3D INDOOR TOPOLOGICAL MODELLING BASED ON HOMOTOPY CONTINUATION

ALI JAMALI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctoral of Philosophy (Geoinformatics)

Faculty of Geoinformation and Real Estate
Universiti Teknologi Malaysia

SEPTEMBER 2017

To my beloved parents and siblings

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Professor Dr. Alias Abdul Rahman, for guidance and critics. I am also very thankful to my co-supervisors Dr. Pawel Boguslawski and Professor. Dr. Francois Anton for their guidance and motivation. And the last but not the least my father Dr. Alireza Jamali for his guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

My fellow postgraduate students should also be recognized for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family members.

ABSTRACT

Indoor navigation is important for various applications such as disaster management, building modelling and safety analysis. In the last decade, the indoor environment has been a focus of extensive research that includes the development of indoor data acquisition techniques, three-dimensional (3D) data modelling and indoor navigation. 3D indoor navigation modelling requires a valid 3D geometrical model that can be represented as a cell complex: a model without any gap or intersection such that the two cells, a room and corridor, should perfectly touch each other. This research is to develop a method for 3D topological modelling of an indoor navigation network using a geometrical model of an indoor building environment. To reduce the time and cost of the surveying process, a low-cost non-contact range-based surveying technique was used to acquire indoor building data. This technique is rapid as it requires a shorter time than others, but the results show inconsistencies in the horizontal angles for short distances in indoor environments. The rangefinder was calibrated using the least squares adjustment and a polynomial kernel. A method of combined interval analysis and homotopy continuation was developed to model the uncertainty level and minimize error of the non-contact range-based surveying techniques used in an indoor building environment. Finally, a method of 3D indoor topological building modelling was developed as a base for building models which include 3D geometry, topology and semantic information. The developed methods in this research can locate a low-cost, efficient and affordable procedure for developing a disaster management system in the near-future.

ABSTRAK

Navigasi dalam bangunan sangat penting bagi pelbagai aplikasi seperti pengurusan bencana, permodelan bangunan dan analisis keselamatan. Sedekad lalu, persekitaran dalam bangunan telah menjadi fokus keseluruhan kajian termasuklah pembangunan teknik-teknik pengumpulan data, model tiga-dimensi (3D) dan navigasi dalam bangunan. Pemodelan 3D navigasi dalaman memerlukan model geometri 3D yang sah dipamerkan sebagai sel komplek: satu model tanpa jurang atau pertindihan seperti dua sel, satu bilik dan koridor, harus saling bersentuhan dengan sempurna. Kajian ini dijalankan bagi membangunkan satu kaedah pemodelan topologi 3D dalam jaringan navigasi dalaman menggunakan persekitaran model geometri bangunan. Bagi mengurangkan masa dan kos proses pengukuran, satu teknik pengukuran kos rendah, tidak bersentuhan berdasarkan jarak telah digunakan bagi mendapatkan data dalaman bangunan. Ketepatan alat tersebut telah dinilai dan model spatial dilakarkan semula menggunakan data sebenar. Teknik pantas ini memerlukan masa yang singkat berbanding teknik lain, tetapi memberikan hasil tidak konsisten pada sudut-sudut mendatar bagi jarak-jarak dekat dalam persekitaran dalaman bangunan. Alat pencari jarak ini telah dikalibrasi menggunakan pelarasan kuasa dua terkecil dan polinomial kernel. Satu gabungan kaedah analisis selang dan kesinambungan homotopy telah dibangunkan untuk pemodelan tahap ketidakpastian dan pengurangan ralat dari teknik-teknik pengukuran tidak bersentuhan berdasarkan jarak pada persekitaran dalaman bangunan. Dan akhir sekali, satu kaedah pemodelan topologi 3D dalaman bangunan telah dihasilkan sebagai satu asas model-model bangunan termasuklah geometri 3D, topologi dan maklumat semantik. Teknik-teknik yang telah dibangunkan dalam kajian ini dapat mengenalpasti prosedur-prosedur kos rendah, cekap dan berpatutan bagi membangunkan satu sistem pengurusan bencana pada masa hadapan.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. Background

3D spatial modelling involves the definition of spatial objects, data models, and attributes for visualization, interoperability and standards (Chen et al., 2008). Due to the complexity of the real world, 3D spatial modelling leads towards different approaches in different Geography Information Science (GIS) applications (Haala and Kada, 2010). In the last decade, there has been huge demand for 3D GIS due to the drastic advances in the field of 3D computer graphics. According to Chen et al. (2008), there is no universal 3D spatial model that can be used and shared between different applications, and different disciplines according to their input and output have used different spatial data models.

3D building modelling is an example of 3D spatial modelling. A building model has three spaces, including geometrical, topological and semantic space. This research focuses on topological space, which is important for network analysis (e.g. shortest path finding). A topological model which is derived from a geometrical model defines the relationship between adjacent objects (e.g. rooms). A topological model is defined by a graph which is a navigable network consisting of nodes and edges. Semantic space presents attributes attached to geometrical and topological models.

According to Donath and Thurow (2007), considering various fields of applications for building modelling and various demands, the geometric representation of a building is the most crucial aspect of building modelling. In previous research works such as Becker et al. (2009) and Liu and Zlatanova (2012), 3D modelling of buildings and their relationships (i.e. topological models) with the surrounding roads and terrain were provided, but their utility is limited in many cases of navigation and emergency planning (i.e. only the exteriors of the buildings were analyzed). For many kinds of emergency response, such as fire, smoke, and pollution, the interiors of the buildings need to be described along with the relative locations of the rooms, corridors, doors and exits, as well as their relationships to adjacent spaces. The relationship between adjacent spaces needs to be defined in a topological model.

Topological modelling is a challenging task in GIS environment, as the data structures required to express these relationships are particularly difficult to be developed. Even within the recent CityGML research community, the structures for expressing the relationships between adjacent objects (i.e. topology) are complex and often incomplete (Li and Lee, 2013; Kim et al., 2014).

A 3D topological model is necessary for disaster management models in network analysis. Network analysis is one of the most significant aspects of GIS (Curtin, 2007). Network analysis is used in disciplines such as medicine (Finnvold, 2006), psychology (Walker et al., 2006), urban planning (Toccolini et al., 2006), and computer science (Bera and Claramunt, 2005). There are two data structures in network analysis: non-topological and topological networks. A non-topological structure (i.e. the “spaghetti” data model) does not contain any topological information related to edges.

Non-topological network models are simple to understand and they are sufficient for digital cartographic maps. The spaghetti data model is widely used in Computer Aided Design (CAD) communities due to its simplicity. Duplication of storage for the same vertices is one of the disadvantages of the spaghetti data model. Non-topological network models are useless for network analysis. The shapefile developed by the Environmental Systems Research Institute (ESRI) is another example of a non-topological network data structure which is insufficient for network analysis (Curtin, 2007). Dual Incidence Matrix Encoding (DIME) (Cooke, 1998) and Topologically Integrated Geographic Encoding and Referencing (TIGER) are examples of topological data structures. One of the biggest issues with topological network data structures is the definition of bridges or tunnels.

For network analysis, this research focuses on indoor building network modelling. Different methods have been used for indoor building network modelling (Li et al., 2010; Goetz and Zipf, 2011), which are mostly based on the 2D floor plan or simple 3D models of buildings. The Geometric Network Model (GNM) has been widely accepted as a 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 the 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 the generation of a GNM from 3D imaging and scanning technologies. Indoor navigation network models including the GNM, Navigable Space Model, sub-division model and regular-grid model lack indoor data sources and abstraction methods.

To generate an indoor network model, a geometrical model is required. Currently there is growing interest in 3D topological modelling in GIS and Building Information Modeling (BIM) expert communities. The GIS group is interested in models of existing buildings for analysis in cases of emergency or disaster management systems (Liu and Zlatanova, 2012). Indoor surveying is vital when no other data sources are available (e.g. there are no paper plans or architectural models). Even if this kind of data is provided, BIM expert group is interested in models with 'as-built' conditions (construction plans are often different from the final building and it is rare that appropriate plans are available to the model builder (Tang et al., 2010; Volk et al., 2014). In this case, the buildings and their rooms must be surveyed in three dimensions to obtain the locations of walls, edges and corners, as well as their relationships to adjacent spaces (i.e. a topological model).

This research is to demonstrate the feasibility of interior surveying for navigable network modelling. The proposed approach uses relatively cheap equipment: a light laser rangefinder appears to be the most feasible, but it needs to be tested to see if the observation accuracy is sufficient for the intended purpose: the construction of a topological indoor building network model. There are three main issues which this research is intended to investigate as follows:

a. Indoor building data collection

Indoor building data collection is currently based on laser scanning technology which is costly and time consuming. This research uses a low-cost non-contact range-based surveying technique alongside a Total Station and Laser Scanner.

b. Uncertainty modelling

Uncertainty modelling is currently based on statistical methods such as least squares which topology is not concerned. In this research, a novel method of combined interval analysis and homotopy continuation is developed. The least squares methods assume a linear statistical model of propagation of the errors and a normal probability distribution function of the measurements. However, in any real measurement experiment, it can be observed that no probability distribution function fits the data set to any desired degree of accuracy.

c. Indoor building navigation network modelling

There are four main navigable network models including dual graph model, navigable space model, sub-division model and regular-grid model, each of which has several drawbacks and requires a precise geometrical model. This research uses an imprecise and precise geometrical model to develop a topological navigable network model.

1.2. Problem Statements

For many kinds of systems like disaster or emergency management systems, interior models are essential (Boguslawski et al., 2011; Liu and Zlatanova, 2012). Indoor models can be reconstructed from construction plans, but they are sometimes unavailable or very often they differ from the 'as-built' plans. In this case, the buildings and their rooms must be surveyed. Unfortunately, many methods used for land surveying cannot be easily applied because of, to name a few: the lack of a Global Positioning System (GPS) signal from satellites in indoor environments; the limited working area inside buildings especially in office space; the very detailed environment with furniture and installations. There are four approaches that seem to be suitable for indoor building surveying:

A. Laser scanning technology

a construction model depends on complex calculations which need to manage many measured points. This is suitable for the detailed geometrical models utilized for representation, yet excessively overstated when a simple model including walls, floors, roofs, entryways, and windows are required; such a basic model being a key for efficient network analysis such as shortest path finding. Laser scanning requires considerable modelling effort to fit sections of the resulting point cloud to basic features such as walls, resulting in extensive manual work after data collection and no easy way to integrate individual scan results with the model of a complete complex building (Dongzhen et al., 2009; Yusuf, 2007).

B. Traditional surveying with a Total Station

A Total Station or equivalent is also possible, but conversion of captured data points into a building model requires complex procedures and so far, limited availability of the software or tools for topological modelling as one of current challenges in 3D GIS community (Anton, 2017; Boguslawski, 2016; Abdul Rahman, 2016). The important disadvantage of traditional Total Station mapping is the enormous amount of work required to study vast regions, with the station administrator usually required to set up and work from several datums, while a second person must constantly move to reset a reflector rod, which causes communication difficulties between the two (Kvamme et al., 2006).

C. A light laser rangefinder

A rangefinder which integrates azimuth (from a digital compass) and inclination along with the laser rangefinder appears to be the most feasible, although it has a lower level of accuracy than the Total Station.

D. Photogrammetry technique

Photogrammetry technique uses uncalibrated non-metric cameras to extract 3D information from a scene of images. For indoor surveying, it is as simple as taking pictures. Additionally, images can be used for texture extraction – textures can be attached to walls, floors, and ceilings in the model, which will increase the realism of the visualization.

In most researches, building models contain exteriors while their interiors are not taken into consideration – interiors are more difficult to measure and the models are more complex (Deak et al., 2012). Based on the literature reviews (e.g. Liu and Zlatanova, 2012; Boguslawski et al., 2011; Luo et al., 2014, and Kim et al., 2014), 3D indoor navigation modelling requires a precise 3D geometrical model that can be represented as a cell complex: a model without any gap or intersection such that two cells such as rooms and corridor perfectly touch each other. GIS integrates spatial information and spatial analysis. An important example of the integration of spatial information and spatial analysis is an emergency response, which requires route planning inside and outside a building. Route planning requires detailed information related to the indoor and outdoor environment (Teo and Cho,2016).

Indoor navigation network models including dual graph model, navigable space model, sub-division model and regular-grid model lack indoor data sources and abstraction methods. For indoor navigation, Geometric Network Model (GNM) is extensively used due to its simplicity. GNM models are mostly extracted from 2D plans and the extracted indoor network information is coarse. GNM models do not contain accurate indoor information and they are complex and time-consuming (Teo and Cho, 2016).

Generation of a 3D indoor network model is a labour-intensive process and it becomes worse if some nodes require extra information (Teo and Cho, 2016). 3D buildings require new data information sources as they change over time. Data information sources generated by Computer Aided Design systems are not useful for detailed indoor applications as they only roughly approximate indoor building entities. According to Vanclooster and Maeyer (2012), indoor navigation communities focus only on the technological aspects of indoor navigation (Mautz and Tilch., 2011) or on the generation of the indoor data structure (Lee and Kwan, 2005; Lorenz et al., 2006).

This research intends to investigate and develop a method of topological navigation network modelling with a less accurate geometrical model. The methods investigated in this research can help to find a rapid and low-cost method of indoor surveying and model construction. The resulting models include the topology of the interior and have less detailed information about irrelevant objects; therefore, they are suitable for analysis such as emergency rescue studies.

An indoor building navigable network model is developed as a base for models which include the 3D geometry, topology and semantic information. Further model development will take the latest theory on 3D indoor navigation into consideration. The hypothesis is: a rangefinder with a digital compass and inclinometer is sufficient to obtain the indoor topology of a 3D building.

1.3. Research Questions

i. What are the the issues encountered with the current non-contact range-based indoor building data collection?

   a) Are the current non-contact range-based surveying techniques including TLS and total station suffiecient for indoor building data collection?

ii. How to model the uncertainty level of a non-contact range-based surveying equipment in an indoor building environment?

   a) How linear and non-linear statistical methods including least square adjustment and polynomial kernel model the uncertainty level of a non-contact range-based surveying equipment in an indoor building environment?

   b) How linear and non-linear mathematical methods including interval analysis and homotopy continuation model the uncertainty level of a non-contact range-based surveying equipment in an indoor building environment?

iii. How to model an indoor building navigation network?

   a) Are the current GNM models icluding the dual graph model, navigable space model, sub-division model and regular-grid model sufficient for representation of indoor navigation modelling?

   b) How are the geometry and topology defined for 3D navigation network modelling?

   c) How can indoor building topology be used for navigable network reconstruction?

1.4. Research Aims

According to the problem statements, this research aims to propose a non-contact range-based surveying technique to develop a topological indoor navigable network model from precise and imprecise geometrical model. A novel method of combined interval analysis and homotopy continuation is developed to model the uncertainty level and to minimize error of the non-contact range-based surveying techniques used in an indoor building environment. A precise geometrical model is reconstructed by merging of imprecise geometrical model features with defined six topological rules.

1.5.Objectives

i. To propose a cheap and rapid non-contact range-based surveying technique.
ii. To develop a novel method of combined interval analysis and homotopy continuation to minimize error of the proposed non-contact range-based surveying technique.
iii. To develop a topological indoor building navigation network from precise and imprecise geometrical models constructed from the proposed non-contact range-based surveying technique.

1.6. Scope of Research

The goal of this research is to investigate the complexity of interior building modelling and to develop a topological indoor navigation network model. Besides laser scanning technologies such as the Leica ScanStation C10 and Faro Photon 120/20 used for range-based indoor surveying, a cheap laser rangefinder with a digital compass, Trimble LaserAce 1000 was used. There are several linear and non-linear statistical and mathematical methods to model the uncertainty level of surveying equipment, but due to the huge diversity and limitation of scope of this research, a few methods such as least squares adjustment, polynomial kernels, interval analysis and homotopy continuation have been researched. Precise and imprecise models are used to reconstruct a topological navigation network, which is tested for path-finding in a building.

1.7.Research Approach

This research is designed according to the “Design Science Research Methodology” (Henver et al., 2004). This research consists of five main phases: conceptual, design, development, evaluation and communication, as follows:

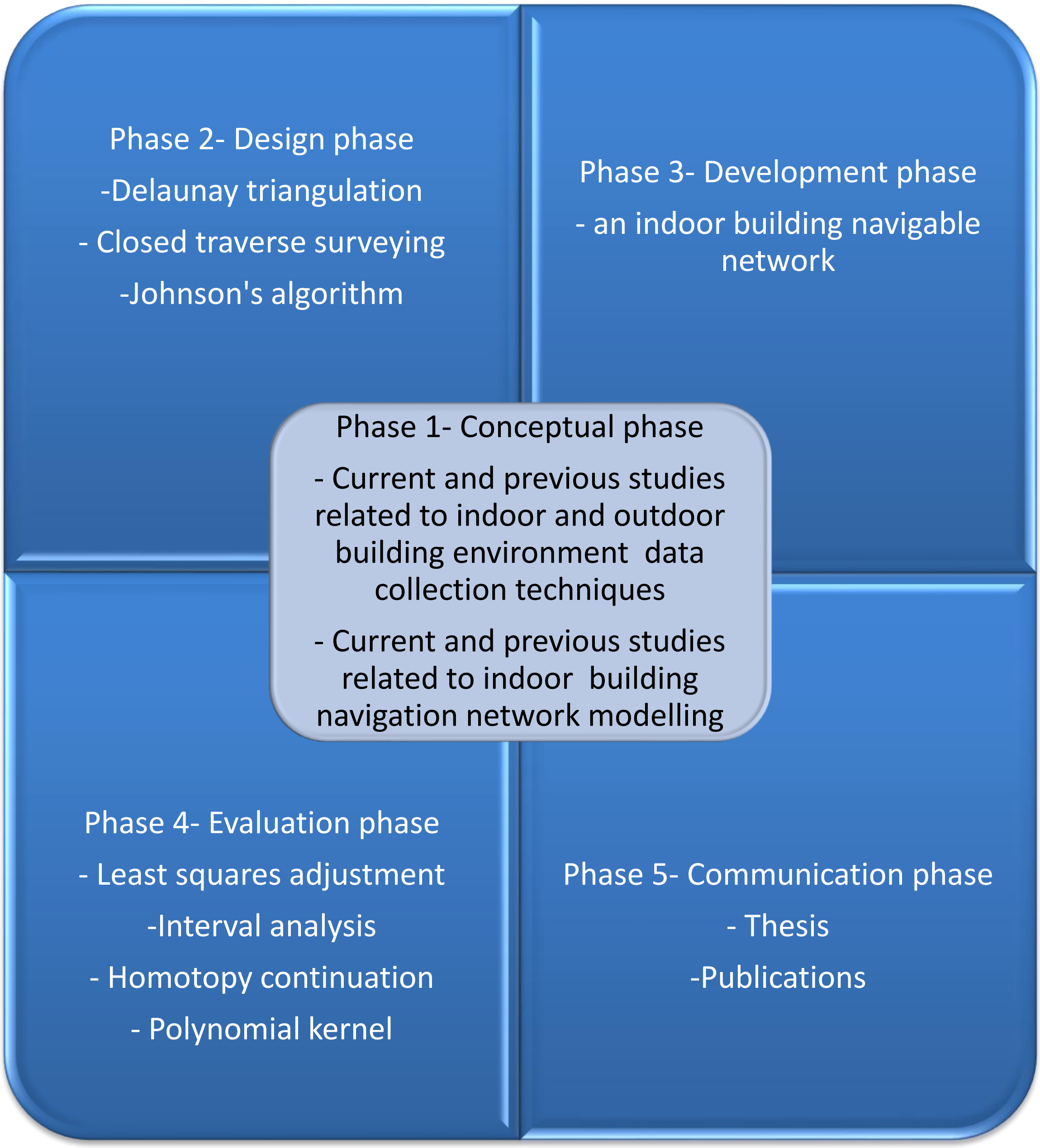

Figure 1.2 Research approach

1.7.1. Conceptual Phase

The conceptual phase includes a literature review of both current indoor building surveying techniques and indoor navigation network modelling, and developing the conceptual framework for the research, case study, and data collection techniques.

In chapter 2, different 3D building data collection techniques including photogrammetry, land surveying and laser scanning technologies are discussed. In chapter 3, current methods of navigation network modelling based on the graph duality concept, navigable space, regular-grid model and sub-division are discussed.

1.7.2. Design Phase

The design phase includes the design of the framework to develop a method of topological navigation network modelling in an indoor building environment. In this phase, in accordance with the knowledge acquired during the conceptual phase, different theories and methods are adopted. Closed traverse surveying as the surveying method and Delaunay triangulation as the connectivity of surveying control points, and Johnson's algorithm as the shortest path finding algorithm are selected in this phase.

1.7.3. Development Phase

The development phase includes implementation of the framework for a topological navigation network model. An indoor building navigation network model is proposed as a base for models which include the 3D geometry, topology and semantic information. A further model development will take the latest theory on 3D indoor navigation into consideration.

1.7.4. Evaluation Phase

The evaluation phase includes demonstration of the framework using a case study, framework verification and validation. Model verification and validation are vital for any simulation model and they present the usefulness of the proposed system. Verification presents the completeness of the model and degree of validation of the correctness of the model. In this research, cross-validation (comparison to alternative models) was used as the validation method.

1.7.5. Synthesis and Communication Phase

The synthesis and communication phase includes the findings of the research, documenting the conclusions, recommendations and future research. The final phase covers outputs including the results and publications.

1.8. Thesis Structure

This thesis is structured in seven chapters as follows:

Chapter 1 delivers the introduction and background of 3D geometrical and topological modelling, indoor navigation network modelling. The problem statements, research questions, aims and scope of this research are discussed and formalized.

In Chapter 2, 3D building data collection techniques and 3D spatial modelling are discussed. Laser scanning technology including Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS) and Aerial Laser Scanning (ALS) is reviewed. CityGML, Building Information Model (BIM) and Dual Half Edge (DHE) are discussed.

Topological and geometrical indoor navigation network modelling is discussed in Chapter 3. Graph, network analysis as a base for the shortest path finding is discussed. Indoor navigation network models including GNM, the navigable space model, sub-division model and regular-grid model are reviewed.

In Chapter 4, a method of cheap and rapid indoor building surveying is proposed. The Faro Photon 120/20, Leica ScanStation C10, Leica 307 TCR and Trimble total station M3 are used for 3D building data collection and to validate the results of the rangefinder.

To model the uncertainty level of the proposed surveying method, several statistical and mathematical analyses including least squares adjustment, polynomial kernels, interval analysis and homotopy continuation are discussed in Chapter 5. The rangefinder's horizontal angle sensor was calibrated using a least squares adjustment algorithm, a polynomial kernel, and novel method of interval valued homotopies. All these methods provide mathematical or statistical models for the inaccuracies of the measurements by the magnetometer.

In Chapter 6, an indoor building navigation network model is proposed and implemented. Johnson's algorithm was used to find the shortest paths for network analysis. The modelling results were evaluated against an accurate geometry of an indoor building environment which was acquired using the highly accurate Trimble M3 total station. The proposed network model consists of two main procedures – 3D modelling and navigable networking. These procedures are explained in six steps.

The conclusions, recommendations and future directions of this study are discussed in Chapter 7.

1.9.Summary

In this chapter, the structure of this research was discussed. Current issues in indoor building modelling and different buiding surveying methods were addressed. The problem statements, the aims of the research and questions which need to be answered were set out. Finally, the structure of the presented thesis was formalised.

REFERENCES

Abolghasemzadeh, P. (2013). A comprehensive method for environmentally sensitive and behavioral microscopic egress analysis in case of fire in buildings. *Safety Science*, *59*, 1-9.

Ahuja, R. K., Magnanti, T. L., & Orlin, J. B. (1993). Network flows: theory, algorithms, and applications.

Allgower, E. L., K. Georg, (1990). Numerical continuation methods: an introduction. Springer-Verlag New York, Inc. New York, NY, USA.

Altan, O., Backhaus, R., Boccardo, P., & Zlatanova, S. (Eds.). (2010). Geoinformation for disaster and risk management: Examples and best practices. *Policy*, *5108*(5115), 5117.

Amato, E., Antonucci, G., & Belnato, B. (2003). The three dimensional laser scanner system: the new frontier for surveying, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences Vol. XXXIV-5/W12, 17-22

Bandi, S., & Thalmann, D. (1998, August). Space discretization for efficient human navigation. In *Computer Graphics Forum* (Vol. 17, No. 3, pp. 195-206). Blackwell Publishers Ltd.

Bast, H., Mehlhorn, K., Schäfer, G., & Tamaki, H. (2003). A heuristic for Dijkstra's algorithm with many targets and its use in weighted matching algorithms. *Algorithmica*, *36*(1), 75-88.

Baumgart, B., G., 1975. *A polyhedron representation for computer vision, National Computer Conference and Exposition*. ACM, Anaheim, California.

Becker, T., Nagel, C., & Kolbe, T. H. (2009). A multilayered space-event model for navigation in indoor spaces. In *3D Geo-Information Sciences* (pp. 61-77). Springer Berlin Heidelberg.

Becker, T., Nagel, C., & Kolbe, T. H. (2009). A multilayered space-event model for navigation in indoor spaces. In *3D Geo-Information Sciences* (pp. 61-77). Springer Berlin Heidelberg.

Béra, R., & Claramunt, C. (2005, December). Connectivity inferences over the Web for the analysis of semantic networks. In *International Workshop on Web and Wireless Geographical Information Systems* (pp. 222-234). Springer Berlin Heidelberg.

Boguslawski, P., Gold, C.M. & Ledoux, H., 2011. Modeling and analysing 3D buildings with a primal/dual data structure. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66(2): 188-197.

Boguslawski, P., 2011. Modeling and Analysing 3D Building Interiors with the Dual Half-Edge Data Structure. *PhD Thesis*, University of Glamorgan, Pontypridd, Wales, UK, 134 pp.

Biljecki, F., & Arroyo Ohori, K. (2015, November). Automatic semantic-preserving conversion between OBJ and CityGML. In *Europhysics Workshop on Urban Data Modeling and Visualisation, Delft (The Netherlands), Nov. 23th, authors version*. Eurographics.

Braid, I.C., Hillyard, R.C. & Stroud, I.A., 1980. Stepwise Construction of Polyhedra in Geometric Modeling. In: e. K.W.Brodlie (Editor*), Mathematical Methods in Computer Graphics and Design*. Academic Press, pp. 123-141.

Brisson, E. (1990). *Representation of d-dimensional geometric objects* (Doctoral dissertation).

Chen, T.K., Abdul-Rahmana, A. & Zlatanova, S., (2008). 3D Spatial Operations for geo-DBMS: geometry vs. topology. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVII(B2): 549-554.

Chen, P. H., & Feng, F. (2009). A fast flow control algorithm for real-time emergency evacuation in large indoor areas. *Fire Safety Journal*, *44*(5), 732-740.

Coors, V. (2003). 3D-GIS in networking environments. *Computers, Environment and Urban Systems*, *27*(4), 345-357.

Cooke, D. F. (1998). Topology and TIGER: the Census Bureau’s contribution. *The History of GIS: Perspectives from the Pioneers*, 52-53.

Criminisi, A., Reid, I., & Zisserman, A. (2000). Single view metrology. *International Journal of Computer Vision*, *40*(2), 123-148.

Curtin, K. M. (2007). Network analysis in geographic information science: Review, assessment, and projections. *Cartography and Geographic Information Science*, *34*(2), 103-111.

Cutter, S. L. (2003). GI science, disasters, and emergency management. *Transactions in GIS*, *7*(4), 439-446.

Daum, S., & Borrmann, A. (2014). Processing of topological BIM queries using boundary representation based methods. *Advanced Engineering Informatics, 28*(4), 272-286.

Deak, G., Curran, K., & Condell, J. (2012). A survey of active and passive indoor localisation systems. Computer Communications, 35(16), 1939–1954.

Demšar, U., Špatenková, O., & Virrantaus, K. (2008). Identifying critical locations in a spatial network with graph theory. *Transactions in GIS, 12*(1), 61-82.

de Laat, R., & van Berlo, L. (2011). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In *Advances in 3D geo-information sciences* (pp. 211-225). Springer Berlin Heidelberg.

Dobkin, D. P., & Laszlo, M. J. (1987, October). Primitives for the manipulation of three-dimensional subdivisions. In *Proceedings of the third annual symposium on Computational geometry* (pp. 86-99). ACM.

Donath, D., & Thurow, T. (2007). Integrated architectural surveying and planning. Automation in Construction, 16(1), 19–27.

Donath, D. (2008). Bauaufnahme und Planung im Bestand. *Grundlagen–Verfahren–Darstellung–Beispiele, Wiesbaden*.

Dongzhen, J., Khoon, T., Zheng, Z., & Qi, Z. (2009). Indoor 3D Modeling and Visualization with a 3D Terrestrial Laser Scanner. 3D Geo-Information Sciences, 247–255.

Elachi, C. , Zyl, J. (2006). Introduction To The Physics and Techniques of Remote Sensing (Second).

El-Mekawy, M., Östman, A., & Hijazi, I. (2012). An evaluation of IFC-CityGML unidirectional conversion. *International Journal of Advanced Computer Science and Applications*, *3*(5), 159-171.

Finnvold, J. E. (2006). Access to specialized health care for asthmatic children in Norway: The significance of parents' educational background and social network. *Social Science & Medicine*, *63*(5), 1316-1327.

Fitzgibbon, A., & Zisserman, A. (1998, September). Automatic 3D model acquisition and generation of new images from video sequences. In *Signal Processing Conference (EUSIPCO 1998), 9th European* (pp. 1-8). IEEE.

Gruen, A., & Wang, X. (1998). CC-Modeler: a topology generator for 3-D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, *53*(5), 286-295.

Haala, N., & Kada, M., (2010). An update on automatic 3D building reconstruction. ISPRS Journal of Photogrammetry and Remote Sensing, 65(6), 570–580.

Haala, N., & Brenner, C. (1999). Extraction of buildings and trees in urban environments. *ISPRS Journal of Photogrammetry and Remote Sensing*, *54*(2), 130-137.

Habib, A.F., Zhai, R., Kim, C., (2010). Generation of complex polyhedral building models by integrating stereo-aerial imagery and LiDAR data. Photogrammetric Engineering & Remote Sensing 76 (5), 609–623.

Hart, P. E., Nilsson, N. J., & Raphael, B. (1968). A formal basis for the heuristic determination of minimum cost paths. *IEEE transactions on Systems Science and Cybernetics*, *4*(2), 100-107.

Hoiem, D., Efros, A. A., & Hebert, M. (2005). Automatic photo pop-up. *ACM transactions on graphics (TOG)*, *24*(3), 577-584.

Hohmann, B., Krispel, U., Havemann, S., & Fellner, D. (2009, February). CityFit-High-quality urban reconstructions by fitting shape grammars to images and derived textured point clouds. In *Proceedings of the 3rd ISPRS International Workshop 3D-ARCH* (Vol. 2009, p. 3D).

Horry, Y., Anjyo, K. I., & Arai, K. (1997, August). Tour into the picture: using a spidery mesh interface to make animation from a single image. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (pp. 225-232). ACM Press/Addison-Wesley Publishing Co.

Huang, H., & Gartner, G. (2010). *A survey of mobile indoor navigation systems* (pp. 305-319). Springer Berlin Heidelberg.

Frueh, C., & Zakhor, A. (2003, June). Constructing 3d city models by merging ground-based and airborne views. In *Computer Vision and Pattern Recognition, 2003. Proceedings. 2003 IEEE Computer Society Conference on* (Vol. 2, pp. II-562). IEEE.

Fu, L., Sun, D., & Rilett, L. R. (2006). Heuristic shortest path algorithms for transportation applications: state of the art. *Computers & Operations Research*, *33*(11), 3324-3343.

Jizhou, W., Zongjian, L., & Chengming, L. (2004). Reconstruction of buildings from a single UAV image. In *Proc. International Society for Photogrammetry and Remote Sensing Congress* (pp. 100-103).

Johnson, D. B. (1977). Efficient algorithms for shortest paths in sparse networks. *Journal of the ACM (JACM)*, *24*(1), 1-13.

Isikdag, U., Underwood, J., & Aouad, G. (2008). An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes. *Advanced engineering informatics*, *22*(4), 504-519.

Isikdag, U., Zlatanova, S., & Underwood, J. (2013). A BIM-Oriented Model for supporting indoor navigation requirements. *Computers, Environment and Urban Systems*, *41*, 112-123.

Girres, J. F., & Touya, G. (2010). Quality assessment of the French OpenStreetMap dataset. *Transactions in GIS*, *14*(4), 435-459.

Gröger, G., & Plümer, L. (2010). Derivation of 3D indoor models by grammars for route planning. *Photogrammetrie-Fernerkundung-Geoinformation*, *2010*(3), 191-206.

Guibas, L., & Stolfi, J. (1985). Primitives for the manipulation of general subdivisions and the computation of Voronoi. *ACM transactions on graphics (TOG)*, *4*(2), 74-123.

Karas, I. R., Batuk, F., Akay, A. E., & Baz, I. (2006). Automatically extracting 3D models and network analysis for indoors. In *Innovations in 3D Geo Information Systems* (pp. 395-404). Springer Berlin Heidelberg.

Kvamme, K. L., Ernenwein, E. G., & Markussen, C. J. (2006). Robotic total station for microtopographic mapping: an example from the northern Great Plains. *Archaeological Prospection*, *13*(2), 91-102.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., ... & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of exposure analysis and environmental epidemiology*, *11*(3), 231-252.

Kemec, S., Duzgun, S., Zlatanova, S., Dilmen, D. I., & Yalciner, A. C. (2010, June). Selecting 3D urban visualisation models for disaster management: Fethiye tsunami inundation case. In *Proceedings of the 3rd International Conference on Cartography and GIS, 15-20 June 2010, Nessebar, Bulgaria*. International Cartographic Association/University of Architecture, Civil Engineering and Geodesy.

Kim, J. S., Yoo, S. J., & Li, K. J. (2014, May). Integrating IndoorGML and CityGML for indoor space. In *International Symposium on Web and Wireless Geographical Information Systems* (pp. 184-196). Springer Berlin Heidelberg.

Kim, J. S., Yoo, S. J., & Li, K. J. (2014). Integrating IndoorGML and CityGML for Indoor Space. In *Web and Wireless Geographical Information Systems* (pp. 184-196). Springer Berlin Heidelberg.

Kolbe, T. H. (2009). Representing and exchanging 3D city models with CityGML. In *3D geo-information sciences* (pp. 15-31). Springer Berlin Heidelberg.

Konecny, M., Zlatanova, S., & Bandrova, T. L. (2010). *Geographic Information and Cartography for Risk and Crisis Management*. Springer, Berlin.

Ledoux, H. and Gold, C.M., 2007. Simultaneous storage of primal and dual three-dimensional subdivisions. *Computers, Environment and Urban Systems*, 31(4): 393-408.

Lee, J. (2001). 3D data model for representing topological relations of urban features. In *Proceedings of the 21st Annual ESRI International User Conference*, San Diego, CA, USA.

Lee, J. (2004). A spatial access-oriented implementation of a 3-D GIS topological data model for urban entities. *GeoInformatica*, *8*(3), 237-264.

Lee, J., & Kwan, M. P. (2005). A combinatorial data model for representing topological relations among 3D geographical features in micro-spatial environments. *International Journal of Geographical Information Science, 19*(10), 1039-1056.

Lee, J., & Zlatanova, S. (2008). A 3D data model and topological analyses for emergency response in urban areas. *Geospatial information technology for emergency response*, *143*, C168.

Lienhardt, P. (1994). N-dimensional generalized combinatorial maps and cellular quasi-manifolds. *International Journal of Computational Geometry & Applications*, *4*(03), 275-324.

Lemmens, M. (2011). *Geo-information: Technologies, applications and the environment* (Vol. 5). Springer Science & Business Media.

Li, N., Becerik-Gerber, B., Krishnamachari, B., & Soibelman, L. (2014). A BIM centered indoor localization algorithm to support building fire emergency response operations. *Automation in Construction*, *42*, 78-89.

Li, Y., & He, Z. (2008). 3D indoor navigation: a framework of combining BIM with 3D GIS. In *44th ISOCARP congress*.

Li, K. J., & Lee, J. Y. (2013). Basic concepts of indoor spatial information candidate standard IndoorGML and its applications. *Journal of Korea Spatial Information Society*, *21*(3), 1-10.

Liu, L., & Zlatanova, S. (2011, May). A" door-to-door" Path-finding Approach for Indoor Navigation. In *Proceedings Gi4DM 2011: GeoInformation for Disaster Management, Antalya, Turkey, 3-8 May 2011*. International Society for Photogrammetry and Remote Sensing (ISPRS).

Liu, L., & Zlatanova, S. (2011). Towards a 3D network model for indoor navigation. *Urban and Regional Data Management, UDMS Annual*, 79-92.

Liu, L., & Zlatanova, S. (2013). A Two-level Path-finding Strategy for Indoor Navigation. In *Intelligent Systems for Crisis Management* (pp. 31-42). Springer Berlin Heidelberg.

Li, J., & Zlatanova, S. (2007). *Geomatics solutions for disaster management* (p. 444). A. G. Fabbri (Ed.). Berlin, Heidelberg, New York: Springer.

Lorenz, B., Ohlbach, H. J., & Stoffel, E. P. (2006). A hybrid spatial model for representing indoor environments. In *Web and Wireless Geographical Information Systems* (pp. 102-112). Springer Berlin Heidelberg.

Luo, F., Cao, G., & Li, X. (2014, November). An interactive approach for deriving geometric network models in 3D indoor environments. In *Proceedings of the Sixth ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 9-16). ACM.

Mautz, R., & Tilch, S. (2011, September). Survey of optical indoor positioning systems. In *Indoor Positioning and Indoor Navigation (IPIN), 2011 International Conference on* (pp. 1-7). IEEE.

Matei, B. C., Sawhney, H. S., Samarasekera, S., Kim, J., & Kumar, R. (2008, June). Building segmentation for densely built urban regions using aerial lidar data. In *Computer Vision and Pattern Recognition, 2008. CVPR 2008. IEEE Conference on* (pp. 1-8). IEEE.

Meijers, M., Zlatanova, S., & Pfeifer, N. (2005, June). 3D geoinformation indoors: structuring for evacuation. In *Proceedings of Next generation 3D city models* (pp. 21-22).

Molenaar, M. (1998). *An introduction to the theory of spatial object modelling for GIS*. CRC Press.

Moreno, A., Segura, Á., Korchi, A., Posada, J., & Otaegui, O. (2011). Interactive urban and forest fire simulation with extinguishment support. In *Advances in 3D Geo-Information Sciences* (pp. 131-148). Springer Berlin Heidelberg.

Nan, L., Sharf, A., Zhang, H., Cohen-Or, D., & Chen, B. (2010, July). Smartboxes for interactive urban reconstruction. In *ACM Transactions on Graphics (TOG)* (Vol. 29, No. 4, p. 93). ACM.

Oh, B. M., Chen, M., Dorsey, J., & Durand, F. (2001, August). Image-based modeling and photo editing. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (pp. 433-442). ACM.

Pilouk, M. (1996). Integrated modelling for 3D GIS.

Pu, S., & Zlatanova, S. I. S. I. (2006, May). Integration of GIS and CAD at DBMS level. In *Proceedings of UDMS* (Vol. 6, pp. 9-61).

Pigot, S. P. (1995). *A topological model for a 3-dimensional Spatial Information System* (Doctoral dissertation, University of Tasmania).

Pollefeys, M., Nistér, D., Frahm, J. M., Akbarzadeh, A., Mordohai, P., Clipp, B., ... & Salmi, C. (2008). Detailed real-time urban 3d reconstruction from video. *International Journal of Computer Vision*, *78*(2), 143-167.

Poullis, C., & You, S. (2009, June). Automatic reconstruction of cities from remote sensor data. In *Computer Vision and Pattern Recognition, 2009. CVPR 2009. IEEE Conference on* (pp. 2775-2782). IEEE.

Ramon Moore, R. K. E., Cloud, M. J. (2009). Introduction to interval analysis. SIAM (Society for Industrial and Applied Mathematics), Philadelphia.

Razavi, S. N., & Moselhi, O. (2012). GPS-less indoor construction location sensing. *Automation in Construction*, *28*, 128-136.

Randall, J., Amft, O., Bohn, J., & Burri, M. (2007). LuxTrace: indoor positioning using building illumination. *Personal and ubiquitous computing*, *11*(6), 417-428.

Remondino, F., & El-Hakim, S. (2006). Image-based 3D modelling: a review. *The Photogrammetric Record*, *21*(115), 269-291.

Richter, K. F., & Duckham, M. (2008, September). Simplest instructions: Finding easy-to-describe routes for navigation. In *International Conference on Geographic Information Science* (pp. 274-289). Springer Berlin Heidelberg.

Rottensteiner, F. (2003). Automatic generation of high-quality building models from lidar data. *IEEE Computer Graphics and Applications*, *23*(6), 42-50.

Rüppel, U., Abolghasemzadeh, P., & Stübbe, K. (2010, June). BIM-based immersive indoor graph networks for emergency situations in buildings. In *International Conference on Computing in Civil and Building Engineering (ICCCBE).*

Rüppel, U., & Schatz, K. (2011). Designing a BIM-based serious game for fire safety evacuation simulations. *Advanced Engineering Informatics, 25*(4), 600-611.

Saxena, A., Sun, M., & Ng, A. Y. (2009). Make3d: Learning 3d scene structure from a single still image. *IEEE transactions on pattern analysis and machine intelligence, 31*(5), 824-840.

Schaap, J., Zlatanova, S., & van Oosterom, P. J. M. (2011). Towards a 3D geo-data model to support pedestrian routing in multimodal public transport travel advices. *Urban and Regional Data Management, UDMS Annual*, 63-78.

Schenk, T. (2005). Introduction to photogrammetry. *The Ohio State University, Columbus*.

Schnabel, R., Wahl, R., & Klein, R. (2007a). RANSAC based out-of-core point-cloud shape detection for city-modeling. *Proceedings of "Terrestrisches Laserscanning*.

Schnabel, R., Wahl, R., & Klein, R. (2007b). Efficient RANSAC for point-cloud shape detection. In *Computer graphics forum* (Vol. 26, No. 2, pp. 214-226). Blackwell Publishing Ltd.

Slingsby, A., & Raper, J. (2008). Navigable space in 3D city models for pedestrians. In *Advances in 3D Geoinformation Systems* (pp. 49-64). Springer Berlin Heidelberg.

Schulte, C., & Coors, V. (2008, August). Development of a CityGML ADE for dynamic 3D flood information. In *Joint ISCRAM-CHINA and GI4DM Conference on Information Systems for Crisis Management*.

Stoffel, E. P., Lorenz, B., & Ohlbach, H. J. (2007). Towards a semantic spatial model for pedestrian indoor navigation. In *Advances in Conceptual Modeling–Foundations and Applications* (pp. 328-337). Springer Berlin Heidelberg.

Surmann, H., Nüchter, A., & Hertzberg, J. (2003). An autonomous mobile robot with a 3D laser range finder for 3D exploration and digitalization of indoor environments. *Robotics and Autonomous Systems, 45*(3), 181-198.

Suveg, I., & Vosselman, G. (2004). Reconstruction of 3D building models from aerial images and maps. *ISPRS Journal of Photogrammetry and Remote Sensing*, *58*(3), 202-224.

Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in Construction*, *19*(7), 829-843.

Tashakkori, H., Rajabifard, A., & Kalantari, M. (2015). A new 3D indoor/outdoor spatial model for indoor emergency response facilitation. *Building and Environment*, *89*, 170-182.

Teo, T. A., & Cho, K. H. (2016). BIM-oriented indoor network model for indoor and outdoor combined route planning. *Advanced Engineering Informatics*, *30*(3), 268-282.

Toccolini, A., Fumagalli, N., & Senes, G. (2006). Greenways planning in Italy: the Lambro River Valley greenways system. *Landscape and urban planning*, *76*(1), 98-111.

Tse, R., Gold, C., & Kidner, D. (2008). 3D City Modeling from LIDAR Data. Advances in 3D Geoinformation Systems, 161–175.

Underwood, J., & Isikdag, U. (2011). Emerging technologies for BIM 2.0. *Construction Innovation*, *11*(3), 252-258.

Vanclooster, A., & De Maeyer, P. (2012). Combining indoor and outdoor navigation: the current approach of route planners. In *Advances in Location-Based Services* (pp. 283-303). Springer Berlin Heidelberg.

Van Oosterom, P., Zlatanova, S., & Fendel, E. (Eds.). (2006). *Geo-information for disaster management*. Springer Science & Business Media.

Verma, V., Kumar, R., & Hsu, S. (2006). 3d building detection and modeling from aerial lidar data. In *Computer Vision and Pattern Recognition, 2006 IEEE Computer Society Conference on* (Vol. 2, pp. 2213-2220). IEEE.

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in construction*, *38*, 109-127.

Vosselman, G., & Suveg, I. (2001). Map based building reconstruction from laser data and images. *Automatic Extraction of Man-Made Objects from Aerial and Space Images (III)*, 231-239.

Walker, L. R., Mason, M., & Cheung, I. (2006). Adolescent substance use and abuse prevention and treatment: Primary care strategies involving social networks and the geography of risk and protection. *Journal of Clinical Psychology in Medical Settings*, *13*(2), 126-134.

Wang, R., & Ferrie, F. P. (2008, June). Camera localization and building reconstruction from single monocular images. In *Computer Vision and Pattern Recognition Workshops, 2008. CVPRW'08. IEEE Computer Society Conference on* (pp. 1-8). IEEE.

Wang, L., Groves, P. D., & Ziebart, M. K. (2013, January). Shadow matching: Improving smartphone GNSS positioning in urban environments. In *China Satellite Navigation Conference (CSNC) 2013 Proceedings* (pp. 613-621). Springer Berlin Heidelberg.

Wang, R. (2013). 3D building modeling using images and LiDAR: A review. *International Journal of Image and Data Fusion*, *4*(4), 273-292.

Weisstein, E. W. (1999). Graph.

Wolf, P. R., & Ghilani, C. D. (2006). Adjustment Computations Spatial Data Analysis. *New Jersey: John Willey & Sons Inc*.

Worboys, M. F., & Duckham, M. (2004). *GIS: a computing perspective*. CRC press.

Xu, M. H., Liu, Y. Q., Huang, Q. L., Zhang, Y. X., & Luan, G. F. (2007). An improved Dijkstra's shortest path algorithm for sparse network. *Applied Mathematics and Computation*, *185*(1), 247-254.

Yuan, W., & Schneider, M. (2010, November). Supporting 3D route planning in indoor space based on the LEGO representation. In *Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 16-23). ACM.

Yuan, W., & Schneider, M. (2010). iNav: An indoor navigation model supporting length-dependent optimal routing. In *Geospatial Thinking* (pp. 299-313). Springer Berlin Heidelberg.

Yuan, L. I., & Zizhang, H. E. (2008). 3D indoor navigation: A framework of combining BIM with 3D GIS. In *44th ISOCARP Congress*.

Yusuf, A., 2007. An approach for real world data modeling with the 3D terrestrial laser scanner for built environment. Automation in Construction, 16(6): 816-829.

Zhang, J. P., & Hu, Z. Z. (2011). BIM-and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Automation in construction*, *20*(2), 155-166.

Zhang, L., Dugas-Phocion, G., Samson, J. S., & Seitz, S. M. (2002). Single-view modelling of free-form scenes. *Computer Animation and Virtual Worlds*, *13*(4), 225-235.

Zho, H., & Shibasaki, R. (2001). Reconstructing urban 3D model using vehicle-borne laser range scanners. In *3-D Digital Imaging and Modeling, 2001. Proceedings. Third International Conference on* (pp. 349-356). IEEE.

Zhou, Q. Y., & Neumann, U. (2008, November). Fast and extensible building modeling from airborne LiDAR data. In *Proceedings of the 16th ACM SIGSPATIAL international conference on Advances in geographic information systems* (p. 7). ACM.

Zlatanova, S., & Baharin, S. S. K. (2008). Optimal navigation of first responders using DBMS. In *3rd International Conference on Information Systems for Crisis Response and Management 4th International Symposium on GeoInformation for Disaster Management* (pp. 541-54).

Zlatanova, S., & Holweg, D. (2004, March). 3D Geo-information in emergency response: a framework. In *Proceedings of the Fourth International Symposium on Mobile Mapping Technology, Kunming, China* (pp. 29-31).

Zlatanova, S., Rahman, A. A., & Shi, W. (2004). Topological models and frameworks for 3D spatial objects. *Computers & geosciences*, *30*(4), 419-428.

Zlatanova, S. (2000). *3D GIS for urban development*. International Inst. For Aerospace Survey and Earth Sciences (ITC).