Project proposal

Smart 3D indoor models to support crisis management in large public buildings

1. KEY INFORMATION

1.1 FURTHER DETAILS MAIN APPLICANT

Name : Dr. Dipl.-Ing. S. (Sisi) Zlatanova
Address : Section GIS Technology, Delft University of Technology
Phone : +31 (0) 15 278 27 14
Email : s.zlatanova@tudelft.nl
Part-time percentage: 100%
Permanent position: yes

1.2 FURTHER DETAILS CO-APPLICANTS

Name : Prof. dr. ir. M.G. (George) Vosselman
Address : Dept. Earth Observation Science, Faculty of Geo-Information Science and Earth Observation, University of Twente.
Phone : +31 (0)53 4874344
Email : george.vosselman@utwente.nl
Part-time percentage: 100%
Permanent position: yes

1.3 TITLE

Smart 3D indoor models to support crisis management in large public buildings
Abbreviated title: SIMs3D (Smart Indoor Models in 3D)

1.4 KEY WORDS

Crisis management, emergency response, indoor navigation, route planning, indoor mapping, 3D modelling, BIM, semantics, shape grammar.

2. SUMMARIES

2.1 RESEARCH SUMMARY

In this proposal we address the lack of up-to-date 3D indoor models for many large public building. This is a problem for many stakeholders, but in particular for organizations that deal with the safety management of public buildings, including BHV (Bedrijfhulpverleners – company/institution employees trained to help in emergencies), fire brigade and safety regions. Currently, for most buildings the only available indoor spatial data are 2D floor plans or design BIMs (for newer buildings). These represent the condition of the building 'as-designed', which may be different from the 'as-built' or the 'as-is' condition of the building. During rescue operations, knowledge of building modifications (e.g. lowered ceilings or raised floors), height of rooms and corridors and available furniture is crucial for firefighters. Such information can only be obtained from an up-to-date 3D indoor model of the building.

Creating 3D indoor models manually is a tedious, time consuming and expensive task. At present, no semi-automatic or automatic methods exist, which can deliver a flexible representation of indoor spaces that can support various users and their tasks. The aim of this project is to develop a 3D modelling approach based on discrete point clouds, which understands the principles of interior architectural design and human perception to identify spaces that can be used for navigation. Therefore, we will focus on bridging research on 3D indoor reconstruction from point clouds, 3D indoor models (geometry, semantics and topology), and 3D indoor navigation for users with various profiles and tasks. We will develop methods based on grammar to collect information from the point cloud and reconstruct the interior structure of the building (such as rooms and furniture), and increase the granularity of the spaces to fit them to the navigation needs. Smart 3D models, i.e. models that combine geometric details, rich semantics and spatial relationships that allow complex queries and spatial operations, are central for this research. The main research question is formulated as: How to reconstruct a smart 3D model from point clouds that can ensure intelligent routing and navigation in emergency situations.

The benefit of creating such smart 3D models is that the process of reconstruction and path finding is formalised, i.e. rules for processing, rules for path computations and the corresponding data models are known and well-defined. If new rules are needed, the grammar can be extended. Each navigation path can be computed with respect to given requirements or preferences. In case of changed structure or furniture, scanning and 3D reconstruction can be performed only in some parts of the building ensuring that the process will end up in the same semantically-rich 3D data model. This approach ensures robustness and flexibility, which are of critical importance for emergencies.

The result of the project will be a set of algorithms and open-source software tools for producing smart 3D indoor models and optimized route planning, which will be used for effective management of large public buildings in emergency situations. The research contributes to the goals of Maps4Society program by addressing the research area “managing big data”, and application areas “crisis management”, “Smart cities/Human environment” and “Object life cycle management for buildings”.

2.2 UTILISATION SUMMARY

In this project, we will develop spatial tools and models that support decision making and effective management of large public buildings, e.g. hospitals, in emergency situations. The strength of this project is that the entire process from 3D reconstruction to 3D analysis will be addressed in its integrity. Our developments are based on points clouds, for which the acquisition technology is fast developing with dropping costs. This will ensure that the indoor models can be updated on a regular basis, e.g. once per year. The theoretical foundation and the focus on standards will ensure that implementations can be developed on different platforms and by using different data sources. The developed prototypes will be made immediately available to end-users (BHVs, fire brigade and safety regions).

A number of strategies will be followed to guarantee utilisation at national and international level. At national level some of the largest companies for data collection and software development will be involved actively via workshops and consultations. These companies will support the research and use the results to create smart 3D indoor models for end-users. The end-users are represented by the Brandweer Netherland and iNowit (a research and development cooperation between emergency responders and companies). The end-users will provide consultation on the utilization of indoor models, and will also validate and promote the use of our prototypes.

Internationally the research will be discussed with many groups working on indoor 3D modelling such as the following universities: University of Munich, University of Greenwich, University of Seoul, Wuhan University (through the JRC TUDelft Wuhan), University of Vigo, RMIT and companies such as Bentley Systems, China National Mapping organisation and IndoorLBS. Internationally, the results will be utilised also by our extended contacts with OGC and ISPRS. This research aims at solutions based on the most accepted 3D standards in BIM and GIS worlds.

The benefit for the society will be the provision of safer living environments indoors. With the tools and models that will be developed in this project user companies will produce smart 3D indoor models, and end users will utilize the models for more effective management of public buildings, especially in emergency situations. This will lead to new business processes for indoor data acquisition and modelling, and will strengthen the position of Dutch companies in the international market. We also expect that the market for 3D indoor models will further expand as indoor models find a wider range of applications, e.g. in energy efficiency analysis and structural health monitoring of buildings.

2.3 SUMMARY STW'S WEBSITE

Effective management of large public buildings, especially in an emergency situation, requires up-to-date 3D indoor models with detailed geometric and semantic information. At present, such models do not exist for many buildings. Project SIMs3D aims at developing methods and tools for rapid and low-cost generation of smart 3D indoor models for public buildings. Our methods combine the principles of indoor architectural design with human perception to recognize interior spaces and their relations, and represent these in a data structure that allows making complex queries for optimized routing and navigation. The resulting indoor models will be used to train the emergency response officers (BHV), and to plan optimized evacuation routes and navigate people with different modes of movement (e.g. of disabled people). Up-to-date indoor models also contain information about the modifications of the interior structures, such as temporary doors, lowered ceilings or raised floors, which is crucial for emergency response officers and fire fighters.

3. CURRENT COMPOSITION OF THE RESEARCH GROUP

The team consists of:
i) Scientific staff who will lead the project work packages (See Section 4.4.1) and supervise the research staff.
ii) Research staff (a PhD student and a postdoc) who will carry out the work packages and for whom funding is requested;
iii) User companies who will facilitate the implementation of the results in industry and application by the end users.

Dr. Sisi Zlatanova, associate professor at section GIS Technology and leading the Theme Group 'Geo-information for Crisis Management' at TU Delft, will be the project leader and the leader of WP2 and WP5. She will be the supervisor of the postdoc researcher.

Prof. George Vosselman, professor and head of the department of Earth Observation Science of the University of Twente, (UT) will lead WP1, and will be the promoter of the PhD researcher.
Dr. Kourosh Khoshelham, assistant professor at the department of Earth Observation Science of the University of Twente, will lead WP4, and will be the daily supervisor of the PhD student.
Drs. Rob Peters, information coordinator and representative of innovation platform for safety regions (iNowit), will coordinate the end-users and will be responsible for WP3.

To involve MSc students in the research, in both institutes (TUD and UT) we have defined MSc thesis topics on indoor modelling and navigation. We expect to have 5-8 MSc students involved in the research during the entire period.

4. SCIENTIFIC DESCRIPTION

4.1 RESEARCH CONTENTS/INTRODUCTION

4.1.1 BACKGROUND

Public buildings are usually equipped with 2D floor plans, and semantically rich 3D indoor models are rarely available. With the development of 3D city modelling, where focus is mainly on outdoor scenes, many applications realize the need for 3D indoor models. One important application that is emerging as heavily reliant on 3D spatial information of indoor spaces is route planning in large buildings in the context of emergency response. In the event of a fire in a crowded multi-storey building complex, such as a hospital, rapid generation of optimal evacuation routes is of crucial importance. To generate optimal routes in an indoor environment, where factors like the number of users, type, size and accessibility of entrances/exits (doors, windows), height of ceilings (lowered ceilings, which create potential danger because of hidden pockets of air) and mode of movement (e.g. of disabled people) have to be taken into account, a 2D map is often insufficient. A 3D model containing information about navigable and non-navigable spaces with their geometric properties as well as topological and semantic relations is essential.

A major reason for the unavailability of up-to-date semantically rich 3D indoor models is the lack of automated or semi-automated modelling methods that can be applied to a variety of indoor architectures to create complete and accurate models effectively and efficiently. Design models (BIM) are available only for newly constructed buildings. Moreover they are often not maintained properly and do not represent the current state of the building. Manual modelling and updating is slow and costly, and thus inefficient for large buildings. Automated approaches are mainly data-driven (in contrast to application-driven), and rely on extracting simple geometric features such as planar surfaces, lines and vertices, to recognize structural elements of the building (walls, floors, ceilings, doors and windows) (Budroni and Boehm, 2010; Sanchez and Zakhor, 2012; Valero et al., 2012; Mura et al., 2013; Xiong et al., 2013). Consequently, they are susceptible to noise and gaps in the data, and the resulting models will not necessarily consist of topologically correct spaces, which are essential for performing complex queries in route planning. Approaches that attempt to recognize interior spaces (Jenke et al., 2009; Xiao and Furukawa, 2012; Becker et al., 2013; Oesau et al., 2014) focus on geometric reconstruction, and do not provide semantic relations like adjacency, part-of and direction (above/below) between the spaces. Therefore, the resulting models do not allow performing complex queries, and are not suitable for optimized path finding and navigation.

4.1.2 THE CHALLENGE

In this project we aim at developing a rapid and low-cost 3D modelling approach based on discrete point clouds, which understands the principles of interior architectural design and human perception to identify spaces and networks needed for navigation.

The first challenge is 3D reconstruction of indoor spaces from point clouds. Point clouds are a suitable source for 3D reconstruction of indoor environments as they provide an accurate representation of 3D geometry of objects. The technology for acquiring point clouds is fast developing, which will allow frequent and low-cost updates in near future. However, existing procedures for 3D indoor reconstruction from point clouds hardly address semantics. In this project, we will address spaces needed for navigation and support of emergency response. These spaces have to be modelled with semi-automatic and automatic procedures, which will allow regular and cheap update of indoor geometry, semantic and connectivity information. These procedures should be robust against possible inaccuracy or incompleteness of the data (e.g. in parts where data acquisition is difficult) and be applicable to a variety of indoor architectures.

A second challenge is the development of required models and algorithms that will support the optimal path finding. Our project aims at quick and on-the-fly space subdivision/aggregation, which will ensure automatic derivation of most appropriate routing through safe areas in emergency situations (Figure 1).

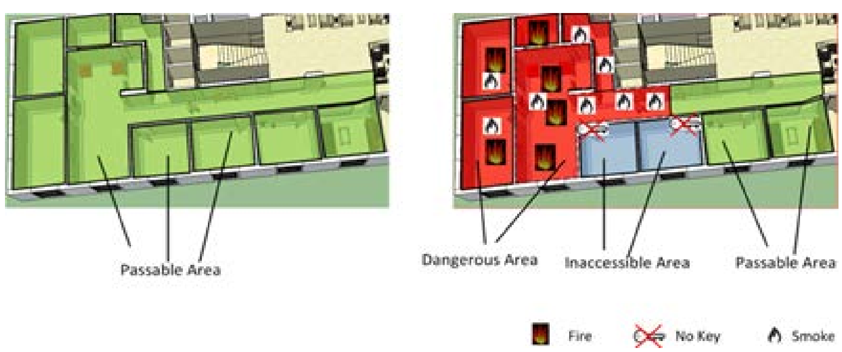

Fig 1: Example of subdivision of space into passable, dangerous and inaccessible area in case of emergency. Before emergency all is ‘passable’ (left) and during emergency the ‘passable’ area is shirked to two rooms and a half of corridor (right)

4.1.3 OBJECTIVES AND RESEARCH QUESTIONS

The main objective of this project is to develop spatial tools and models for buildings, which enable optimized routing and navigation indoors in emergency situations. Our approach is based on grammar, which is a concept that explains the configuration and inter-relations of spaces in indoor environments. To reach the main objective the following sub-objectives are defined:

i) To develop a shape grammar for (semi-) automated generation of semantically-rich 3D models of indoor environments from large point clouds;
ii) To develop a space subdivision/aggregation grammar to create a network and support navigation of multiple stakeholders who need to orient and find resources (exits, rooms, indoor facilities, items in cupboards) in case of emergencies.

To reach the above objectives the following research questions need to be answered:
- How can grammar rules (their sequence and parameters) be learned from the point cloud?
- What level of semantics (rooms, corridors, furniture) is needed for optimal path finding to support emergency situations?
- Which of the semantic information that is needed for path finding can be derived automatically from the data or the model?
- What kind of data models can integrate the information about spaces, their properties and relationships?
- Which kind of grammar is needed to allow subdivision/aggregation of spaces into sufficiently small or large cells to provide the best networks for navigation in crisis situations?

4.1.4 METHODOLOGY

Indoor architecture is characterized with three elements: repetition, regularity and creativity. Regular structures like cuboid spaces repeatedly appear in indoor environments but in very many different configurations reflecting the creativity of the architect. A design principle that combines these elements and explains their working in architecture is the shape grammar. It establishes that different designs can be made by iteratively applying grammar rules to simple shapes (Stiny, 2008). By choosing different shape parameters and varying the sequence of rules many different creative designs can be created. Shape parameters also contain semantics of spaces such as the height of walls, ceilings, floors, doors and windows.

For the 3D modelling of interior spaces we will define a parametric shape grammar similar to the Palladian grammar, which has been used to describe Palladian style indoor designs (Stiny and Mitchell, 1978). It consists of a starting shape and a set of rules that are iteratively applied to the starting shape to produce intermediate shapes and eventually the final spaces of the interior. We use a parameterized cube of unit size as the starting shape as it represents a 3D subspace. The rules can then change the size of the unit cube, place it in certain positions and merge multiple cuboids to form more complex interior spaces. Figure 2 shows an example a simple interior space modeled by placing and merging cuboid shapes. The advantage of shape grammar over similar methods, e.g. split grammar as used by Becker et al. (2013), is that it is based on an architectural indoor design concept and is therefore better suited for modelling indoor spaces. In addition, the shape parameters are part of the required semantics and can be directly used in optimal path finding.

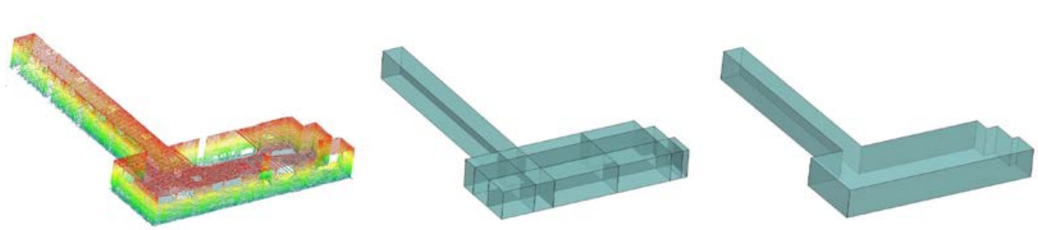

Figure 2: Example point cloud of a simple interior space (left) modeled by placing cuboid shapes (middle) and merging them (right).

We will develop and extend the shape grammar to enable modelling of complex indoor environments up to the level of details required for optimal routing and navigation. We will augment the grammar with semantic rules, which makes it possible to extract and add semantics to the reconstructed spaces. Any object that is not part of the interior structure of the building will be classified as clutter and further to different types of furniture. We will also develop methods to learn the sequence and parameters of the grammar rules from the point cloud. Our preliminary experiments show that the distribution of points in the point cloud provides information on the position of the main structural elements, and can be used to estimate the parameters of the grammar rules (Khoshelham and Diaz-Vilarino, 2014). Although we aim to minimize user interaction by learning the grammar from the data, in the implementation we will develop software tools that allow and facilitate user interaction to correct or modify the procedure and the models.

To be able to provide navigation and guidance, the models (geometry and semantics) have to be enhanced with connectivity information, i.e. a network has to be created. One approach to create such a network is to apply Poincare Duality, according to which each node represents a space and an edge depicts the (connectivity) link between spaces (Becker et al., 2008; Lee, 2004; Lee and Zlatanova, 2008). This concept is central for IndoorGML, an OGC candidate standard (http://www.opengeospatial.org/projects/groups/indoorgmlswg). By changing the space subdivision, different networks can be created completely automatically. The semantics and the properties attached to the geometric spaces can be propagated to the nodes and the edges of the network. Space can be subdivided using different geometric or semantic criteria or combinations of them (Afyouni et al., 2012). For example, Khan and Kolbe (2013) provide an approach for space subdivision, which considers the locomotion types of humans (walk, drive).

Fig 3: Examples of space subdivision using parameters of resources (left and middle) and the resulting navigation on a mobile phone showing 3D oblique view of the building (right, Xu et al., 2013)

We will follow an approach making use of user perception of space (Hall, 1969; Junestrand et al., 2001; Nakauchi and Simmons, 2002; Scheflen, 1975) and 'attractiveness' of objects of interest. We have developed a framework in which we distinguish between *agents* (humans and human proxies), which perform *actions* to approach *resources*. The agents, actions and recourse can be affected by *modifies* (i.e. events that modify the status of any of the three). Modifies can be emergencies such as a fire or smoke (Zlatanova et al., 2013). Our initial investigations have shown that resources can hold a number of characteristics (function, attractiveness, time, accessibility, number of agents, social distance, etc.). These properties are used to assign a space around the resources, which can be used for localisation of agents but cannot be used to navigate other agents through. These spaces delineate the possible navigable space (i.e. the spaces which are outside the spaces for resources as on Figure 3). By developing a proper grammar to utilise these criteria, we can change the spaces around resources dynamically. For example, the area around a coffee corner can be several metres during coffee break and only a meter outside the coffee hours.

4.2 FIT INTO THE PROGRAMME

The proposal addresses the research area: "Managing Big Data", and application areas: "Crisis management", "Smart cities/Human environment" and "Object life cycle management for buildings" as specified in the programme plan (section 3). We seek an answer to the research question: How to reconstruct a smart 3D model from point clouds that can ensure intelligent routing and navigation in emergency situations. From a technical point of view, processing of indoor point clouds and creating smart 3D models is a managing of big data. Point clouds of a floor can easily reach a size of gigabytes.

This proposal is dedicated to crisis management in indoor environments, and is therefore closely related to Smart cities/Human environment. Buildings are an important element of cities and human environment as humans spend most of their time indoor. To have safer living environments requires buildings to become spatially intelligent; i.e. they have to be supported by an indoor spatial information system, which facilitates, among other things, effective and efficient management of the indoor environment especially in an emergency situation. Such an indoor information system requires up-to-date 3D models that are sufficiently detailed in geometry and rich in semantics. Point clouds are a suitable source of spatial data to represent indoor environments in 3D. The technology for producing point cloud data is gradually getting cheaper, faster and more accurate. This allows update of the indoor model on a regular basis. However, indoor point clouds typically contain billions of points and lack semantic information.

The objectives of the proposal are very well aligned with the goals and activities of the Maps4Society programme partners (Kadaster, RWS, NSO, NCG) as spatial data of indoor environments form an integral part of a healthy and innovative geo-information infrastructure. Smart 3D indoor models have societal relevance, as they can lead to safer living environments, and their production and utilization will create economic value. The development and utilization of 3D indoor models involve the golden triangle: science (research and development), companies (that will produce the models) and governance (that will devise policies for utilization of indoor models), which is at the core of the Maps4Society programme.

4.4 TIME PLAN AND DIVISION OF TASKS

4.4.1 WORK PACKAGES

The research is divided into five work packages (WP), for which one PhD student and one postdoc position are requested. The tasks defined in the work packages are tidily related, as described below. Therefore, all work packages will be carried out in close collaboration with each other.

WP1 will focus on automated 3D modelling of indoor environments. Our primary source of data for modelling will be point clouds as these provide an accurate representation of 3D geometry, which is essential for indoor modelling. Images will be used as supplementary data to texture the model and recognize difficult components such as furniture and closed doors. The tasks include defining the grammar (years 1 and 2), developing methods to learn the grammar rules from the data (years 2 and 3) and evaluation using data of a number of test buildings (year 3). The work within this WP will be performed by the PhD student.

WP2 will concentrate on the semantic models (geometry and topology) and the grammar needed for the multi-purpose indoor navigation. All existing models (IndoorGML, CityGML, IFC) can be used for some dedicated purposes, but they require significant user-defined modifications to obtain appropriate subdivisions for multi-purpose navigation. A main task in this work package is to develop a grammar for deriving different indoor spaces considering agents, activities, resources and modifiers. By applying this grammar, 3D models can automatically be adapted for cases which require different indoor details: from navigation to an exit (common case) to navigation to an item hidden in another item (e.g. a fire extinguisher in a cabinet) (Wang and Zlatanova, 2013). WP2 will start in year 2 of the project so that the methods for 3D reconstruction, which will be developed in year 1 within WP1, can to be used for the development of semantic models and the multi-purpose navigation. The work within this WP will be completed by the postdoc.

WP3 will be devoted to the user requirements and use cases. In this project we will concentrate on the work of fire brigade in the Netherlands. The partners from the Brandweer Netherlands, the researchers and the data providers of point clouds Cyclomedia will discuss what kind of information is needed and how to collect it. Two use cases will be specified in large public buildings such a school/university and a hospital. Several floors of both buildings will be scanned. This WP will be active at the beginning and end of the project. At the end of the third year the user community will be gathered to validate and evaluate the developed prototypes. This will be completed in several workshops, demos and hands-on at two Safety regions in Netherlands. All the participants in this project will be involved in this WP.

WP4 aims at the integration of developments from WP1 and WP2 to develop the software prototype. The development of concepts within WP1 and WP2 will be performed in close cooperation. The results obtained will be discussed at monthly meetings to evaluate to which degree the grammar for 3D reconstruction can be linked to the grammar developed for the space subdivision. Components, rules and operations, which can be re-used will be unified for use in both grammars. The developed prototypes will be linked together in such a way as to form a continuous workflow. The company CGI will advise in preparing the final prototype.

WP5 is dedicated to dissemination. The dissemination of results will be completed via web site (wiki), organisation of workshops and hands-on sessions, presentations at OGC meetings and international conferences and 4-6 journal publications. One PhD thesis will be completed. The developments within the project will be documented in a series of reports providing detailed information in the form of manuals suitable for a broad group of users.

4.4.2 TIME PLAN

The table below summarizes the time plan of the project.

Work Packages vs. years	1 2015	2 2015	1 2016	2 2016	1 2017	2 2017	1 2018	2 2018
WP1: 3D reconstruction								
WP2: 3D models and algorithms								
WP3: Case Studies								
WP4: Prototype development								
WP5: Dissemination								

4.3 EXPECTED OUTCOMES

We expect the following deliverables from the proposed research:
- A hierarchical concept for indoor model that combines 3D geometry with rich semantics to support multi-purpose routing and navigation in indoor spaces;
- Software for (semi-) automated 3D modelling of indoor environments from point clouds;
- Software for automatic space subdivision to support routing and guidance
- Publications in high impact international journals and international conferences.

The overall result of smart 3D indoor models and optimized routing will be an increased safety of large public buildings. When emergency situations like fire or terrorist attacks occur, rapid generation of multi-purpose navigations on actual (as-is) 3D models can speed up rescue operations and save lives. The results of this project will contribute to more effective management of indoor environments for many other purposes like maintenance and renovation. Our partners from Brandweer Nederland will be the first users to apply the result of this research for routine work and emergency management.

5. UTILISATION PLAN

5.1 THE PROBLEM AND THE PROPOSED SOLUTION

Currently, for most buildings the only available indoor spatial data are 2D floor plans or design BIMs (for newer buildings). These represent the condition of the building 'as-designed', which may be different from the 'as-built' or the 'as-is' condition of the building. In many situations, we need an up-to-date smart 3D model of the building interior containing detailed information on the geometry and function of building components as well as relations between them. For example, to better manage a fire emergency in a hospital, a 3D model can be used to train the emergency response officers, and later to generate optimized evacuation routes for people that can walk or are on a wheelchair/brancard. During the rescue operation, knowledge about lowered ceilings or raised floors is crucial for fire fighters, because those features indicate enclosed spaces containing oxygen which can spread the fire, often unseen. Such information can only be obtained from an up-to-date 3D indoor model of the building.

The problem that we address in this proposal is that currently up-to-date 3D indoor models do not exist for many large public building. This is a problem for many stakeholders, but in particular for organizations that deal with the safety management of public buildings, including BHV, fire brigade and safety regions. The unavailability of up-to-date indoor models can have social consequences, e.g. loss of people's lives during a crisis, as well as economic consequences, e.g. increased renovation costs.

One reason for the unavailability of up-to-date indoor models is the lack of easy-to-use and efficient software tools for creating as-is indoor models from raw data like point clouds and imagery. The technology for collecting images and point clouds indoors (e.g. cyclorama imaging and static/mobile laser scanning) is getting cheaper and faster, and is available to us through our industry partners. But the tools for creating 3D models from such data, which can be used for emergency management, do not exist. Another reason is that there is no policy that would require large public buildings to have an indoor model and to update it when modifications are made to the building. We will develop methods and software tools for efficient generation of 3D indoor models from point cloud data. After making the developed tools available to the user companies (including our consortium partners), the safety regions (via iNowit, partner in the proposal) will be able to negotiate with relevant authorities to introduce policies that will oblige public buildings to have indoor models and to update their models every time modifications are made to the building.

The result of the project will be algorithms and open-source software tools, which will be available for companies involved in data acquisition and software development, including our consortium partners, to produce 3D indoor models for the end users. This will create revenue for these companies. The end-users, i.e. the BHVs, fire brigade and safety regions, will use the indoor models to manage crisis situations more effectively. The benefit for the society will be the provision of safer living environments indoors. We also expect that the market for 3D indoor models will further expand as indoor models find a wider range of applications, e.g. in energy efficiency analysis and structural health monitoring of buildings.

We expect that within three years from the start of the research we will develop a new method and prototype software for producing 3D indoor models from point cloud data. To test the software we will produce 3D indoor models for two hospitals. Our consortium partner iNowit will assist in obtaining the necessary permits, while our industry partner Cyclomedia will collect the point cloud data of the hospital. The resulting models will be used by the consortium partners to promote further utilization of the research results.

To disseminate the generated knowledge and results we will make all data, models, software and publications freely available on the internet. The software will be made open-source, which will allow end-users, companies and researchers to freely use, modify, customize and expand the software. The free access to the software will also promote its utilization and will facilitate the use of indoor models in other applications. For the publications we will mainly choose open-access journals to facilitate the dissemination of the generated knowledge.

On basis of our results in indoor modelling, on-going Dutch standardisation initiatives such as geo-register concepts, BGT (basis registration topography), BAG (basis registration buildings), all in geo-domain; and CB-NL (Concept Library Netherlands) in BIM-domain can be adapted and extended for the purpose of emergency response and safety in buildings. Together with the safety regions we will organise a workshop for municipalities and standardization organizations to demonstrate how our results can improve the safety of public buildings. We will also contact Geonovum to further discuss the extension of existing standards for indoor models. We will present the grammar for space subdivision at OGC meetings to be considered as a generic approach for network computation in the IndoorGML standard.

5.4 PAST PERFORMANCE

The group at TU Delft has developed several prototypes related to navigation: e.g. two-level door-to-door indoor navigation (utilized by Bentley Systems), multi-agent based navigation among dynamic obstacles (in process of utilization by NMPO), guiding instructions for indoor navigation. The group has participated in several projects related to this proposal: 2 national projects developing models for crisis response, an NGI project on 3D SDI for the Port of Rotterdam (on semantically reach 3D models). The group currently has three running projects from the Dutch scientific organisation (one VIDI and two STW/NWO) related to 5D and 3D outdoor models. Members of the group have received various prises for scientific research.

The group at the University of Twente has developed a number of software tools which have been utilized (non-commercially) by various companies and organizations. These include: software for processing laser scanned data of rail tracks used by Movares, tools for 3D building reconstruction used by iDelft, NEO, TNO and TopScan, software for the generation of the 3D version of TOP10NL used by Kadaster. The group is currently involved in two European projects on disaster mapping. Members of the group have received multiple awards for their excellent contributions to research on geo-information extraction.

6. INTELLECTUAL PROPERTY

6.1 CONTRACTS

There are no existing contracts (including material transfer agreements, licences, cooperation agreements) with third parties in relation to the subject of the research.

6.2 PATENTS

Sisi Zlatanova has a registered patent US8504292 (Indoor localization based on ultrasound sensors). The patent is on the name of several people from the Bentley Systems Incorporated and TU Delft. The patent is property of Bentley Systems Incorporated. This patent does not obstruct development and dissemination of results as planned in this proposal. Technology similar to the patented one is not going to be utilised within this research.

We have not found any other patents that directly address the use of semantic 3D indoor models for routing and navigation indoors.

7. POSITIONING OF THE PROJECT

This project proposal focuses on several topics, which elsewhere have been only addressed in isolation but not in their integrity. The project aims at bridging research on 3D indoor reconstruction from point clouds, 3D indoor models (geometry, semantics and topology) and 3D indoor navigation for users with various profiles and tasks. Presently, a procedure for semi-automatic or automatic 3D reconstruction from point clouds that creates a 3D semantically rich model, which can be further subdivided or aggregated to support diverse users and activities in crisis situations, does not exist.

Indoor maps and models that are currently used in practice are mostly in the form of 2D floor plans and 360° cyclorama images. Floor plans are usually used for navigation purposes (See for instance Google Indoor Maps: http://www.google.com/maps/about/partners/indoormaps/) whereas cycloramas are common in virtual tours and online exhibitions. Examples of using cycloramas are Anne Frank's house (http://www.annefrank.org/en/Subsites/Home/) and RAI Amsterdam (http://www.exhibitcitynews.com/exploring-amsterdam-rai-google-indoor-streetview/) in the Netherlands, and National Museum of Natural History (https://www.mnh.si.edu/panoramas/) and Louvre (http://www.louvre.fr/en/visites-en-ligne) respectively in USA and France. These kinds of models are not suitable for complex spatial analysis that is needed for crisis management indoors. They do not contain detailed 3D geometry and function of building components and relations between them in a proper structure, which can be queried for instance to generate an optimized evacuation route. Few newly designed buildings may have IFC models but they are rarely used for navigation due to their complexity and lack of qualified personnel to maintain them. Detailed information may also exist for particular buildings whose security is very important. An example in the Netherlands is Schiphol airport that has a GIS department responsible for collecting and maintaining indoor spatial data of the airport. In such cases the indoor model is often produced manually. Manual modelling requires trained staff, and is a tedious, expensive and time-consuming task. It can take several months depending on the complexity of the building and the modelling requirements (Tang et al., 2010).

Within the research community there have been efforts to generate 3D indoor models automatically from point cloud data and/or imagery. The common approach is to recognize planar surfaces of walls, floors and ceilings (Budroni and Boehm, 2010; Sanchez and Zakhor, 2012; Valero et al., 2012; Díaz-Vilariño et al., 2013; Mura et al., 2013; Xiong et al., 2013). Although these elements are 3D, they still have little use in spatial analyses, which require knowledge of indoor spaces rather than their constituent elements. Although it is possible to convert a surface representation to a volumetric space representation (Shapiro and Vossler, 1991), the process is computationally expensive and its success depends on the accuracy and completeness of the surfaces. Recent research shows a clear tendency to volumetric modelling of indoor spaces. Jenke et al. (2009) and Xiao and Furukawa (2012) describe methods for reconstructing constructive solid geometry (CSG) models of indoor spaces. Oesau et al. (2014) describe a space partitioning approach. Gröger and Plümer (2010) and Becker et al. (2013) use grammars based on split rules to model spaces in indoor environments. These methods focus on the reconstruction of geometry and do not address the semantics that is required for various spatial analyses, and the derivation of such semantics from the data or the model.

Research and developments on routing is very extensive, but relatively little research focuses on real 3D solutions. Most of the approaches consider routing on navigable surfaces (2D, 2.5D), which creates difficulties when the height of ceilings, doors, windows or tables is needed for navigation to resources in walls or ceilings. Several models have been proposed, which consider the real 3D situation, but they are mostly conceptual. A very few of them are linked to the 3D reconstruction procedure (e.g. Meijer et al., 2005). The concept of network creation applying Poincare duality is applied in several developments (Lee, 2004; Becker et al., 2008). However these approaches focus mostly on very generic spaces (such as rooms), and result in rough networks inappropriate for complex analysis. Additional algorithms are used (i.e. medial axis transformation and/or visibility graph) to enhance the network with location of doors and windows and to avoid obstacles. Such approaches can be used for a large group of navigation applications in daily life when users have sufficient time to observe and explore the indoor environment. They fall short for emergency situations.

7.1 UNIQUENESS OF THE PROPOSED PROJECT

From a scientific point of view our proposal is original and innovative because it aims at integrated research and developments to provide solutions to flexible 3D navigation for emergency navigation:
i) We will develop methods to generate 3D indoor models that are rich in semantic relations, which are essential for doing complex spatial analyses such as routing and navigation indoors. Creating semantically rich 3D indoor models from raw data has not been addressed before and remains an open problem.
ii) We will develop semi-automated tools, which allow user interaction to correct or modify the modelling process. Existing approaches aim at full automation, which might fail in complex interiors or when data contains noise or gaps.
iii) We will design models which can best represent the reconstructed indoor environments with their semantics, geometry and topology. Existing semantic models are insufficient for emergency situations.
iv) We will design grammar and corresponding algorithms for automatic subdivision of spaces with respect to the user profile (characteristics and tasks) to derive a user-adapted network for navigation. Automatic subdivision/aggregation of spaces to support individual navigation is still an open issue.

From a utilization point of view the proposal is unique because it addresses the important issue of crisis management in large public buildings and will result in new business processes. We foresee that creating up-to-date 3D indoor models for safety and security purposes will become a requirement for all large public buildings. This will lead to new business processes for data acquisition and generation of such models.

7.2 EMBEDDING OF THE PROPOSED PROJECT

The proposed research will be carried out at two research groups, namely the section GIS technology of TU Delft and the department of Earth Observation Science (EOS) of University of Twente.

One of the research themes in the Section GIS technology is Geo-information for Crisis management, which is led by Sisi Zlatanova. The group has expertise in 3D modelling and specifically data models, semantics and analysis for emergency response. A large number of international publications reflect the completed research. Currently, two PhD students (e.g. Wang and Zlatanova, 2013, Liu and Zlatanova, 2013) and several MSc students are working or have completed their research on topics related to 3D modelling for indoor navigation (Xu et al., 2013; Moreno et al., 2012; Pu and Zlatanova 2005; Meijers et al., 2005). One external PhD student has completed his work on semantically-rich 3D model for facility management (Hijazi et al., 2012). More information about the group can be found at: www.gdmc.nl/pubs.

The research theme of EOS is acquisition and quality of geospatial information. It involves the development of methodology for the extraction of geometric and semantic information from imagery and point clouds for various applications. The group has extensive experience in 3D modelling of the built environment including buildings, railroads and indoor environments. In the last few years, several MSc theses have been completed in the research group on topics related to 3D indoor modelling. In this respect, the topic of the proposal embeds perfectly within the ongoing initiatives of the research group. More information about the research activities of the group can be found at: http://www.itc.nl/acqual/. The group also has ongoing collaborations with the University of Vigo on generating indoor models for energy efficiency analysis of old building (See e.g. Díaz-Vilariño et al., 2014; Khoshelham and Díaz-Vilariño, 2014).

8. REFERENCES

8.1 SELECTION OF KEY PUBLICATIONS RESEARCH GROUP

Isikdag, U., S. Zlatanova and J. Underwood, 2013, A BIM-Oriented Model for supporting indoor navigation requirements, Computers, Environment and Urban Systems, Volume 4, September 2013, pp. 112-123

Zlatanova, S., L. Liu, and G. Sithole, 2013. A Conceptual Framework of Space Subdivision for Indoor Navigation. ISA '13 Proceedings of the Fifth ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness, ACM New York, NY, USA. pp. 44-48

Khoshelham, K. and Oude Elberink, S.J. (2012) Accuracy and resolution of Kinect depth data for indoor mapping applications. In: Sensors: journal on the science and technology of sensors and biosensors : open access, 12 (2012)2 pp. 1437-1454.

Vosselman, G. and Maas, H.-G. (2010) Airborne and terrestrial laser scanning. Whittles Publishing, ISBN 978-1904445-87-6, 320 p.

Pu, S. and Vosselman, G. (2009) Knowledge based reconstruction of building models from terrestrial laser scanning data. In: ISPRS Journal of Photogrammetry and Remote Sensing, 64 (2009)6 pp. 575-584.

8.2 LIST OF PUBLICATIONS CITED

Afyouni, I., C. Ray, and C. Claramunt, 2012, Spatial models for context-aware indoor navigation systems: A survey, Journal of Spatial Information Science, Number 4 (2012), pp. 85–123

Becker, S., Peter, M., Fritsch, D., Philipp, D., Baier, P., Dibak, C., 2013. Combined Grammar for the Modeling of Building Interiors. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.* II-4/W1(1-6.

Becker, T., C. Nagel, T.H. Kolbe, 2008, A Multilayered Space-Event Model for Navigation in Indoor Spaces. In: Lee, Zlatanova (eds.). 3D Geo-Information Scienes, Lecture Notes in Geoinformation and Cartography, 2009, Part II, 61-77.

Budroni, A., Boehm, J., 2010. Automated 3D reconstruction of interiors from point clouds. *International Journal of Architectural Computing* 8(1), 55-73.

Díaz-Vilariño, L., Lagüela, S., Armesto, J., Arias, P., 2013. Semantic as-built 3d models including shades for the evaluation of solar influence on buildings. *Solar Energy* 92(0), 269-279.

Díaz-Vilariño, L., Martínez-Sáncheza, J., Lagüelaa, S., Armestoa, J., Khoshelham, K., 2014. Door recognition in cluttered building interiors using imagery and Lidar data. ISPRS Technical Commission V Symposium "Close-range imaging, ranging and applications", Riva del Garda, Italy.

Gröger, G., Plümer, L., 2010. Derivation of 3D Indoor Models by Grammars for Route Planning. *Photogrammetrie-Fernerkundung-Geoinformation* 2010(3), 193-210.

Hall, E. T. (1969). *The hidden dimension* (Vol. 1990). New York: Anchor Books.

Hijazi, I., M. Ehlers and S. Zlatanova, 2012, NIBU: a new approach to representing and analyzing interior utility networks within 3D geo-information systems, In: International Journal of Digital Earth, Vol. 5. Issue 1, pp. 22-4

Jenke, P., Huhle, B., Straßer, W., 2009. Statistical reconstruction of indoor scenes, Proc. WSCG.

Junestrand, S., Keijer, U., & Tollmar, K. (2001). Private and public digital domestic spaces. *International Journal of Human-Computer Studies*, *54*(5), 753-778.

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

Lee, J. and S. Zlatanova, 2008, A 3D data model and topological analyses for emergency response in urban areas, In: Zlatanova&Li (Eds.), Geospatial information technology for emergency response (ISPRS book series), Taylor & Francis Group, London, UK, pp. 143-168.

Liu, L. and S. Zlatanova, 2013, A two-level path-finding for indoor navigation, In: S. Zlatanova, R. Peters, A. Dilo and H. Scholten (Eds.); Intelligent systems for crisis response, LNG&C, Springer, Heidelberg, New York, Dordrecht, London, pp. 31-42

Khan, A.A. and T. H. Kolbe, 2013,Subspacing based on connected opening paces and fro different locomotion types using geometric and graph based representations in multi-layered space event model (MLSEM), Annals of ISPRS, Volume II-2/W1, ISPRS 8th 3DGeoInfo Conference & WG II/2 Workshop, 27 – 29 November 2013, Istanbul, Turkey, pp. 173-185

Khoshelham, K., Díaz-Vilariño, L., 2014. 3D modeling of interior spaces: learning the language of indoor architecture. ISPRS Technical Commission V Symposium "Close-range imaging, ranging and applications", Riva del Garda, Italy.

Meijers, M., S. Zlatanova and N. Pfeifer, 2005, 3D geo-information indoors: structuring for evacuation, In: Proceedings of Next generation 3D city models, 21-22 June, Bonn, Germany, 6 p.

Moreno, A., Á. Segura, S. Zlatanova, J. Posada and A. García-Alonso, 2012, Benefit of the integration of semantic 3D models in a fire-fighting VR simulator, Applied Geomatics, September 2012, Volume 4, Issue 3, pp. 143-153

Mura, C., Mattausch, O., Villanueva, A. J., Gobbetti, E., Pajarola R., 2013. Robust Reconstruction of Interior Building Structures with Multiple Rooms under Clutter and Occlusions. In Proc. 13th International Conference on Computer-Aided Design and Computer Graphics, November 2013.

Nakauchi, Y., & Simmons, R. (2002). A social robot that stands in line. *Autonomous Robots*, *12*(3), 313-324

Oesau, S., Lafarge, F., Alliez, P., 2014. Indoor scene reconstruction using feature sensitive primitive extraction and graph-cut. *ISPRS Journal of Photogrammetry and Remote Sensing* 90(0), 68-82.

Pu, S. and S. Zlatanova, 2005, Evacuation route calculation of inner buildings, In: van Oosterom, Zlatanova & Fendel (Eds.), Geo-information for disaster management, Springer Verlag, Heidelberg, pp. 1143-1161

Sanchez, V., Zakhor, A., 2012. Planar 3D modeling of building interiors from point cloud data, 19th IEEE International Conference on Image Processing (ICIP), Orlando, FL, pp. 1777-1780.

Shapiro, V., Vossler, D.L., 1991. Construction and optimization of CSG representations. *Comput. Aided Des.* 23(1), 4-20.

Scheflen, A. E. (1975). Micro-territories in human interaction. *Organization of Behavior in Face-to-Face Interaction, Mouton Publishers, Den Hague*, 159-173

Stiny, G., 2008. *Shape: talking about seeing and doing*. The MIT Press.

Stiny, G., Mitchell, W.J., 1978. The Palladian grammar. *Environment and Planning B* 5(1), 5-18.

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.

Valero, E., Adán, A., Cerrada, C., 2012. Automatic Method for Building Indoor Boundary Models from Dense Point Clouds Collected by Laser Scanners. *Sensors* 12(12), 16099-16115.

Wang, Z. and S. Zlatanova, 2013, Taxonomy of Navigation for First Responders, In J. Krisp (Eds.) Progress in Location-Based Services, LNG&C, Springer, Heidelberg, New York, Dordrecht, London, pp. 297-315

Xiao, J., Furukawa, Y., 2012. Reconstructing the world's museums. Proceedings of the 12th European conference on Computer Vision - Volume Part I, Florence, Italy.

Xiong, X., Adan, A., Akinci, B., Huber, D., 2013. Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in Construction* 31(0), 325-337.

Xu, W., M. Kruminaite, B. Onrust, H. Liu, Q. Xiong, and S. Zlatanova, 2013, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-4/W4, 2013. 51 – 55 December 2013, Cape Town, South Africa

9. ABBREVIATIONS AND ACRONYMS

3D	Three Dimensional
BIM	Building Information Model
BHV	Bedrijfshulpverlening (company/institution employees trained to help in emergencies)
CSG	Constructive Solid Geometry
EOS	Scientific Department Earth Observation Science
ISPRS	International Society for Photogrammetry and Remote Sensing
NGI	Next Generation Infrastructure

OGC	Open Geospatial Consortium
OTB	Department OTB - Research for the Built Environment
SWG	Standard Working Group
TUD	Technische Universiteit Delft
UT	Universiteit Twente
WP	Work Package