Automating the Generation of Indoor Space Topology for 3D Route Planning Using BIM and 3D-GIS Techniques

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Abstract

3D Indoor space topology, mainly referred as floor layouts and navigation routes, is the foundation of indoor Location-based Services (LBS), such as navigation in large shopping malls or interchange in large transport stations. Manually generating this topology is highly time-consuming, less cost effective, and prone to errors. This research adopts 3-D GIS technology and proposes a novel workflow to automatically generate the indoor space topology based on 3D building models in a format of Industry Foundation Classes (IFC). Floor layouts and paths including stairs will be identified and generated in the environment of ESRI ArcScene . Several categories of navigation routes are defined and constructed by a collective algorithm called *i-GIT*. This paper demonstrates the entire workflow and concepts to produce floor layouts and navigation routes using a 3-story commercial building model. More details related to *i-GIT* as well as their validation based on real buildings will be revealed in an upcoming article.

Keywords –
3-D GIS, Indoor Space Topology, 3D Navigation graph, Building Information Modeling

1 Introduction

With the popularity of mobile devices and positioning technology, there has been a rise of smart cities around the world in a recent decade, in which Location-Based Services or LBS, such as vehicle navigation and freight tracking, play an important role of fulfilling their goals by providing citizens with more effective and efficient accesses to locations. The Demand of wayfinding has expended its applications from outdoor streets to indoor spaces in recent years. Equipped with indoor positioning technology like i-Beacon, there brings more and more smart services inside the buildings. In order to realize indoor navigation, it also requires the indoor space topology of buildings as the base map for navigation. Indoor space topology mainly consists of floor layouts and accessible paths among indoor spaces. Indoor paths can be horizontally or vertically distributed. Vertical paths connect two floor levels with different elevations, such as stairs, elevators, escalators, or ramps. Manually creating indoor space topology is extremely time-consuming and prone to error [1], no matter what digital source, either 2D CAD drawings or 3D building models, is used. In response of likely massive demands of indoor navigation in near future, automation of generating indoor space topology is necessary [2].

Since indoor space topology contains non-planar paths, 3D building models, such as BIM, with most straight-forward 3D geometry information are the better choice of materials than 2D drawings when constructing the topology. However, 3D building models composed of structural elements, such as walls, columns, slabs, and beams, do not contain the geometric information of navigable paths. Therefore, it remains a challenging task extracting necessary information from 3D building models to construct the topology. Although there existed several studies in this field and algorithms developed to automatically produce indoor navigation paths [1-5]，most of them merely focused on horizontal paths [1-3] and were based on an assumption that the spatial semantic information of buildings or floor layouts are already known. For those studies discussing vertically distributed paths, the representation of vertical paths were highly simplified [5].

This study attempts to propose a workflow based on 3D GIS technology for automatically generating indoor space topology. We developed a collective algorithm called Intelligent Generation of Indoor Topology, or *i-GIT*, that reads 3D building models in a format of Industry Foundation Classes (IFC) as the only input, then automatically identifies boundaries of indoor spaces for each floor, and finally generates horizontal and vertical navigation paths for 3D route planning. We implemented and tested *i-GIT* with a demonstrative building model in a single environment of 3D GIS software, ESRI ArcScene. Equipped with the proper

indoor positioning technology, the research results can be widely used in indoor navigation of large-scale shopping malls or office complexes, guiding of indoor emergency escape and evacuation, or interchange in large transport stations.

The remainder of this paper is structured as follows: Section 2 addresses some important properties of indoor space topology as well as introduces three major navigation models and algorithms proposed by previous studies for generating centreline-based models. We explains the reason why we adopt Delaunay Triangulation to generate horizontal paths and how we improve its performance by removing redundant nodes it might generate. Section 3 explains the overall concept of how we automate the generation of indoor space topology, including the formation of indoor space from the perspective of wayfinding. Two categories of indoor paths and the workflow based on 3-D GIS technology will be introduced. Section 4 demonstrates the testing results of *i-GIT* using a 3-story building model, followed by a summary and discussion in Section.

2   Related Work

The biggest difference between outdoor vehicle navigation and indoor pedestrian navigation is that paths of vehicle navigation are limited to a fixed road network, while the freedom of accessibility for indoor navigation on the same floor is two-dimensional. Indoor navigation also allows with vertical paths, like stairs and elevators. Although the degree of freedom for indoor navigation can be three-dimensional, its horizontal movement is still subject to walls, columns, furniture and other barriers; its vertical paths are also limited to stairs, elevators or ramps. Taneja [1] summarized the following three different indoor navigation models：centerline-based models, metric-based model, and grid-based models. Among them, grid-based models would best fit the above-mentioned degree of freedom for indoor navigation; thus widely used within the robotics and computational graphics domains. However, for those indoor pedestrians with definite destinations, the main purpose of route planning is just for wayfinding, so centerline-based models can satisfy the goal of routing since it represents the paths in a very similar way that humans recognize the direction in indoor space.

Most existing algorithms to construct centerline-based models are based on three methods [2]: Visibility Graphs, Straight Skeletons, and Delaunay Triangulation.

A Visibility graph is a navigational space composed of a set of nodes and edges. Nodes represent the stop points in indoor space, normally referring to the accesses like doors. Edges are straight lines connecting two inter-visible nodes. If these exists no direct edge between two accesses, some intermediate nodes need to be added in order to form a navigation network. One of the drawbacks of Visibility Graphs is the explosive number of edges in a space with no obstacles because the combination of inter-visible nodes is nearly boundless [4]. Besides, the direction instructions it gives are less easily comprehended by humans.

Straight-Skeletons is a method that transforms polygons into a navigation network based on Medial Axis Transform proposed by Blum in 1967 [1, 2, and 4]. Straight-Skeletons has its name because the indoor paths it generates are approximately along the medial axis of the space. For a rectangle space, Straight-Skeletons first equally divides the four right angles, and connects the intersect points of two shorter angle bisectors to form a navigation network with one longer and 4 shorter paths. For spaces with simple and regular shapes, methods based on Straight-Skeletons, such as S-MAT [3], can obtain fairly good results; however, they may create redundant nodes in irregular shapes [1, 2].

Delaunay Triangulation is the dual of the famous Voronoi Diagram. It divides a plane into triangles ensuring that no triangle vertex lies within other triangles in the network. It also maximizes the minimum angle of triangles so that it can avoid creating long and thin triangles as far as possible. This characteristics makes it suitable for constructing 3D terrain model. Triangular Irregular Networks (TIN), a famous digital format to present surface morphology in the GIS community, is also based on this algorithm. By dividing a single indoor space using Delaunay Triangulation and connecting the midpoints of inner edge of each triangle, a navigation network can thus constructed [4, 5]. The advantages of this method include: 1) it can apply to almost any shape of indoor space; 2) the distribution of paths is roughly the same as the contour of the indoor space; and 3) the paths can also be roughly spread throughout the indoor spaces. It might produce more nodes and paths near those relatively irregular or broken regions. Some researchers [2] regarded this as a drawback of this method while others [4] have a different perspective because more nodes indicate a fine-grained navigation model with a higher resolution. We hold the same viewpoint as the latter since the navigation model with an appropriate number of paths can avoid unwanted detours as S-MAT often results in, and thus can produce better outcome of route planning.

In summary, adoption of Delaunay Triangulation to construct centerline-based models for indoor navigation would be the best choice for our research. However, how to maintain the number of nodes produced by Delaunay Triangulation in an 'appropriate' range will be one of important concerns when directly taking 3D building models in the real world as the input since they may contain many indoor spaces with irregular or broken areas, especially in the corners. To resolve this

issue, we adopt an algorithm of regularization [6] upon the original indoor spaces derived from 3D building models before applying Delaunay Triangulation to remove those unnecessary nodes as far as possible. This measurement will be introduced in Section 4.1.

3   Concept and Workflow

3.1   Formation of Indoor Space

For indoor movement by walking, every accessible corner in indoor space could be the destination of a trip while for indoor wayfinding there usually comes with a clear location reference of the building for trip destinations, such as Room 101, Office 605, or the 3rd Meeting Hall, etc. Therefore, the navigation graph must go through all these named spaces. In other words, these named spaces are the most important destinations of indoor trips for wayfinding. Thus, the first task of generating the navigation graph from 3D building models is to identify these named spaces, and select the adequate points, such as the centroid or doors, to represent them. Most 3D building models do provide floor plans, but require modellers manually to specify this information. In cases of no floor plan being available in the models, the algorithm still needs to identify indoor spaces from those structural components by itself.

i-GIT is a set of algorithms we propose to perform all related tasks of generating the indoor space topology. To identify floor layouts, *i-GIT* first conducts the "3D intersection operation" upon the Slab with Columns, Walls, Doors, and Windows of 3D building models, thus generating the bounding lines of "partition separators" as shown in Figure 1. All the structural components come in 3D surface format in a 3-D GIS environment. Those boundaries derived by Walls and Columns are unnavigable obstacles while those derived by Doors and French Windows are navigable. Next, *i-GIT* conducts the "2D difference operation" upon the Slab footprints with partition separator areas, and generates the indoor spaces as shown in Figure 2.

In Figure 2, black ribbons are the boundary of accesses with physical doors or French windows. Green pushpins are centroids of accesses while red and blue ones are centroids of identified indoor spaces. As shown in Figure 2, some of the identified indoor spaces do not have any access, such as balconies and pipeline zones. Since these spaces are not accessible, they will not become the nodes of the indoor paths. In this research, the indoor spaces are divided into two categories according to their shapes: "*Cabins*" for rectangle spaces (as red pushpins in Figure 2) and "*Corridors*" for non-rectangle (as blue pushpins in Figure 2) due to their different characteristics when generating Floor-Level

Paths. Paths within *Cabins* and *Corridors* will be generated in different methods, which will be introduced in Section 3.2 and 4.2.
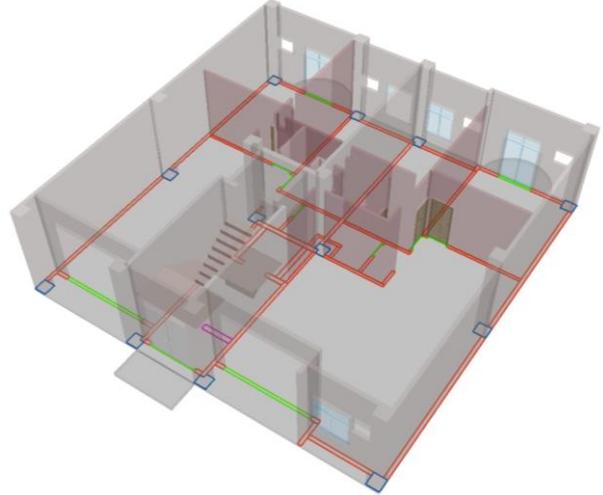
Figure 1. Bounding lines of partition separators derived by conducting 3D intersection operation upon the Slab with Columns, Walls, Doors, and Windows of a 3D building model
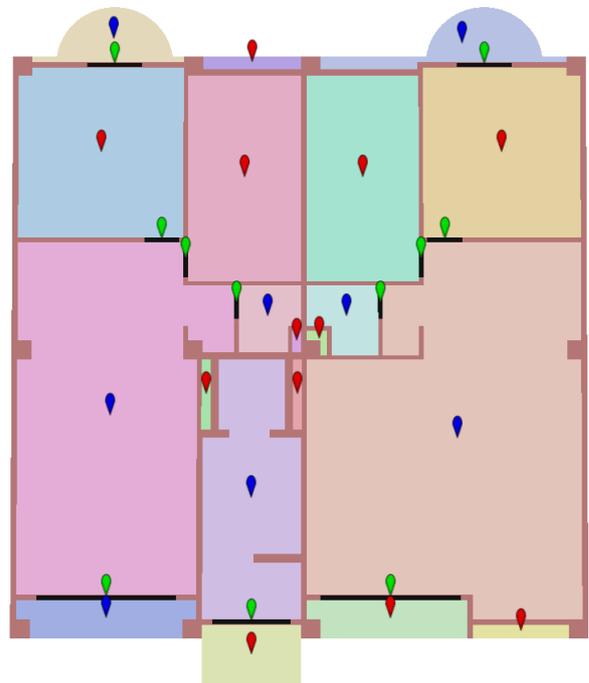
Figure 2. Automatic formation of indoor spaces along with their centroids, derived by conducting 2D difference operation upon the Slab footprint with partition separator areas

3.2   Categories of Paths

The indoor paths of this study are divided into two categories: "Floor-Level Paths" and "Non-Planar Paths". The former falls on the same floor with the same elevation, and is subdivided into "Inside-Corridor Paths", "Access-To-Corridor Paths", and "Access-To-Cabin Paths" according to their locations. The latter is the paths connecting two floors or two planes with different elevations on the same floor, such as stairs, elevators, escalators, and ramps. The following sub-sections define each category of paths mentioned above.

3.2.1   Floor-Level Paths

Figure 3 shows an example of the "Floor-Level Paths". "Inside-Corridor Paths" (shown as red lines) are only located within "*Corridors*", and the distribution is roughly consistent with the contour of the corridor in which it is located. They are spread through the corridor but do not touch the accesses. "Access-To-Corridor Paths" (shown as purple lines) are the linking paths connecting accesses to "Inside-Corridor Paths". "Access-To-Cabin Paths" are straight lines located within "*Cabins*" connecting the centroid of a cabin and all its accesses, as shown in the green lines of Figure 3. They are simplified as straight lines because there is no obstruction on the line of sight in "*Cabins*". The three above-mentioned paths constitute "Floor-Level Paths".
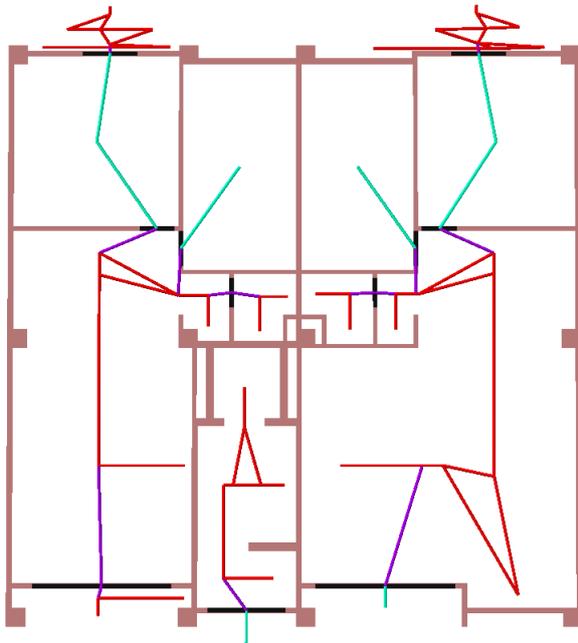
Figure 3. Three categories of Floor-Level Paths: Inside-Corridor Paths in red, Access-To-Corridor Paths in purple, and Access-To-Cabin Paths in green

3.2.2   Non-Planar Paths

As stated earlier, the indoor paths also contain paths connecting planes with different elevations，including of stairs, elevators, escalators, and ramps. This research only focuses on stairs with multiple straight flights and platforms because they are the most common in all types of buildings; meanwhile, they are more difficult to generate than others. We will expend *i-GIT* to other types of "Non-Planar Paths" in the future. Figure 4 illustrates the "Stair-Associated Paths" for a typical stair, including "Stair-Flight Paths" (yellow lines), "Stair-Platform Paths" (pink lines) and "Stair-To-Floor Paths" (blue lines). The first two types are just as their names imply while the third one is the linking path connecting "Stair-Flight Paths" to "Floor-Level Paths", either "Inside-Corridor Paths" or just the centroid of the "*Cabins*".
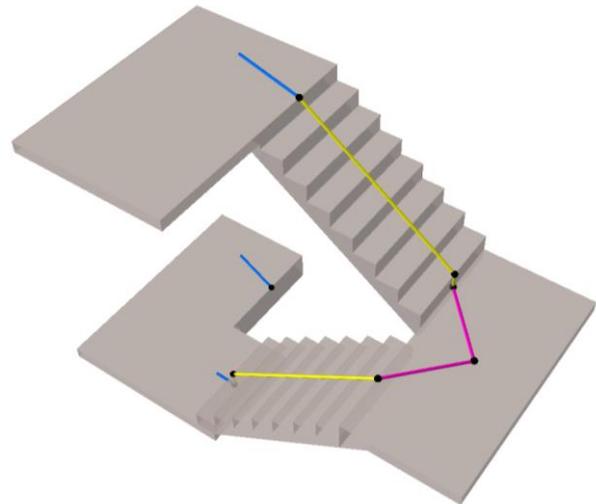
Figure 4. One category of Non-Planar Paths: Stair-Associated Paths with sub-categories of "Stair-Flight Paths" (yellow lines), "Stair-Platform Paths" (pink lines) and "Stair-To-Floor Paths" (blue lines)

3.3   Geoprocessing Workflow

Figure 5 illustrates the entire workflow of generating indoor space topology based on 3-D GIS technologies. The development, testing and validation of *i-GIT* are all proceeded in a single environment of 3-D GIS software: ESRI ArcScene. The workflow includes three phases: (1) generating floor layouts, (2) generating "Floor-Level Paths", and (3) generating "Non-Planar Paths". We use *Model Builde*", an IDE tool embedded in ArcScene for designing geoprocessing procedures, to develop *i-GIT*. *Model Builder* provides a graphical interface for designers to drag and drop those geoprocessing and

spatial analysis tools offered by ArcScene. Besides, it also provides the syntax of iterators and conditions for processing batch files. Figure 6 is an example of geoprocessing model that generates partition separators using *Model Builder*.

Phase 1: Generating Floor Layouts

Intersect 3D slab with vertical components to generate 'partition separator areas'

Difference slab footprints with 'partition separator areas' to generate floor layouts

Phase 2: Generating Floor-Level Paths

Regularize corridor partitions with a maximum deviation

Create TIN triangles for each corridor partition and generate Inside-Corridor Paths

Generate Access-To-Room Paths and Access-To-Corridor Paths

Phase 3: Generating Non-Planar Paths

Generate Stair-Flight Paths

Generate Stair-Platform Paths

Generate Stair-To-Floor Paths

Figure 5. The workflow of generating indoor space topology based on 3D GIS technologies
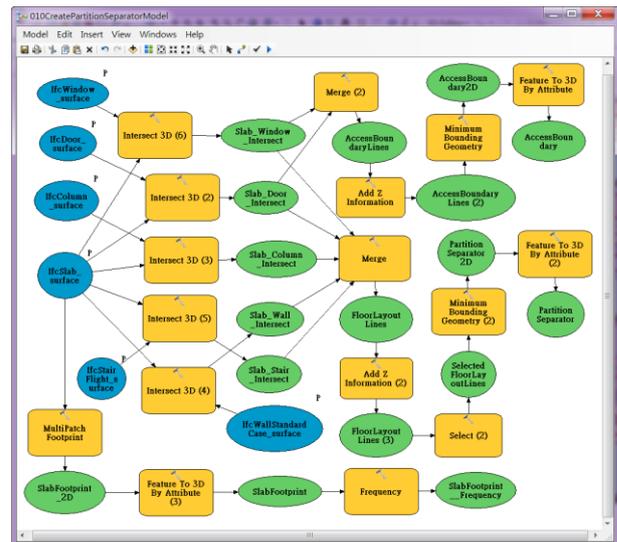
Figure 6. Geoprocessing model that generates partition separators using Model Builder of ESRI ArcScene 10.4.1

The method of producing floor layouts in Phase 1 is described in Section 3.1, *i-GIT* first identifies partition separators and then generates floor layouts. The detailed process of generating partition separators is shown in Figure 6.

In Phase 2, *i-GIT* applies the "Polyline Compression Algorithm" [6] with a maximum allowable deviation upon those original floor layouts derived from Phase 1 to remove undesirable artifacts in their geometry, which will ultimately regularize the footprint of original indoor space to become smooth polygons. Next, *i-GIT* applies Delaunay Triangulation upon those regularized floor layouts constructing TIN triangles. Connecting the midpoints of inner edges of each triangle will produce "Inside-Corridor Paths". Furthermore, "Access-To-Corridor Paths" are created by connecting the centroid of access areas with the nearest node of "Inside-Corridor Paths". At last, connecting the centroid of "*Cabins*" to accesses will generate "Access-To-Cabin Paths".

In Phase 3, the process of producing "Stair-Associated Paths" starts with identifying the boundaries of the stair flights，and then generates "Stair-Flight Paths" using the relationship of those bounding lines. Next, connecting the centroid of the stair platform and the end node of "Stair-Flight Paths" touching the platform will produce "Stair-Platform Paths". Finally, "Stair-To-Floor Paths" are generated by connecting the end node of "Stair-Flight Paths" touching the floor and the nearest node of "Inside-Corridor Paths" or the centroid of the "*Cabin*" depending on where the end node locates.

4   Demonstration

We use a three-story building as shown in Figure 7 as an example to demonstrate the results of our workflow and test the correctness of *i-GIT*. The building is part of the six-story commercial office building, which is roughly divided into two households by the staircase in the middle. The second floor to the top floor have the same floor layout and floor height. This section only presents the results of "Floor-Level Paths" on the second floor as well as "Stair-Associated Paths" derived from the stair with 3 flights and 2 platforms.
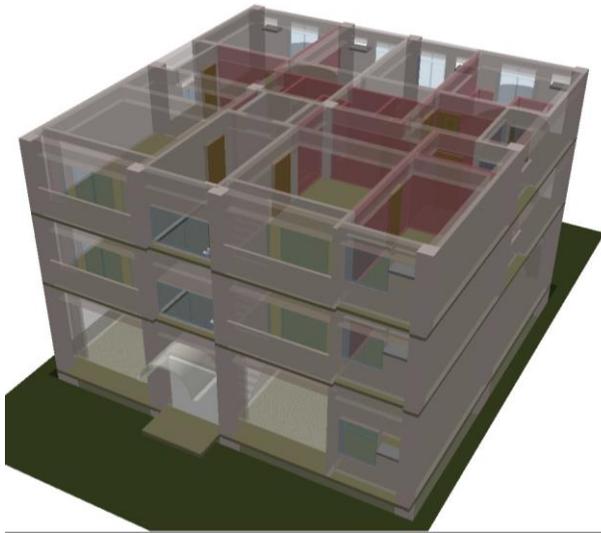
Figure 7. Three-Story building model for demonstration

4.1   Phase 1: Generating Floor Layout

Figure 8 shows the results of floor layouts identified by *i-GIT* after deducting the slab footprint of the 2nd floor by its "partition separator areas". Each indoor space and its accesses are correctly identified. Two or more navigable indoor spaces that do not have physical doors or windows in between are regarded as the same space (which is also a "*Corridor*").

4.2   Phase 2: Generating Floor-Level Paths

Before applying the Delaunay triangulation to generate "Inside-Corridor Paths", the original floor layouts obtained in Phase 1 should be regularized in order to reduce the unnecessary nodes. The patch in Figure 9 is the result of regularizing the floor layouts in Figure 8 with a maximum allowable deviation of 0.2 m. Compared with the partition separator areas shown as black lines in Figure 9, we can see that the original jagged corners because of columns and walls have disappeared and the shape becomes a smooth polygon.
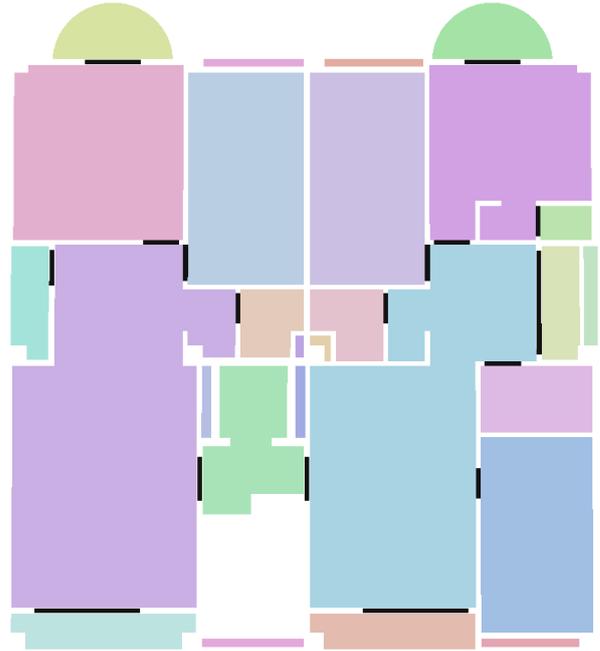
Figure 8. 2nd floor layout (painted areas) of the demonstrative building along with access boundaries (black areas)
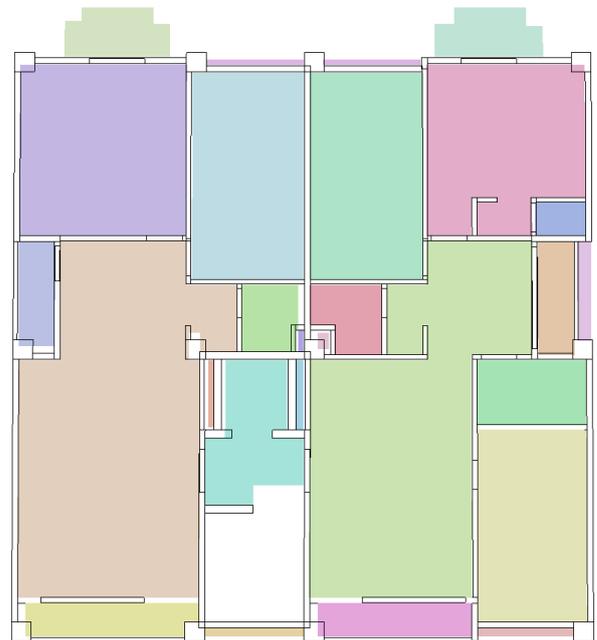
Figure 9. Regularized 2nd floor layout (painted areas) of the demonstrative building with a maximum deviation of 0.2 meter (black lines are original boundary of partition separator areas)

The black lines in Figure 10 are boundaries of triangles derived by applying Delaunay Triangulation on regularized floor layouts shown in Figure 9. Black dots in Figure 10 are the midpoints of inner boundaries of these triangles. *i-GIT* then connects those midpoints within each triangle, and produces "Inside-Corridor Paths", as shown in the red lines of Figure 10. As seen from the figure, these paths are substantially spread throughout the "*Corridor*", and their distribution is consistent with the contour of the "*Corridor*" where they are located. The principle paths are almost straight, too. These features attribute to the performance of Delaunay Triangulation.

Figure 10 also shows that some rectangular spaces, or "*Cabins*", only contain one midpoint of the inner boundary, which happens to be the centroid of the cabin, and thus cannot form any path using the same process. Instead, *i-GIT* connects the cabin's centroid with all its adjacent accesses, and obtains Access-To-Cabin Paths, as shown in the yellow lines of Figure 11. At last, *i-GIT* connects all adjacent accesses of each "*Corridor*" to the nearest node of the "Inside-Corridor Paths", and obtains "Access-To-Corridor Paths" as shown in the purple lines of Figure 11.

Figure 11. Access-To-Corridor Paths (purple lines) and Access-To-Cabin Paths (yellow lines) on 2ⁿᵈ floor of the demonstrative building along with access centroids (markers) and cabin centroids (red flags)

4.3 Phase 3: Generating Non-Planar Paths

Figure 12 shows the "Non-Planar Path" of the stairs from Floor 1 to Floor 3, including three flights and two platforms. The "Stair-Flight Path" starts vertically upward from the midpoint of the first step's bottom edge to its upper edge, and then extends along the midpoints of each step's upper edge to the intersection point touching the upper platform or slab, as shown in the yellow lines of Figure 12. The pink lines in Figure 12 are "Stair-Platform Paths" connecting the platform's centroid and two "Stair-Flight Paths" while the blue lines in Figure 12 are "Stair-To-Floor Paths", the linking paths that connect "Stair-Flight Paths" to "Inside-Corridor Paths".

4.4 Testing Results

Figure 13 shows the entire result of all indoor paths that *i-GIT* generates for the demonstrative building model, including 180 "Inside-Corridor Paths" (193.9m), 62 "Door-To-Corridor Paths" (67.6m), 28 "Door-To-Cabin Paths" (48.9m), 3 "Stair-To-Floor Paths" (1.6m), 6 "Stair-Flight Paths" (5.5m), and 4 "Stair-Platform Paths" (4.1m). The total length of the paths is 327.7 meter segmented by 290 links. The generated paths can be directly used for route planning

Figure 10. Inside-Corridor Paths (bold red lines) on 2ⁿᵈ floor of the demonstrative building along with TIN triangles (black lines)

in 3-D GIS software. Figure 14 is an example of a routing from the main gate on the first floor to the offices on the second and the third floor, with a total route length of 62.2 meters.
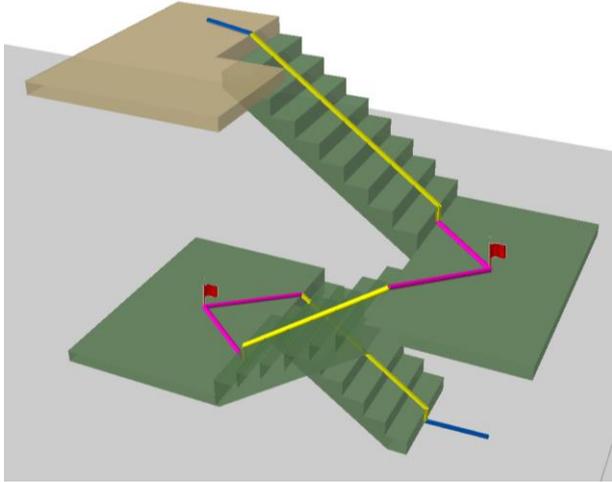
Figure 12. Stair-Associated Paths of the demonstrative building: Stair-Flight Paths (yellow lines), Stair-Platform Path (pink lines), and Stair-To-Floor Paths (blue lines)
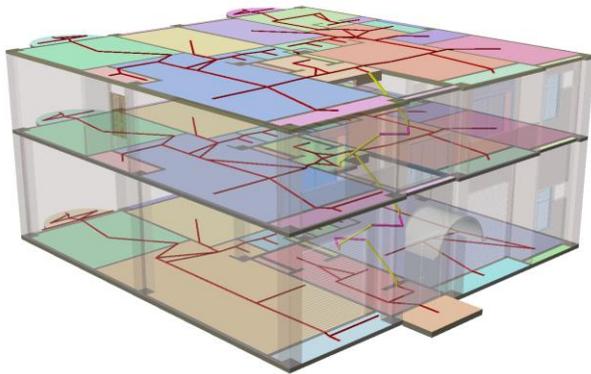
Figure 13. Indoor navigation paths of the demonstrative building

5   Conclusion

Manually generating indoor space topology using 3D building models is expensive and easily incurs errors, so it is necessary to develop an algorithm to automate the process in order to meet the massive demand of indoor navigation in near future. This research develops a collective algorithm called i-GIT along with a geoprocessing workflow using *Model Builder* embedded in ESRI ArcScene, which can accurately identify the floor layouts and generate indoor paths. For Floor-Level Paths, we regularize the original floor

layouts before applying Delaunay Triangulation，which can effectively remove unnecessary nodes. In the future, we will extend the functionality of i-GIT to parse and generate other types of "Non-Planar Paths", such as elevators and ramps, making it even more applicable.
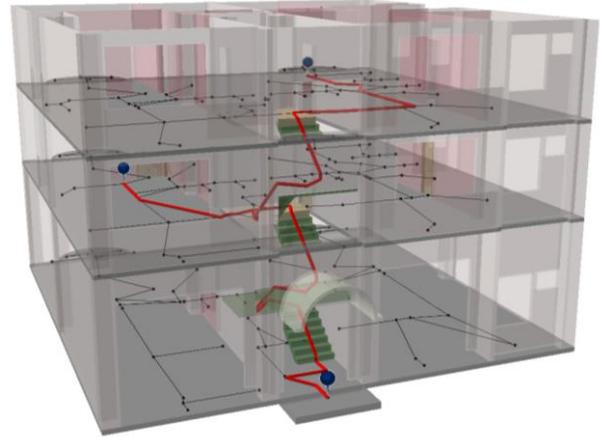
Figure 14. An example of indoor route planning in the demonstrative building

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