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An automated 3D modeling of topological indoor navigation network

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Abstract Indoor navigation is important for various applications such as disaster management, building modeling, safety analysis etc. In the last decade, indoor environment has been a focus of wide research that includes development of indoor data acquisition techniques, 3D data modeling and indoor navigation. In this research, an automated method for 3D modeling of indoor navigation network has been presented. 3D indoor navigation modeling requires a valid 3D model that can be represented as a cell complex: a model without any gap or intersection such that two cells (e.g. room, corridor) perfectly touch each other. This research investigates an automated method for 3D modeling of indoor navigation network using a geometrical model of indoor building environment. In order to reduce time and cost of surveying process, Trimble LaserAce 1000 laser rangefinder was used to acquire indoor building data which led to the acquisition of an inaccurate geometry of building. The connection between surveying benchmarks was established using Delaunay triangulation. Dijkstra algorithm was used to find shortest path in between building floors. The modeling results were evaluated against an accurate geometry of indoor building environment which was acquired using highly-accurate Trimble M3 total station. This research intends to investigate and propose a novel method of topological navigation network modeling with a less accurate geometrical model to overcome the need of required an accurate geometrical model. To control the uncertainty of the calibration and of the reconstruction of the building from the measurements, interval analysis and homotopy continuation will be investigated in the near future.

Keywords Indoor surveying · Automation · 3D data modeling · Indoor navigation · Topology

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Introduction

People spend almost 90 % of their life in indoor building environment (Klepeis et al. 2001; Li and Lee 2010). Indoor building navigation is therefore necessary for moving objects like human to navigate. Indoor building navigation model has different challenging issues such as suitability of 3D building models, indoor navigation networks, vertical and horizontal connectivity, which are required to be addressed.

Different methods have been used for indoor building navigation (Zlatanova and Baharin 2008; Stoffel et al. 2007; Lamarche and Donikian 2004; Li and He 2008; Li et al. 2010; Gilliéron and Merminod 2003; Lee 2004; Yuan and Schneider 2010a; Goetz and Zipf 2011; Liu and Zlatanova 2011a, 2013) which mostly are based on the 2D floor plan or simple 3D models of buildings. Geometric Network Model (GNM) has been widely accepted as suitable navigable network (Gröger and Plümer 2010; Choi and Lee 2009). A GNM is a graph consisting of nodes and edges in which nodes represent position or location of an object such as a room while edges represent connection between nodes. Li and Lee (2010) attempted to integrate GNM with Indoor GML. Luo et al. (2014) proposed generation of GNM from 3D imaging and scanning technologies.

In this paper, an automated 3D modeling of topological indoor navigation network is presented. In this approach, surveyed benchmarks are considered as dual node and generated 3D building model is considered as primal graph. Indoor navigation network is modeled using surveying benchmarks which are connected based on Delaunay triangulation. This paper is organized as follows: Background section presents background of indoor building navigation. Experimentation section elaborates literature review of indoor building surveying and current study of indoor topological navigation network. Result and performance analysis of proposed 3D indoor topological navigation network is presented in Result evaluation and performance analysis section. Contribution and novelty of this research is described in Contributions and novelty section. Conclusion and future research is discussed in Conclusion and future research section.

Background

According to Liu and Zlatanova (2011b), an up-to-date and accurate navigation model is considered as most crucial aspect for developing a robust emergency response system. Semantically rich knowledge, automated generation of network, dynamic routing capacity and door-to-door movement capability are some of the main requirements for modelling indoor navigation network.

Semantically rich knowledge provides useful information about geometrical objects such as door locations or exit points in a building. Liu and Zlatanova (2011b) explained door-to-door route as the straight medial axis of a corridor i.e. *D1-M1-M2-M3-M4-D4* as shown in Fig. 1. Even if the person could not see the door *D3* from *D1*, the door-to-door route could be *D1-S1-D3* (dashed line), which means that the person would be able to see *D3* after he reaches *S1*. The dual graph route would be *D1-M1-M2-M3-D3* in this case.

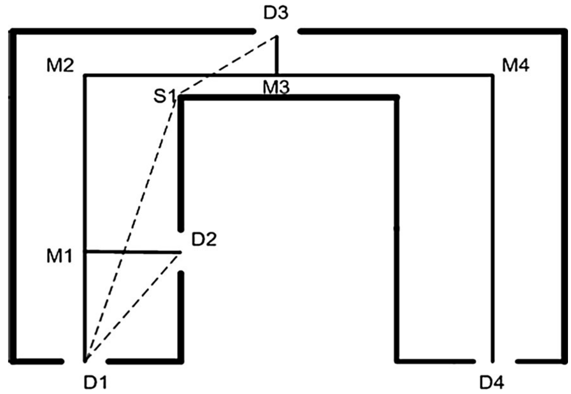


Fig. 1 An example of door-to-door routes (Liu and Zlatanova 2011b)

Lee (2001) proposed conventional dual based on the Poincare Duality theory. The concept of Poincare Duality was used by Lee (2007) and Lee and Kwan (2005) to perform indoor navigation. In their work, they defined a 3D topological data structure for modelling building and then the dual nodes were extracted for indoor navigation and routing. For connectivity of building, conventional dual uses Node-Relation Structure (NRS) which was further extended to GNM in order to represent more accurate representation of indoor building environment (Lee 2004). For improving the construction of GNM, a skeleton-abstraction algorithm was proposed by Lee (2004) which is based on the straight-medial axis transformation (S-MAT). Becker et al. (2009) proposed a Multilayered Space-event in which each space layer is divided into primal and dual space based on topology and geometry.

Many researchers have used Conventional Dual Graph (Lee 2004; Meijers et al. 2005; Li and He 2008; Becker et al. 2009; Boguslawski et al. 2011). To improve S-MAT, Yuan and Schneider (2010a) proposed Direct Path Graph (DPG) in order to improve S_MAT which consisted of cells, path segments and accessibilities.

Navigable space model (Slingsby and Raper 2008; Schaap et al. 2011) is topologically-connected and navigable space (surfaces) which leads to pedestrian's movement. Navigable space model is a 2.5D reconstructed model of 2D plan with limited height and space constraints. However, automated generation of network in complex scenarios and lack of door-to-door movement are some of the challenges in this model.

Yuan and Schneider (2010b) proposed LEGO-graph which is a Regular-grid graph based on the 3D voxel; 3D voxel model can be used to represent indoor building structure. In Regular-grid graph, nodes represent grid while edges represent relationship between the node and its surrounding neighbors (Li et al. 2010). Bandi and Thalmann (1998) discredited building parts into 3D voxel to compute an obstacle-free route with surmountable and insurmountable obstacle.

Lamarche and Donikian (2004) used constrained Delaunay triangulation algorithm and Convex Cell optimization in which 2D plan was divided into cells by considering several criteria such as distance between walls and visibility. Lorenz et al. (2006) divided a 2D plan into cells to create a graph structure with the centre of cells connects to doors as shown in Fig. 2.

Stoffel et al. (2007) used visibility criteria to divide a plan into cells. In their model, a plan was partitioned into non-overlapping convex sub-regions (cells) in accordance with the visibility conditions as can be seen in Fig. 3.

According to Liu and Zlatanova (2011b), a 3D subdivision based on visibility consideration is more accurate and suitable approach for indoor navigation routing as shown in Fig. 4 which possible outlets encompass, room doors, stairs and windows have been represented by *I, D, S and W* respectively. Each opening has been abstracted as a node of a network model as can be seen in the bottom-left part of Fig. 4. If two openings are mutually visible to each other, then there would be an edge between the two nodes of the network. The dash-line edges in Fig. 4 indicate that windows could be used for escape only in some specific conditions (e.g. broken in an emergency situation).

Perfect geometrical model in the most of previous researches was a necessity. By opposition; we tried to overcome this problem and to investigate and propose a novel method of generating a topological navigation network model with a less accurate geometrical model. Pervious researches focus was mostly on the computer science side of 3D topological navigation network modeling (pervious researches mostly assume that they have perfect geometrical model and tried to generate topological or geometrical navigation network model extracted from those geometrical models). Surveying process for data collection was basically ignored. In the most of previous researches, connection between rooms is extracted from primal cells without any consideration for existing furniture of a room. In the previous researches, dual nodes are in the center of a cell (there can be some furniture in the real world situation) and then shortest path and routing is calculated. In this research, we used a real world situation with furniture

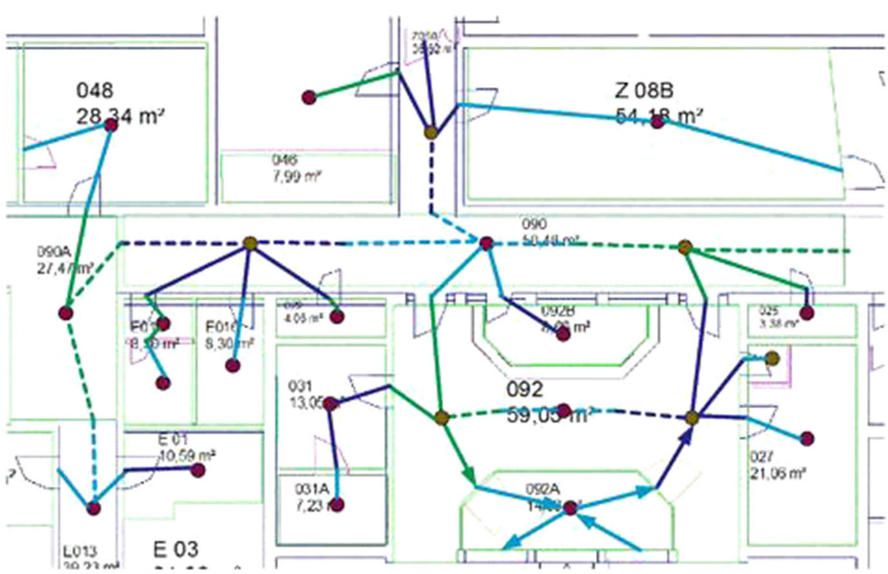


Fig. 2 Cell centers and paths overlaid with a floor Plan (Lorenz et al. 2006)

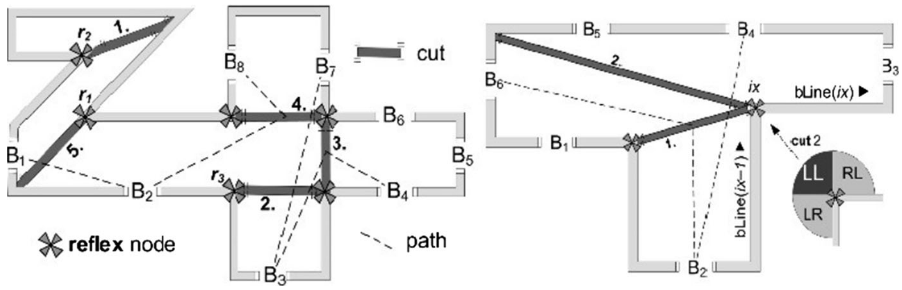


Fig. 3 Visibility criteria based partitioning result (Stoffel et al. 2007)

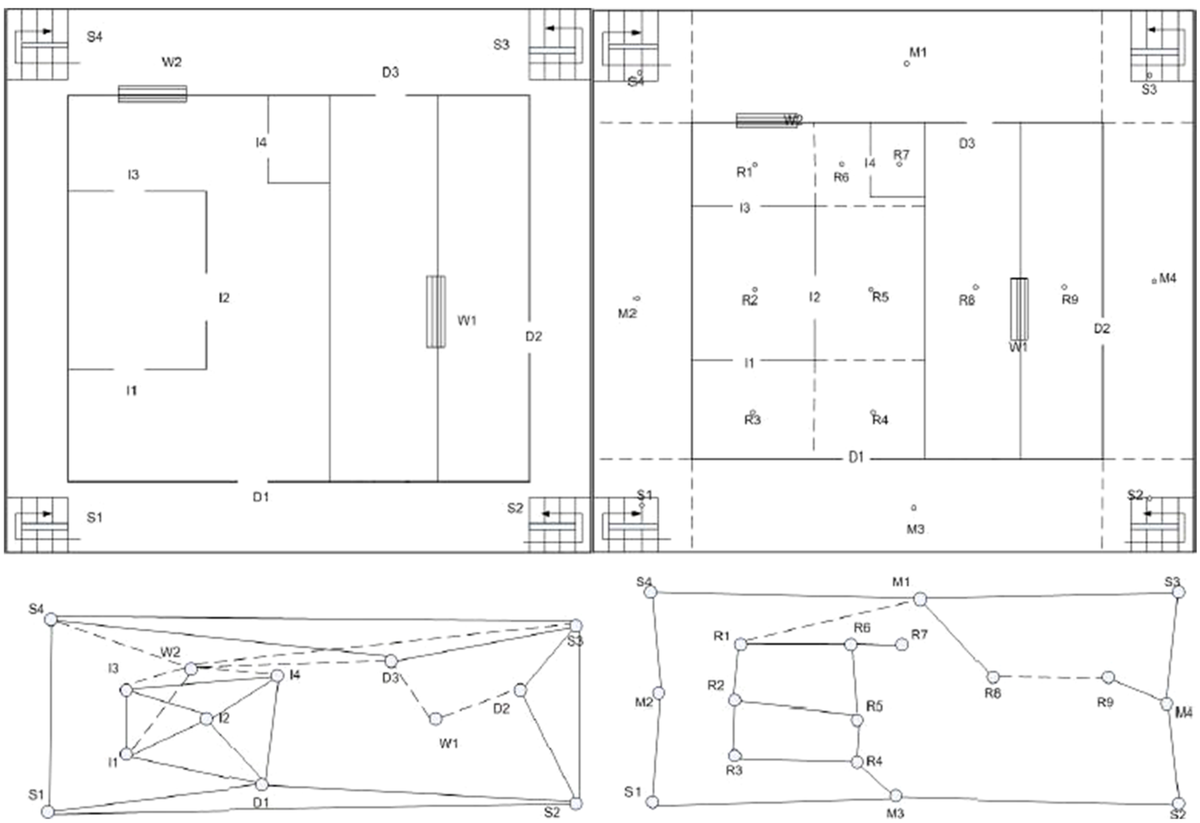


Fig. 4 Indoor visibility structure and conventional dual graph model (Liu and Zlatanova 2011b)

consideration (dual nodes are independent from primal graph). In this paper, an automated 3D modeling of topological indoor navigation network is presented. In this approach, surveyed benchmarks are considered as dual node and generated 3D building model is considered as primal graph. Indoor navigation network is modeled using surveying benchmarks which are connected based on Delaunay triangulation. As an application, shortest path between control points was estimated using Dijkstra algorithm.

Experimentation

Data collection

Currently a growing interest for indoor building surveying has been observed in geography information system (GIS) and building information modeling (BIM) research communities. The first group is interested in modelling existing building structures for emergency response and disaster management systems. Indoor building surveying is vital especially when other data sources such as paper plans and architecture models are not available. The second expert group is interested in models with 'as-built' conditions—construction plans are often different from the final constructed building and it is rare that appropriate plans are available to the builders. In this case, the buildings and its rooms must be surveyed to obtain the locations of walls, edges, corners and their relationship with adjacent spaces (i.e. rooms, corridors). Unfortunately many methods used for land surveying cannot be easily applied due to lack of Global positioning System (GPS) signal from satellites in indoor building environment, limited working area inside buildings especially in office space and very detailed environment with furniture and installations. Traditional land surveying often produces 2.5D models with each measuring point representing two-dimensional coordinates (i.e. X and Y), while the elevation of each point (*Z*) is stored as an attribute. There are three approaches that seemed to be suitable for indoor surveying including:

1. Laser scanning which is expensive, time consuming and requires considerable modelling effort in order to fit sections of the surveyed point clouds to basic features such as walls. This results in extensive manual work post-data collection and there is no any easy way to integrate individual scan results with the model of a complete complex building.
2. Traditional surveying with Total Station or equivalent is also possible, but conversion of captured data points into a building model is very complex.
3. A third approach, using a light rangefinder which integrates azimuth (from a digital compass) and inclination appears to be the most feasible for surveying indoor building environment, although it has a lower level of accuracy than Total Station and Laser Scanner based surveying approaches

Trimble LaserAce 1000 rangefinder was used as a surveying equipment to acquire data in indoor building environment which is based on point and shoot workflow. This rangefinder includes a pulsed laser distance meter and a compass, which can measure distance, horizontal angle and vertical angle up to 150 m without a target and up to 600 m with a reflective foil target. A rangefinder can be considered as a basic mobile Total Station with limited functionality and low accuracy (Jamali et al. 2013, 2014).

It has been assumed that geometry of rooms and corridors is not required to be as much accurate for this research. The presented 3D modeling of indoor navigation network is based on surveying control points. In order to establish surveying benchmarks as control points, closed traverse surveying was used which is a method in surveying for establishing control points along traveling or movement path. In closed traverse approach, surveying starts from one point with known coordinates and then ends at same point.

Indoor navigation network modeling

In the proposed indoor navigation network modeling, surveying benchmarks are considered as dual nodes while the generated 3D model as primal graph. Each room, corridor and benchmark has a specific ID which is referred as a primary key. Surveying benchmarks and building model are connected in accordance with their IDs, as shown in Fig. 5.

The indoor navigation network modeling consists of two main procedures—3D modeling and navigation networking as shown in Fig. 6. These procedures can be further explained in six steps as follows:

1. In the indoor navigation modeling, rooms and corridor coordinates are input as first step.

Geometry of each room and corridor constitutes at least eight vertices along with their x, y and z coordinate. These vertices for each room and corridor are read in this step as can be seen in Fig. 7.

2. In the second step, surveying benchmarks are input as control points as shown in Fig. 8. These surveying control points belonging to doors, elevators, stairs, rooms and corridor are considered as dual nodes.

3. In the third step, 3D modeling of indoor building environment is done based on input 3D coordinates of rooms and corridor as shown in Fig. 9.

In this research, 3D modeling is based on boundary representation of vertices and faces. Due to low accuracy of Trimble LaseAce 1000 rangefinder (Jamali et al. 2014), 3D geometrical building model is not as much accurate as gaps and intersections are found in between rooms and corridors, as can be seen in Fig. 9.

Fig. 5 Connection between surveying benchmarks and 3D building model based on their IDs

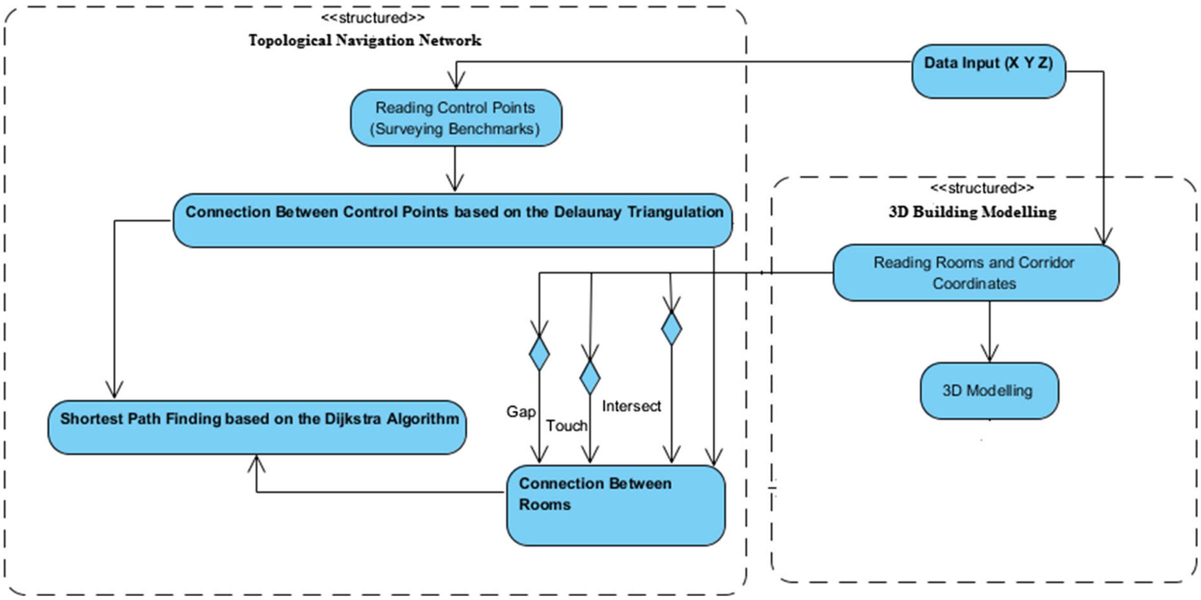


Fig. 6 Proposed indoor navigation network procedures

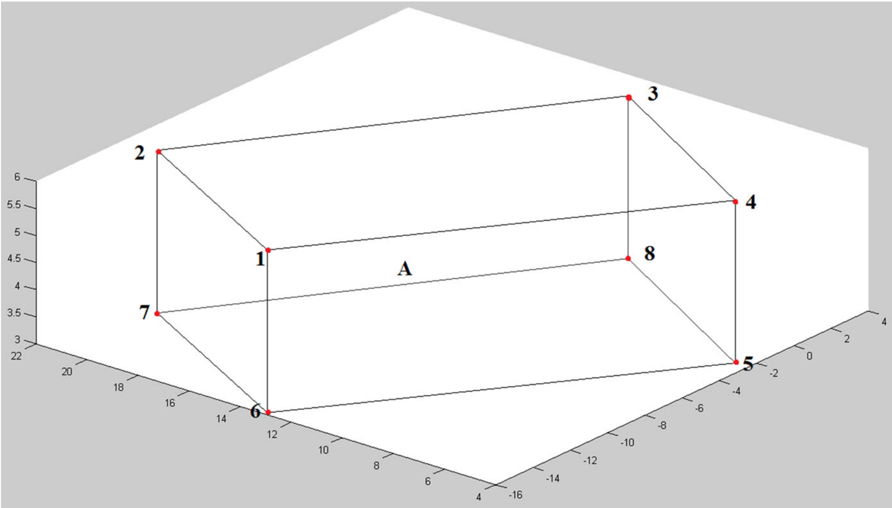


Fig. 7 A room block where vertices are represented as *red points*. (Color figure online)

4. In the fourth step, connection between control points is generated.

Topological connection between control points is generated using Delaunay triangulation method. The connection of control points using Delaunay triangulation facilities navigation and neighborhood queries along rooms and corridor network. There are three conditions for connecting control points. If there is one

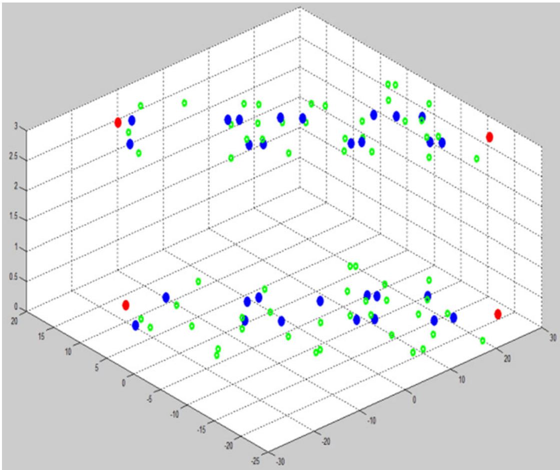


Fig. 8 Surveying control points as dual nodes: doors are represented as *blue points*, elevators as *red points* while room and corridor control points as *green points*. (Color figure online)

control point, then there will be no connection. If there are two control points, then there will be one connection between the control points. In case of three or more control points, connection is made using Delaunay triangulation method as shown in Fig. 10.

5. In the fifth step, connection between rooms is generated.

In order to build connection, three different scenarios i.e. gap, intersect and touch are considered. Connection between rooms has been considered as it is important for various applications such as disaster management and safety analysis, for example, if there is a need to break walls between two rooms. Due to low accuracy of laser rangefinder, the modeled shape of building might be inaccurate, therefore, two adjacent rooms might intersect each other, there might be a gap between them and in the best scenario they might touch each other. These connections in between rooms have been described as follows:

1. Intersection

In the first step, intersection between two adjacent cells (A and B) (see Fig. 11), is found by checking sematic information of two adjacent cells. Each control point has semantic information including room number and control point ID which allows the recognition of its neighborhood. In the second step, intersection between two adjacent cells A and B is found by estimating intersection points in between overlapping edges.

2. Gap

For finding gap between two cells (A and B), distance between the vertices of cell A and cell B is calculated Eq. (1).

$$D = \sqrt{(X_i - X_j)^2 + (Y_i - Y)^2 + (Z_i - Z_j)^2} \quad (1)$$

where X_i, Y_i and Z_i are coordinates of *i* vertices in cell A, X_j, Y_j and Z_j are coordinates of *j* vertices in cell B.

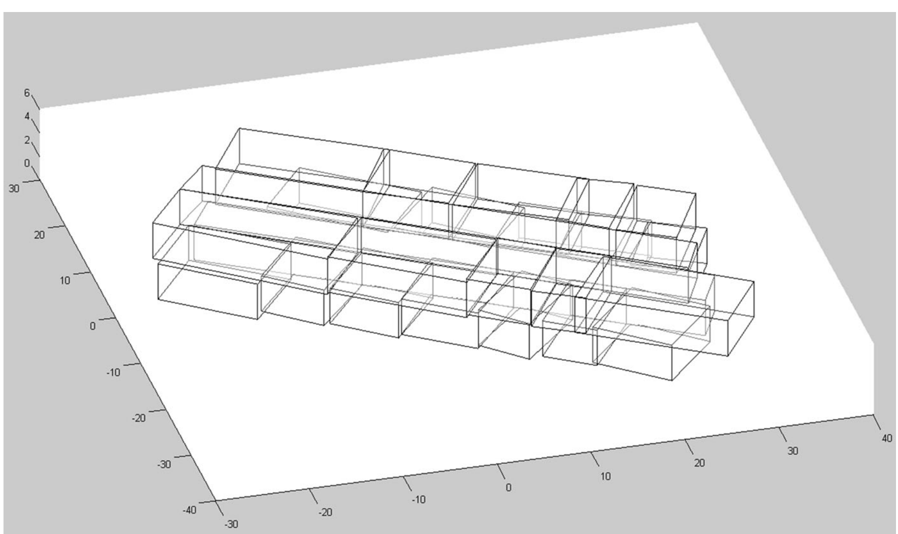


Fig. 9 3D Building modeling with two floors using Trimble LaserAce 1000 rangefinder

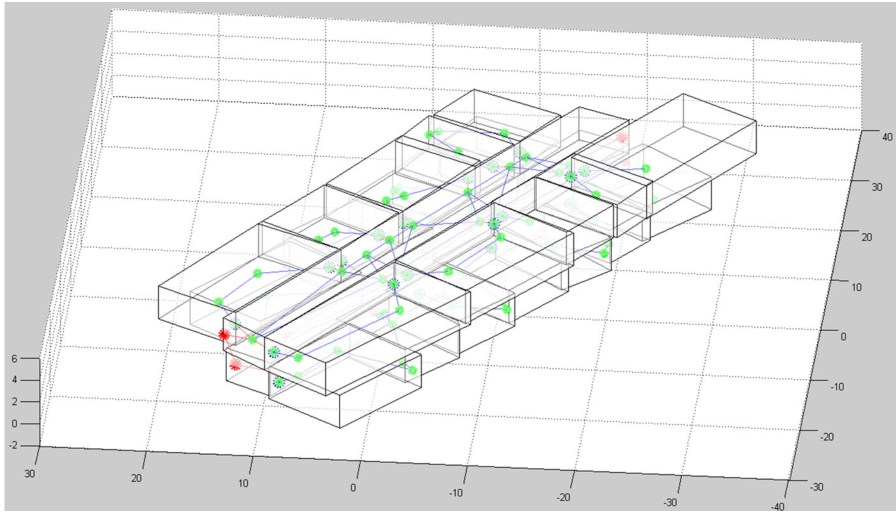


Fig. 10 Connection between three or more control points (*green points*) using Delaunay triangulation (*blue lines*). (Color figure online)

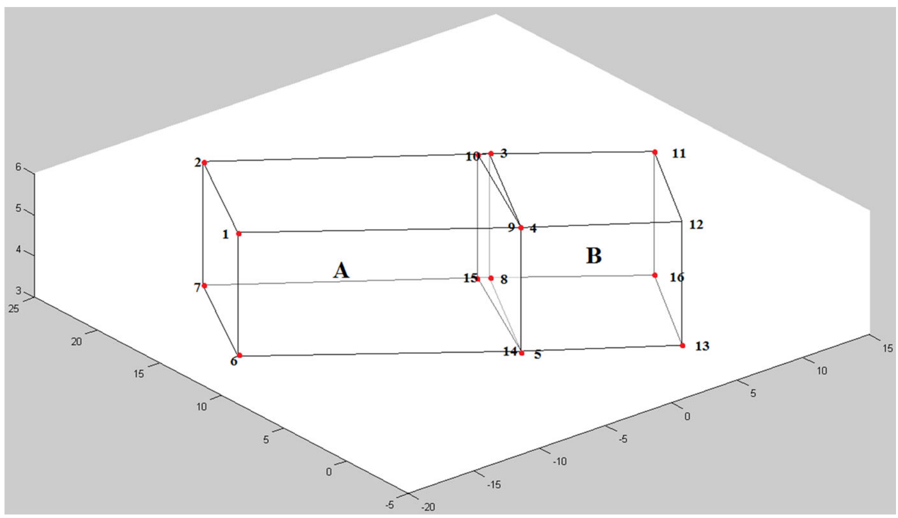


Fig. 11 Intersection between cells A and B

For finding gap between two cells (A and B), a distance tolerance is defined. This tolerance value is empirically estimated as 1 m. If the two cells do not intersect each other but their distance is less than the defined tolerance, two cells are neighbors but they have gap between them (see Fig. 12).

3. Touch

If the distance between two cells (A and B) is equal to zero then they touch each other (see Fig. 13).

Figure 14 shows connection between adjacent cells (rooms).

6. In the sixth step, shortest path between control points is calculated.

In order to find shortest path between nodes in a graph, Dijkstra algorithm (Dijkstra 1959) is implemented. For an assigned source dual node, Dijkstra algorithm finds shortest path to any exits in the building (exit nodes can be known or unknown). An exit can be in any cell in a 3D building model, but usually it is a door connecting interior of a building to its exterior. Dijkstra algorithm calculates shortest path by estimating geometrical distance between dual nodes (see Fig. 15). Different weights are assigned to dual nodes, for example, connection in between two adjacent rooms through wall or doors would have different weights.

A building consists of several connected parts i.e. rooms, corridors, office, storage space which are

Fig. 12 Gap between cells A and B

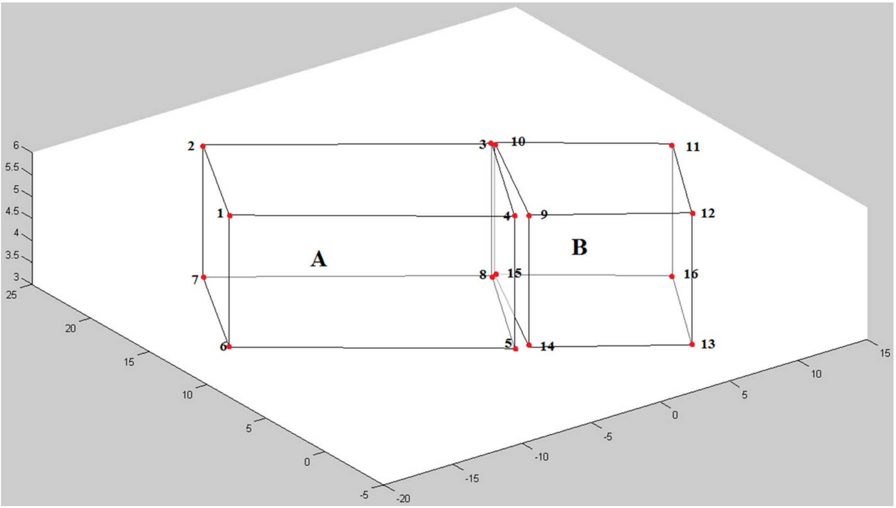
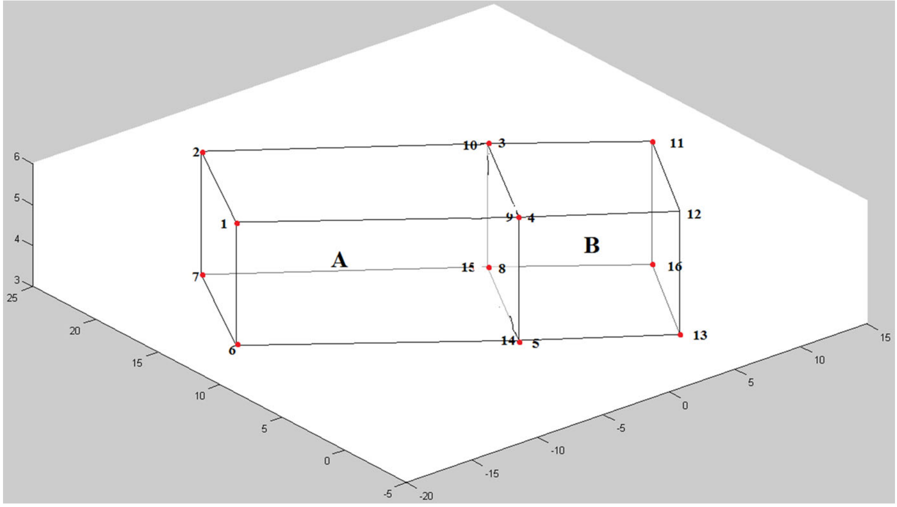


Fig. 13 Touch between cells A and B



represented as primal cells. Topological connection between rooms can be modelled with dual edges connecting adjacent rooms. Moving from one room to another room is possible by doors. Doors can be represented by a cell with/without volumes with their specific attributes. According to Boguslawski et al. (2011), two approaches can be utilized for representing doors as follows:

1. Wall as a cell

In this approach, rooms along with doors, walls, windows and other installations are separately represented ascells with volumes.

2. Wall as part of a cell

In this approach, only rooms are considered as cells with volumes. Other objects including doors, walls and windows are considered as faces without volumes. Adjacent rooms are connected directly- there is no wall between two adjacent rooms. In this particular research, we consider walls as part of rooms (wall's thickness was added to room's thickness).

Result evaluation and performance analysis

The indoor navigation network result was evaluated with the network model generated using an accurate dataset. This accurate data of indoor building

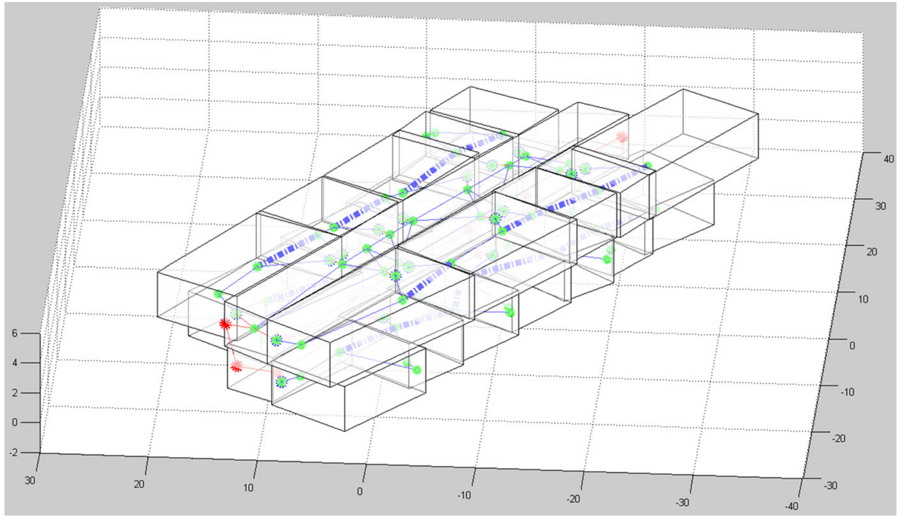


Fig. 14 Connection between adjacent rooms are represented as *blue dash lines*. (Color figure online)

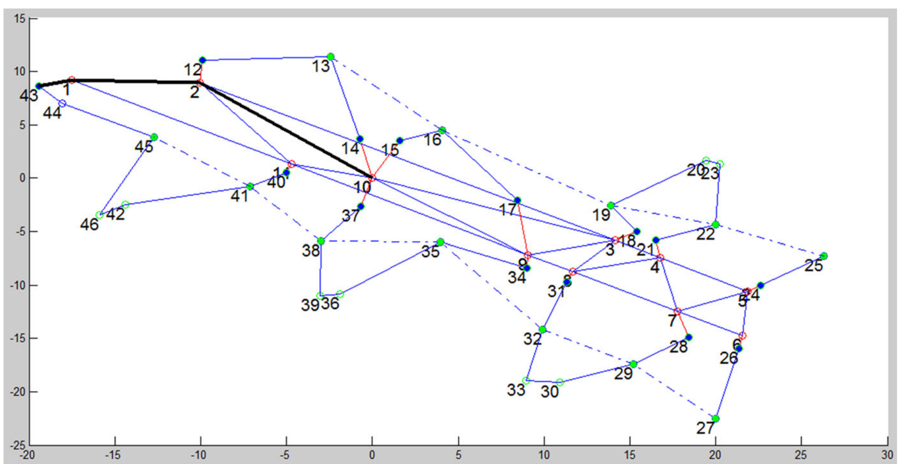


Fig. 15 Dijkstra algorithm finds shortest path between control points

environment was acquired using Trimble M3 total station which led to the generation of 3D building model without any gap between cells (i.e. rooms and corridor) as can be seen in Fig. 16.

In accordance with the device specifications, the accuracies of the Trimble M3 total station and Trimble LaserAce 1000 rangefinder are shown in Table 1.

The topological indoor navigation network models generated using Trimble LaserAce 1000 rangefinder and Trimble M3 total station are shown in Fig. 17.

The presented indoor topological navigation network is fully automated and does not require user interaction in any form. The time required for 3D building modeling and topological indoor navigation network generation is around one second. This 3D modeling was performed on a computer with i7 core@ 3.4 GHz processor, 8 GB RAM and 64-bit operating system. A Graphical User Interface (GUI) has also been developed using MATLAB computing language as shown in Fig. 18.

The presented topological modeling uses semantic and geometrical information and does not require an accurate geometric model. It can be proposed that the navigation network in indoor building environment can also be generated using less accurate and cheap surveying instrument such as Trimble LaserAce 1000 rangefinder.

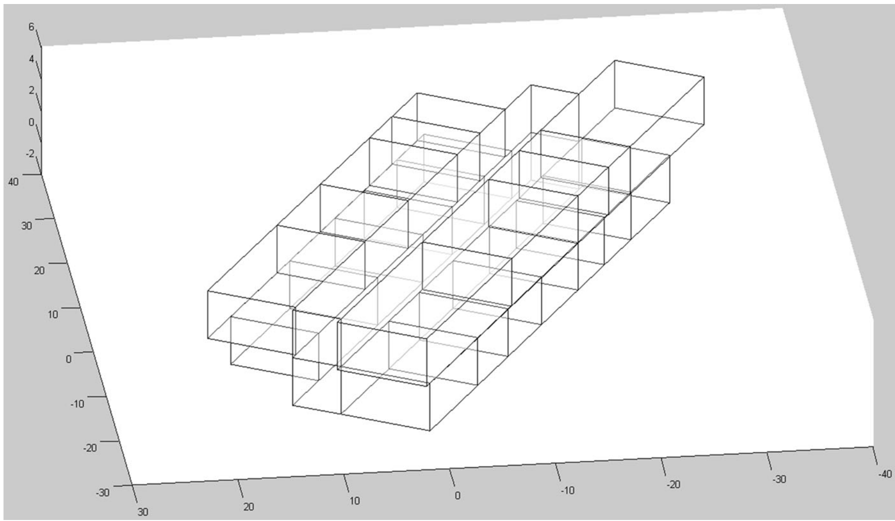


Fig. 16 3D building modeling using Trimble M3 total station

Table 1 Accuracy of Trimble M3 total station and Trimble LaserAce 1000 rangefinder according to the product specifications

Surveying equipment	Distance accuracy	Horizontal angle accuracy	Vertical angle accuracy
Trimble M3 total station	±3 mm ±2 ppm	2″	2″
Trimble LaserAce 1000 rangefinder	±100 mm	7200″	720″

Contributions and novelty

The proposed method in this research comprises surveying processes and computer science methodologies. In this study, the researchers proposed a methodology for an automated modelling of 3D topological indoor navigation network using data acquired with laser rangefinder. The proposed technique can be used for modelling of basic indoor environment however; it does not produce satisfactorily results to model buildings that have complex indoor environment. Indoor surveying is currently based on laser scanning, which is time and resource consuming. A model construction is based on complex algorithms which have to deal with a huge number of measured points. This is suitable for very detailed geometrical models used for visualization, but too exaggerated when a simple model (including walls, floors, ceilings, doors, and windows) is required—such a simple model is essential for efficient analysis. New methods investigated in this research can help to find a rapid method of indoor surveying and model construction. Resulting models include topology of the interior and has less detailed information about irrelevant objects; therefore, they are suitable for analysis such as emergency rescue studies.

Proposed method of indoor surveying is rapid (shorter time compared to Total Station and Terrestrial Laser Scanner). Proposed method decreases cost for acquiring indoor data and model reconstruction (a simple model with less details). Building management/information systems, emergency management systems, cadastre/Land Administration Domain Model (LADM) and architectural planning are some fields which can use our proposed method of surveying. Less dependency of navigation network modeling from geometry of building is another contribution of this research.

Conclusion and future research

In this paper, an automated 3D modeling of indoor navigation network has been presented. Trimble

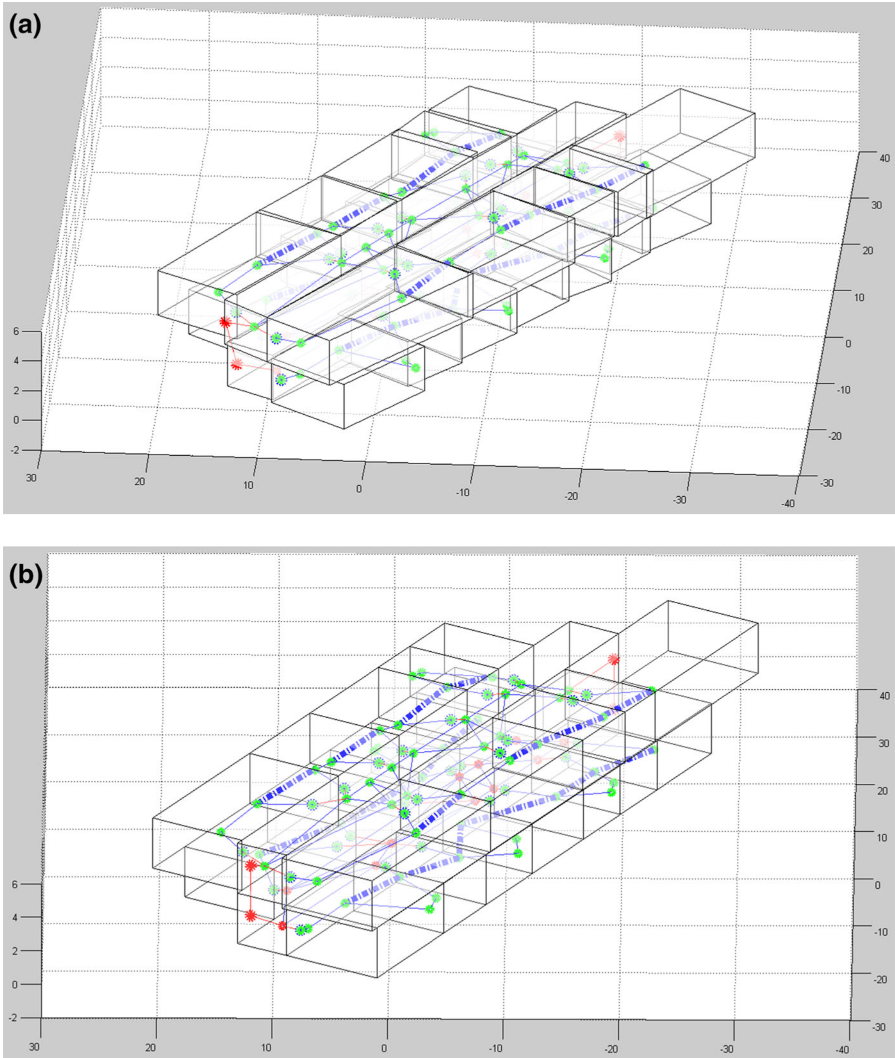


Fig. 17 Topological indoor navigation network model generated using **a** Trimble LaserAce 1000 rangefinder and **b** Trimble M3 total station

LaserAce 1000 rangefinder was used to acquire datasets in indoor building environment which are usually not as much accurate. In the presented indoor navigation network modeling, there is not any requirement of accurate geometry as the model is based on surveying benchmarks. The indoor navigation network model includes two main procedures i.e. 3D building modeling and topological navigation networking. The connection between surveying benchmarks was established using Delaunay triangulation.

Shortest path between the surveying benchmarks was estimated using Dijkstra algorithm. This research shows that indoor navigation network modeling does not require accurate shapes of rooms and corridors. Inaccurate 3D models and inconsistency in Horizontal angle for short distances are drawbacks of this particular method. In order to get more accurate geometrical model, the laser rangefinder is required to be in the center of a room or corridor to avoid narrow and wide angles. Researchers of this study intend to investigate object reconstruction from calibration of rangefinder using interval analysis and homotopy continuation in the near future.

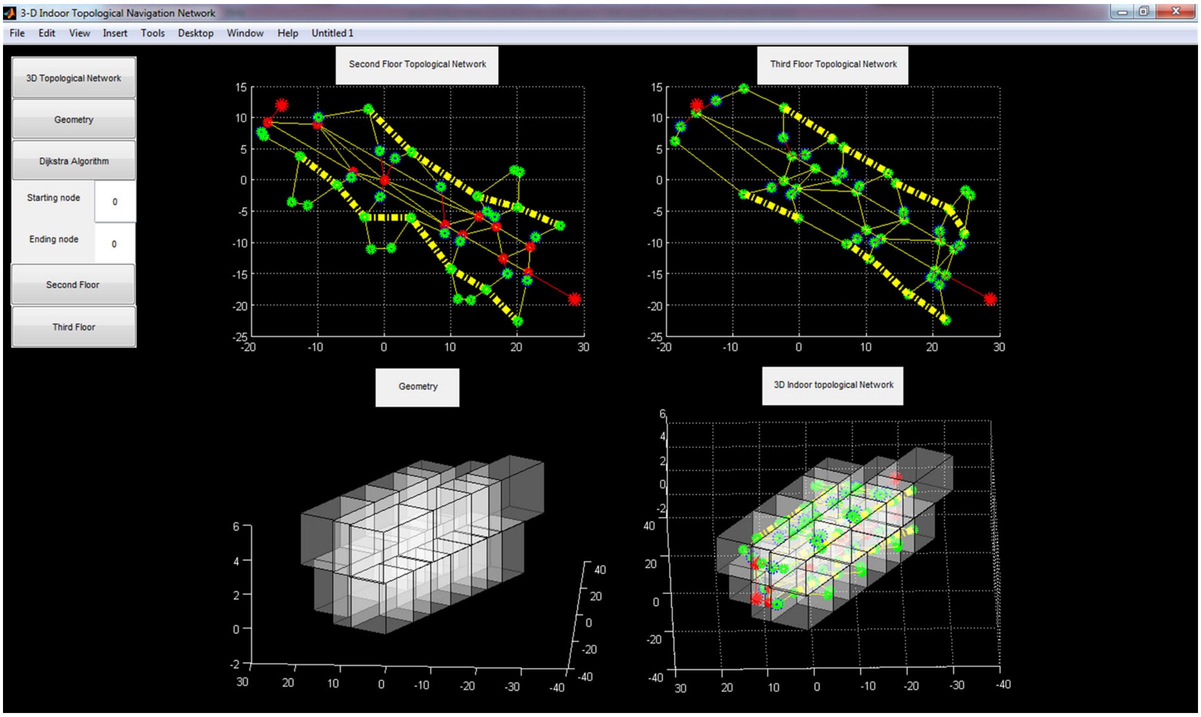


Fig. 18 Developed GUI of topological indoor navigation network model

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