorGML in representing navigable space to support location-based services.

## 1. INTRODUCTION

With rapid development of urban sprawls, the complexity of built environments has increased significantly, creating a demand for applications to provide efficient navigation services. In recent years, a few studies have been conducted to develop models and tools for seamless integration in indoor and outdoor navigation (Yan et al., 2021; Vanclooster and De Maeyer, 2012; Wang and Niu, 2018). Despite the promising results obtained from these studies, how to seamlessly integrate indoor and outdoor navigation services to allow agents continuously move from indoor to outdoor space or vice versa is still a major challenge for researchers on navigation.

The transitional space that connects indoor and outdoor spaces plays a very important role in the integration of indoor and outdoor navigation. While the entrances of buildings can be easily defined, there are still many situations where there is no clear boundary between indoor and outdoor spaces (as shown in Figure 1). The structures of building entrances can be entirely bounded or partially bounded, which makes it difficult to distinguish between indoor and outdoor environments. Moreover, the intermediate space between buildings and road networks varies with sizes and forms, which makes it difficult to identify the navigable spaces that can link indoor network and outdoor networks. Moreover, different types of agents (e.g., wheelchairs, pedestrians, and vehicles) have their own requirements on the usage of space for mobility, which requires different partitions of spaces.

The complexity of indoor-outdoor transitional space makes it very difficult for the existing standards to capture navigable space. Each of these standards has its limitation in the modeling of either indoor or outdoor environments (Cantarero Navarro et al., 2020). For example, the OpenStreetMap (OSM) standard is well suited for mapping city outdoor objects, such as trees, roads, and bridges, it is very limited in the modeling of indoor components (such as stairs). The existing indoor data models, such as BIM (Building Information Modeling), Apple IMDF (Indoor Mapping Data Format), CityGML (City Geography Markup Language), mainly focus on geometric representation of architectural components and are not navigation-oriented. Based on a simple representation of indoor spaces (e.g., cells and edges), IndoorGML has been published by OGC (Open Geospatial Consortium) to support indoor location services (Kang and Li, 2017). Although it has some mechanisms to define edges and nodes to connect indoor and outdoor networks, there are no concrete guidelines or clear specifications in the determination of indoor-outdoor connecting edges or nodes in IndoorGML models. Some extended models have been proposed to enhance IndoorGML with descriptive power in representing transitional spaces surrounding buildings (Claridades and Lee,

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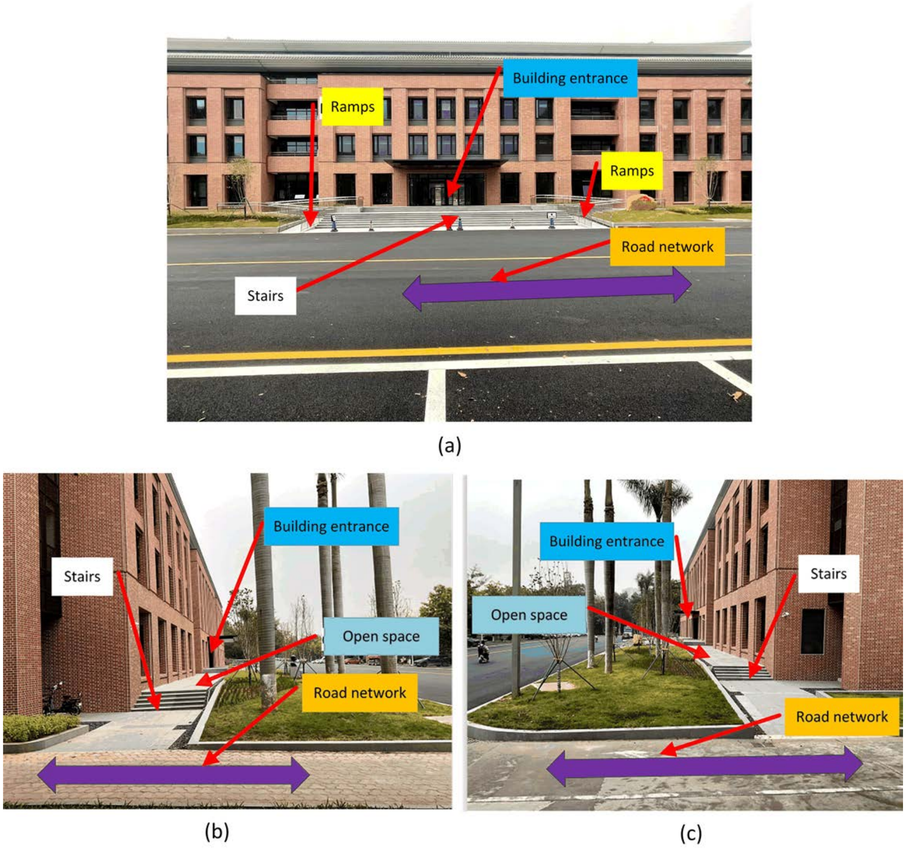


Figure 1. Transitional space around the Yifu Science building at the Wushan campus of the South China university of technology: (a) the main entrance of the building; (b) the left side of the main building entrance; (c) the right side of the main building entrance.

2021; Kim et al., 2019), but generation of such models requires manual work and is very time-consuming when they are applied to the city level.

To ensure seamless navigation, a unified framework on representation of indoor-outdoor transitional space is needed. Such a framework should not only provide a clear space definition and classification but also enable efficient computation of the characteristic of space (Zlatanova et al., 2020). Some attempts have been devoted to space definition and classification in navigation and four types of space have been classified: indoor, semi-indoor, semi-outdoor, and outdoor (Yan et al., 2019, 2021). However, traditional boundary-based or vector-based representation is limited in performing 3D spatial operations (such as volume computation), which makes it difficult to identify those types of space and to derive navigable space based on space requirements of agents (pedestrians, wheelchairs, vehicles). On the other hand, based on volumetric representation, voxels can be an appealing alternative to identify different types of navigation spaces and to find navigable space needed for agents (e.g., humans (Figure 2) and drones (Figure 3)), taking into account their specific space constraints (Gorte et al., 2019; Li et al., 2018; Fichtner et al., 2018).

Voxel based modeling has been widely used in many applications, including modeling of urban environments (Aleksandrov et al., 2019; Zhao et al., 2019), fire simulation (Moreno et al., 2012, 2010), and geological modeling (Griffioen et al., 2012). Voxelization of city models can be done by using point clouds. Various city objects, such as

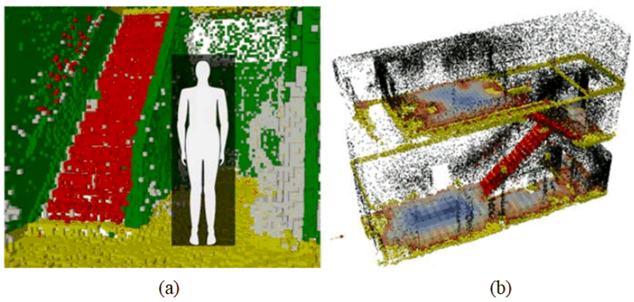


Figure 2. Voxel-based navigation for humans: (a) Consideration of the human size constraint for finding walkable space; (b) Clearancemap of the floors taking into account the human constraint and obstacles, e.g, walls and furniture (from Fichtner et al. (2018)).

buildings, streets, or trees (which were traditionally modelled with 2D surfaces, lines or points), can be easily converted to 3D voxels from point clouds (Nourian et al., 2016). For modeling of indoor-outdoor spaces, point clouds can be obtained from different platforms (air, ground) and equipment (cameras, laser or combination of them) and provide a relatively quick and cheap option to capture navigable space surrounding buildings. Another advantage of voxelising point clouds is that the amount of data can be significantly reduced, which would greatly facilitate data processing and analysis. Naturally, based on voxel models (from fine-grained resolution

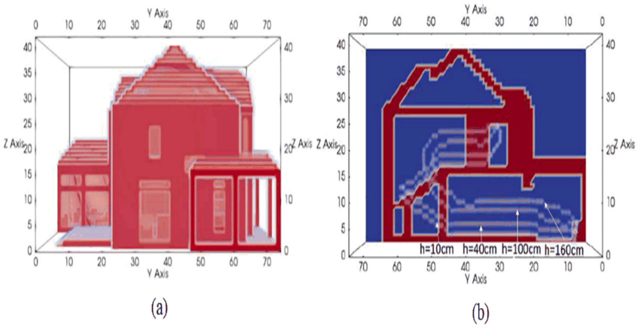


Figure 3. Voxel based navigation for drones: (a) 3D voxel model of an indoor environment (resolution=20cm); (b) Calculated paths for drones flying at different heights, i.e., 10 cm, 40 cm, 100 cm, and 160 cm (from Li et al. (2018)).

to course resolution), complex semantic of different real-world objects and their topological interrelations can also be derived for navigation. Based on agent characteristics, voxels can be re-classified and re-grouped, offering flexibility in space divisions (Fichtner et al., 2018). All of these make voxel models a promising approach for modeling indoor-outdoor transitional space and constructing transitional graphs for navigation purpose. Some efforts have been mode to use voxels for modeling of indoor navigable space (Staats et al., 2017, 2019; Flikweert et al., 2019). However, there still is a gap in research on how voxels can be used for modeling of indoor-outdoor transitional spaces and constructing navigation graphs from these spaces.

## 2. AIM AND OBJECTIVES

In this study we focus on modeling of indoor-outdoor transitional space, and aim to develop a tool which can automatically construct navigation graphs for indoor-outdoor transitional space to seamlessly link the outdoor road networks (from OpenStreetMap) and indoor networks (from IndoorGML). To this end, we will address the following two research objectives:

- **Research Objective I**: Development of voxel models for indoor-outdoor transitional space. We will explore the use of voxel-based modeling to capture the space between indoor and outdoor environments (e.g., parking slots, stairs, and sidewalks). Voxels will be enriched with semantics and segmented to distinguish between navigable space and non-navigable space.
- **Research Objective II**: Development of a tool for automatic routing graph generation for indoor-outdoor transitional space. The intended tool will: 1) generate voxel models from point clouds of building entrances and their surrounding environments; 2) identify navigable space and perform space division based on the characteristics of agents (e.g., pedestrians, wheelchairs, and vehicles); 3) build navigation graphs that link OpenStreetMap road networks and IndoorGML networks.

We will test the developed models and tool with several public buildings or transit stations, where there is a large transitional space connecting indoor and outdoor environments. We expect that the developments from this project will enhance the capability of IndoorGML in representing the navigable space. We also believe that the output of this project will facilitate research and development on indoor-outdoor navigation services and not only research communities but also industries and companies will benefit from this project and advance their developments on location-based services.

## 3. PROPOSED APPROACH

To achieve the aim of developing a tool for automatically constructing a navigation graph of indoor-outdoor transitional space, we have defined four phases, which are shown in Figure 4 below.

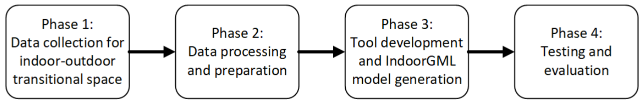


Figure 4. Research phases defined for the development of the intended tool.

**Phase 1: Data collection**

We will select several public buildings or transit stations for our case study. The indoor data of these buildings/stations will be obtained from existing floor plans or building models (such as BIM/IFC). To collect point clouds of indoor-outdoor transitional space, we will use iPad Pro built-in Lidar sensors and scan building entrances and their surroundings (e.g., stairs, sidewalks, and parking slots). The iPad Pro has been proven by a few studies to be a fast and reliable 3D data acquisition tool (Spreafico et al., 2021; Díaz-Vilariño et al., 2022). Existing building models (e.g., CAD model, CityGML models, and BIM models) will also be collected and used in other research phases (Phase 4) to compare the results generated from our approach with those from other models.

**Phase 2: Data processing and preparation**

The collected indoor data of buildings will be transformed into IndoorGML models, using exiting tools (e.g., ifc2indoorgml (Diakite et al., 2022)). The OpenStreetMap will be used to extract outdoor road networks. The collected point clouds of indoor-outdoor transitional space will be preprocessed and outliers will be filtered out. All the collected datasets will be aligned in the same reference system. In case of dealing with vast amount of 3D datasets beyond the PC capability, the uniform sampling techniques will be used to select representative points to reduce computational load.

**Phase 3: Tool development and IndoorGML model generation**

We will develop a tool which will be based on Python and can automatically build routing graph for linking indoor and outdoor networks. Figure 5 shows the workflow proposed for the intended tool. The tool will first generate voxel models from point clouds of the studied buildings. The voxels will be segmented and semantically enriched. Based on the characteristics of agents (vehicles, wheelchairs, and pedestrians), the voxels will be further divided to generate navigable space. Then it will automatically extract nodes and edges from voxels to describe the geometry and topology of the indoor-outdoor connecting environment. Based on the routing graph generated by the developed tool, an IndoorGML model will be generated to integrate indoor networks and outdoor road networks (from Phase 2).

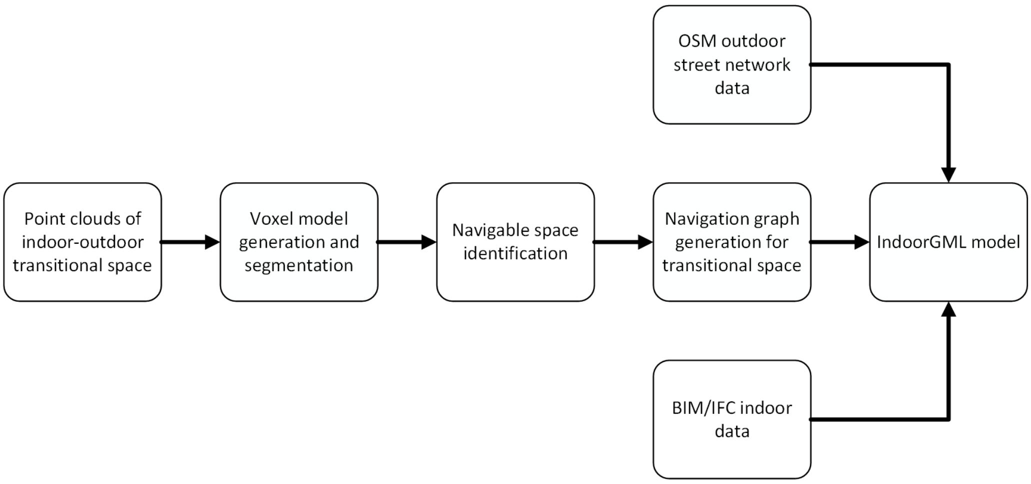


Figure 5. Workflow proposed for the development of the intended tool.

**Phase 4: Validation and evaluation**

We will test the developed tool with the collected datasets of the selected buildings, taking into account the space requirements of different agents (pedestrians, wheelchairs, and vehicles). The routing graph generated by the tool will be examined and compared with the graphs generated from two other approaches: 1). from manual generation; 2). form exiting models (e.g., CAD models, CityGML models). A survey with several participants (10-20) will be conducted to evaluate to which degree the constructed indoor-outdoor graph can represent the actual movements of users from outdoor to indoor and vice versa.

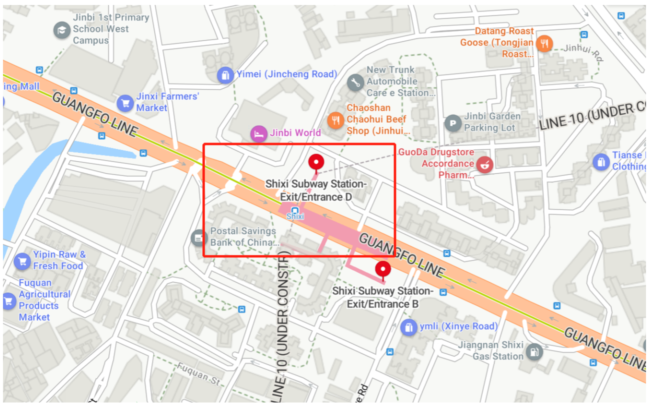


Figure 6. The geo-location of the Shixi metro station (in red) in Guangzhou (from Bing Maps platform).

## 4. PRELIMINARY RESULTS

As the first step, we have selected a metro station named Shixi station (lat:23.068059, lon:113.285516) of Guangfo Line, which is located in Guangzhou, China and connects Foshan and Guangzhou (Figure 6). The metro station has three exits (Exit A, Exit B, and Exit D)and there is a large portion of transitional space that connects the road network and the exits. We obtained the BIM/IFC models of the internal space of the station and the point clouds of the indoor-outdoor transitional space around the exits. Figure 7 shows the BIM model of the interior space of the station. The point clouds have been semantically segmented (i.e., buildings, vegetation, and grounds). Based on the Python packages (i.e., Numpy, Pandas, and Mayavi), we have developed a set of Python tools to voxelize the BIM models and the point clouds and to visualize the voxel models via the GUI. The results are shown in Figure 8 and Figure 9.

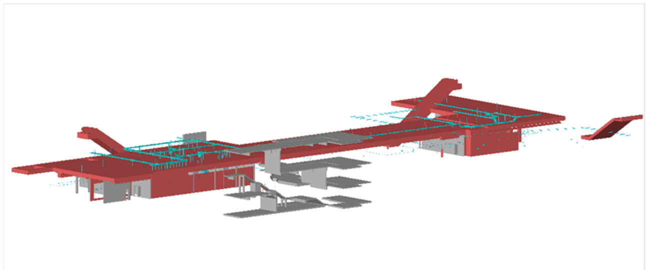

Figure 7. The BIM model of the interior space of the Shixi metro station.

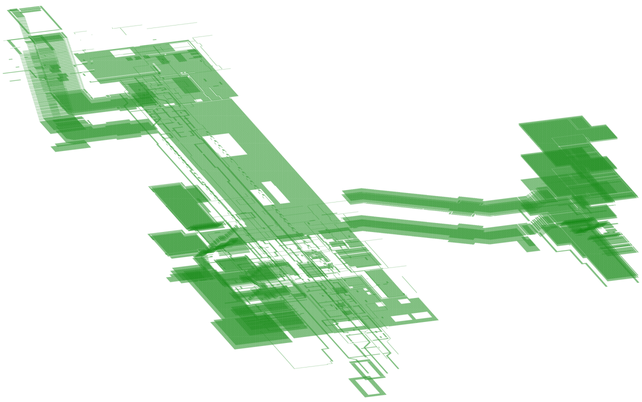

Figure 8. The voxel model of the internal space of the metro station.

## 5. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented a framework which aims to generate routing graph for transitional space to link IndoorGML models and outdoor networks. In this framework we use point clouds to capture indoor-outdoor transitional space. Voxel models have been generated from the BIM models as well as the point clouds. Currently we are extracting navigable


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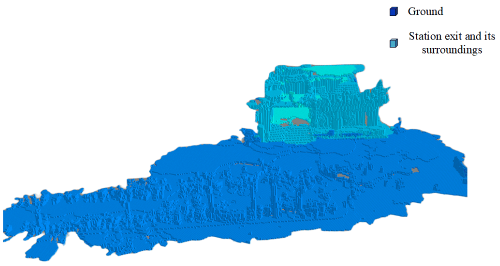
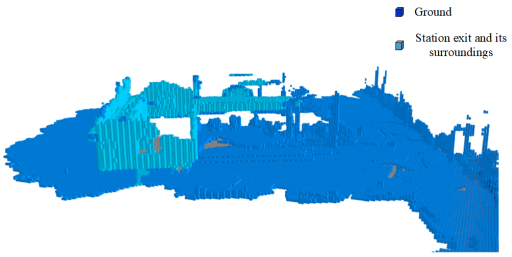
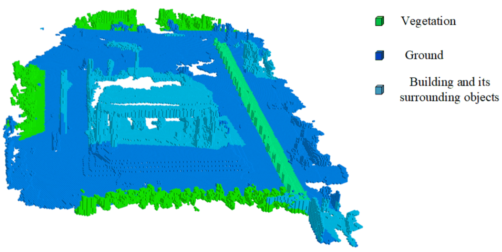



(a) The voxel model of Exit A and its surroundings




(b) The voxel model of Exit B and its surroundings




(c) The voxel model of Exit D and its surroundings

Figure 9. Voxel models of the exits of the Shixi metro station.

space from the voxels, taking into account the characteristics of different agents (e.g., pedestrians and wheelchairs) and building the navigation graphs based on the space requirements for their movement. Future work includes generation of IndoorGML models, testing and validation of the proposed approach, comparison with other approaches (e.g., manual generation of navigation graphs).

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