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# A geometrical-based approach to recognise structure of complex interiors

by

**Shazmin Aniza Abdul Shukor**

A thesis submitted to in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering

Warwick Manufacturing Group, University of Warwick
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# List of Abbreviations

| | |
|---|---|
| AEC | Architecture, Engineering, Construction |
| BIM | Building Information Modeling |
| CAD | Computer Aided Design |
| CNC | Computer Numerical Control |
| EM | Expectation-Maximization |
| FM | Facilities Management |
| ICP | Iterative Closest Point |
| LADAR | Laser Detection And Ranging |
| LIDAR | Light Detection And Ranging |
| LoD | Level of Detail |
| NASA | National Aeronautics and Space Administration |
| PCA | Principal Component Analysis |
| RADAR | Radio Detection And Ranging |
| RANSAC | RANdom SAmple Consensus |
| RP | Rapid Prototyping |
| SLAM | Simultaneous Localization And Mapping |
| SVM | Support Vector Machine |
| UAV | Unmanned Aerial Vehicle |

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# Declaration

I declare that all the work described in this report was undertaken by myself (unless otherwise acknowledged in the text) and that none of the work has been previously submitted for any academic degree. All sources of quoted information have been acknowledged by means of references.

# Abstract

3D modelling of building interiors has gained a lot of interest recently, specifically since the rise of Building Information Modeling (BIM). A number of methods have been developed in the past, however most of them are limited to modelling non-complex interiors. 3D laser scanners are the preferred sensor to collect the 3D data, however the cost of state-of-the-art laser scanners are prohibitive to many. Other types of sensors could also be used to generate the 3D data but they have limitations especially when dealing with clutter and occlusions. This research has developed a platform to produce 3D modelling of building interiors while adapting a low-cost, low-level laser scanner to generate the 3D interior data. The PreSuRe algorithm developed here, which introduces a new pipeline in modelling building interiors, combines both novel methods and adapts existing approaches to produce the 3D modelling of various interiors, from sparse room to complex interiors with non-ideal geometrical structure, highly cluttered and occluded. This approach has successfully reconstructed the structure of interiors, with above 96% accuracy, even with high amount of noise data and clutter. The time taken to produce the resulting model is almost real-time, compared to existing techniques which may take hours to generate the reconstruction. The produced model is also equipped with semantic information which differentiates the model from a regular 3D CAD drawing and can be use to assist professionals and experts in related fields.

# Chapter 1

# Introduction

*"For, usually and fitly, the presence of an introduction is held to imply that there is something of consequence and importance to be introduced"*

**-** Arthur Machen*

3D modelling of existing building interiors has gained a lot of interest since the late 1990s, due to the increasing development of Building Information Modeling (BIM), as well as the rapid development of 3D laser scanners. BIM is a process developed to assist prior to and during construction stages of new buildings that combines visualization technologies (3D modelling) with related information such as cost and timing. Due to its benefits, BIM is then extended further for currently in-use interiors. To develop this 3D model, 3D measurement systems such as the 3D laser scanner have been used to collect 3D data representing the interiors. Despite this growth, developing 3D modelling of interior that is still in-use, however, is challenging. Quoting Smith and Tardif (2009) in their book about BIM, although BIM has been implemented widely in developing new buildings, adapting BIM in existing

* BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 19 May 2011].

buildings is 'continually improving'. This is due to several reasons such as the existence of clutter, in terms of furniture and people as well as its complex interiors.

This research is being developed with these challenges in mind - with the intention that all the professionals involved in the above mentioned applications could obtain some benefit from the developed method. People from a variety of backgrounds - from architects, engineers, to geospatial intelligence as well as computer graphics developers - all have shown a lot of interest in working within the same field since knowing the potential of this area of work. Nevertheless, there are still some restrictions from these methods developed by them that could not be overlooked.

This chapter will discuss the context of this research, and the motivation behind the reason of conducting this research. It will also mentioned the problem, aim and objectives of this research, based on the description of current problems in this topic's area. Contributions from this research will also be pointed out, together with their description on where to refer to for more details on them, plus with a list of publications made throughout completing this research. It will end with an outline of the overall thesis to show the flow of its structure.

## 1.1 Background, motivation and context of the research

Before going further into detail about this research, it is good to know about its background first. Although 3D digital representation or 3D modelling in short, has benefited a lot of other applications such as assisting industries in design, measurement and inspection of their products, it has only been introduced to the Architectural, Engineering, Construction (AEC) sector over the past 20 years. Before that, not so much 3D modelling has been created to represent a building, especially building interiors, apart from archaeologists who try to conserve and record important and historical building interiors, mainly through photogrammetry, which will be discussed further in Chapter 4.

But when American architects and engineers introduced 3D modelling to aid building construction, which is part of Building Information Modeling (BIM), experts and professionals in AEC have now started to use 3D modelling in constructing new buildings. By using BIM, architects and engineers use 3D modelling to illustrate how the building will look like to the owner and contractors before the construction starts. Contractors will be using the same model to build up the building, and later, building owners and managers can use the same model as the as-built drawings for maintenance purposes. The continuous use of the same 3D model in BIM,  is being referred to as building lifecycle and is very functional as all related people are only using and depending on the same 3D model to design, construct and use the building, compared to the current method where different drawings and platforms are used. Apart for AEC, 3D modelling of building interiors are getting more attention in mobile robotics navigation as well as preserving historical buildings applications too.

However, in order to develop a 3D model for an indoor environment that is currently in use, a suitable measurement system is needed to gather and collect the data representing this real environment. But, as these buildings are often occupied and full of clutter, getting the information about the spaces inside the buildings could be difficult. In the context of this research, "clutter" represents other things apart from the one defining the closed-surfaces of the room (wall, ceiling, floor), such as the furniture and other equipment like computers, bins, book shelves, etc. This clutter will create occlusions during data collection, i.e. the holes and shadows within the data signifying the surfaces due to clutter, which create incomplete and missing data.

Although there are a lot of sensors that are currently available to collect necessary 3D data for the modelling, not all of them are suitable to handle these clutter and occlusion issues. Earlier work even used sensor fusion systems to collect these 3D data sets. The term "sensor fusion" refers to a system which consists of similar or different sensors together or both, where in here, the data that is collected by all the sensors needs to be fused or processed together to obtain the 3D data. Sensors like cameras and 2D lasers are often fused together to enable the system to collect data in 3D. But the most recent development is to use a 3D laser scanner to collect the interior data. Being a rapid acquisition system that is capable of producing a high density point cloud data with good accuracy, these elements are necessary when developing such modelling as these are needed by the professionals to assist their work, thus making the system more preferred to collect the interior data. However, the supplied 3D point cloud data does come with redundant data called "noise data", which represents the point cloud that does not resemble the overall image of the space, for example outliers that are outside of the room. Another related issue is the correct modelling method that needs to be applied to the data obtained in order to produce an accurate 3D model which represents the desired interior. Existing methods that can be used to process point cloud data generated by the laser scanner are sometimes limited to process synthetic items data. "Synthetic items data" is referring to the data of man-made objects like toys and historical statuettes, that have been collected in a controlled environment, where the surroundings (lighting, percentage of clutter and occlusions, etc) is changeable according to the needs. All this information about methods to process 3D point cloud data generated by the laser scanner, as well as the suitable hardware to be used to collect the interior data, will be examined further in Chapter 3 and 4, respectively.

Hence, we can see the importance of 3D modelling that represents building interiors, for the above applications. Due to this importance, this research is being done to handle several issues related with the development of 3D modelling of indoor environments. The context of this research is within the scope of investigating the usage of point cloud data obtained from a 3D laser scanner to develop in-use building interior models. Here, the interior is a closed space that usually exists in most buildings, for example office space (individual and open plan office), class rooms, lecture halls, discussion or meeting rooms, etc. As most of the spaces inside this type of building are within the scope of this definition of closed interior, it should cover most of them, with exception for spaces like a large open space or a long corridor where the wall may be outside the scanner's range. The algorithm developed from this research will be used to reconstruct 3D digital representation models and mapping of the closed space, whether they are "complex indoor environments" or just "sparse rooms". In this research, "complex indoor environments" represents an interior with complex geometry construction or composition of the building (for example, layered ceiling, existence of pillars) as well as non-structural interior (such as cable skirting), together with the presence of furniture and equipment that will create occlusions and clutter issues, while "sparse room" is a cubic structure of a room (box-type) with less objects that would create slight clutter and occlusion problems. The resulting 3D model will consist of some "mapping" features as well, where it labels the important surfaces that exist in the interior. These features are important, as it will aid visualization for humans and mobile robots too.

The resulting model should consist of a level of detail which suits any type of application that might want to employ it and it has no preference for a particular application. Therefore the reconstruction can be used to represent the closed space in general for architecture, property management, historical building conservation as well as autonomous vehicle mapping applications.

Based on the above explanation, this research is about developing an algorithm that is suitable to process 3D point cloud data from a laser scanner that has been used to collect data of a room that is currently in use. The algorithm will reconstruct existing surfaces within the room and map the entity accordingly to aid visibility. This 3D map can act as a valuable record for architects and civil engineers - which is very helpful for future structural renovation or maintenance, as the current interior might differ from the initial design, that is the drawing that was used to construct the building originally, may have altered. Furthermore, old buildings may not have any blueprint or diagram to represent its interior conditions. From a facility and building management point of view, this 3D map can be used to verify space usage and efficiency. Apart from that, it can also serve for building conversion and conservation. Mobile robots can use the map for navigation around the interior. As the future will predict a lot of usage of domestic robots, these autonomous mobile robots will start to inhabit a normal building and as such, 3D maps will be useful to help them to perform any task that they are required to do, for example cleaning and surveillance.

## 1.2 Research questions, aim, objectives and contributions

### 1.2.1 Research questions

- What are the limitations of current approach in producing modelling of existing building interiors that can be overcome?
- Where can advances in knowledge be made?
- How can this knowledge advancement be used to overcome some of these limitations?

### 1.2.2 Aim

This research aims to produce a modelling solution to process 3D point cloud data obtained from a low-cost, low-specification laser scanner, in order to resolve current limitations and gaps for developing 3D models of building interiors using laser scanner data. Lower specification for this research, is defined as having a resolution of less than the state-of-the-art laser scanner (less than 5 points per degree).

### 1.2.3 Objectives

- To carry out a wider investigation into current approaches used in developing 3D modelling for indoor surroundings through literature and survey to validate the gaps and current limitations
- To provide a solution for the cost of state-of-the-art laser scanner by using a low-cost, low-specification laser scanner in collecting 3D building interiors data

- To develop a suitable algorithm to process the data obtained from the low-cost, low-specification laser scanner by adapting current methods and combining them with novel methods
- Finally, this research must incorporate a proof of concept by the means of empirical evaluations that leads to the justification of novel contributions to knowledge.

### 1.2.4 Contributions

Contributions this body of research makes are as follows:

- A review of existing techniques in producing 3D models of building interiors using laser scanner data, plus additional information on current advantages and limitations from 19 experts (refer to Chapter 3). These experts are individuals identified during research who use interior 3D models or could use the models such as architects, surveyors, AEC engineers, facility managers and geospatial intelligence.
- An alternative, low-cost solution to collect 3D data representing building interiors. As compared in Chapter 2, the state-of-the-art laser scanner is costly and prohibitive to some, having a low-cost laser scanner could provide an alternative to collect 3D data. More information on the adapted laser scanner can be obtained in Chapters 2 and 4.
- A new platform that can be used to model realistic environments with clutter and occlusions which can have ideal (or sparse) as well as non-ideal geometrical structure, without the limitation of being applied to a single sample interior only. By combining a new algorithm as well as adapting existing methods, this platform can be extended to model new environments. Data which represents these environments of a sparse room, with little clutter as well as complex indoor environments will be mentioned in

Chapter 4 and Chapter 5 to show the workability of the algorithm in different environments.

- A new, novel technique for point cloud data registration. As current methods require a high percentage of overlapping points, furthermore most of them are for registering newly acquired data into model data, a new method to register interior data within point clouds has been developed. This method will be discussed further in Chapter 5.
- A new pipeline of algorithm for surface reconstruction modelling of building interior from point cloud data. The approach of algorithm developed in this research is unique and different from others, and will be mentioned further in Chapter 5.
- An automatic solution, based on prior knowledge, to model 3D interior data. This is developed due to the needs of greater automation in interior 3D modelling. This is also discussed in Chapter 5.
- Implication of proposed framework in the domain of AEC (Architecture, Engineering, Construction), archaeology visualization application and mobile robot navigation as potential future users of this work, as mentioned in Chapter 7.
- Semantic information features offered by this algorithm differs from an ordinary 3D CAD drawing, which is essential in assisting future renovation work. More information on these semantic features can be obtained in Chapter 7.

## 1.3 Publications

Throughout conducting this research, several publications have been made on parts of the work. Below is the list of peer-reviewed publications achieved:

- Abdul Shukor, S.A. & Young, K. (2011). A fast knowledge-based plane reconstruction method from noisy 3D point cloud data. In: Hamza, M.H. & Zhang, J.J., eds. IASTED (International Association of Science and Technology for Development), *12th International Conference on Computer Graphics and Imaging*. Innsbruck, Austria 16-18 February 2011. IASTED, pp. 24-31.
- Abdul Shukor, S.A., Young, K. & Rushforth, E.J. (2011). 3D modeling of indoor surfaces with occlusion and clutter. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Mechatronics*. Istanbul, Turkey 13-15 April 2011. IEEE, pp. 282-287.
- Abdul Shukor, S.A., Rushforth, E.J. & Young, K.W. (2011). A method for 3D modelling of building interior from laser scanner data. In ISPRS (International Society for Photogrammetry and Remote Sensing), *Working Group V/2 Conference*. York, UK 17-19 August 2011. ISPRS (Abstract).

## 1.4 Thesis outline

Chapter 2 will review recent methods available in processing 3D point cloud data obtained from laser scanners, starting from collecting the data, the data preprocessing, modelling, mapping and finally measuring the accuracy of the final model. Some issues with laser scanner data modelling will also be highlighted. Then, Chapter 3 is designed to highlight the overall method used to meet the aim of this research. Next, Chapter 4 will discuss the hardware used and the method of collecting 3D data in this research. A short chronology about collecting 3D data to develop 3D interior model is also included for reference, and this chapter will discuss the method chosen to collect the interior data of various indoor environments. After that, Chapter 5 will discuss the overall algorithm to process, model, interpret and measure the data. Comparison of other available methods with the chosen method used here will be highlighted to support the decision of using this particular method. Chapter 6 will focusing on the verifications and validations of the resulting models produced by this research. Some potential applications based on the results obtained are being mentioned in Chapter 7, to give more understanding and idea on how experts could exploit the modelling developed in this research. Finally, Chapter 8 will conclude the research, with a summary on the overall work done with its limitations and what future work can be done afterwards.

# Chapter 2

# Review of 3D Modelling Methods from Laser Scanner Data

*"You can have data without information,*

*but you cannot have information without data"*

**-** Daniel Keys Moran*

Laser scanners have been used extensively since the late 1990s for gathering data to produce 3D modelling. At first, no specified application was being highlighted for the processing and modelling of a laser scanner's point cloud data. Gradually, point cloud production from laser scanners was being used for texture reconstruction, surface reconstruction and modelling of various objects from simple geometric shapes to historical monuments and statuettes. Some advantages of 3D laser scanners are:

- High point density
- Rapid acquisition of 3D data
- Good accuracy (varies with type)

* BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 19 May 2011].

Although 3D laser scanners provide a lot of benefits in collecting 3D data, this approach still has challenges that need to be addressed. As the most natural conditions for 3D modelling applications, like building interiors and exteriors, will involve a great deal of occlusions and clutter, one must prepare a solution on how to reconstruct affected surfaces. 3D laser scanners are also used to reconstruct surfaces and textures for synthetic items. In this research, "synthetic item data" would be referred to as the data that has been collected in a controlled environment. In other words, the surroundings where the laser scanner is used to collect the data of any particular item can be changed, like lighting and percentage of clutter and occlusions. This would include data representing simple objects like toys, blocks, and even historical statuettes and carvings.

Apart from the occlusions and clutter issue, due to the 3D laser scanner capability of producing high point density, some scans could generate millions of points. Therefore, a suitable method must be arranged to handle them. Although commercial software packages such as Revit (by Autodesk) and Pointools (by Pointools Ltd) are available to handle this matter, many interactions from users are still needed which makes these processes 100% manual. Plus, the cost of the software is still high. Object recognition process is also important especially in 3D interior modelling as there are a lot of surfaces and structures that exist within a normal scene and most applications require them to be identified as well. All these entities could then be labelled and mapped together to produce a semantic map that represents the interior scene.

Due to the lacking of suitable method to handle these issues in processing point cloud data (i.e. clutter and occlusions, raw data handling, manual process of commercial software, features of semantic mapping), it is important to develop a method that is able to deal with them. But, before revealing the method developed in this research, it is good practice to recognize existing methods in handling this matter. Thus, this chapter will highlight some of the available methods published by other researchers for point cloud data processing generated by the 3D laser scanners, especially towards interior modelling. It starts by reviewing some commercially available laser scanners that have been used by others, then continues with the methods of data preprocessing. After that, methods used for point cloud reconstruction will be discussed. Techniques used in producing the semantic mapping from 3D point cloud data are also highlighted. As it is important to measure the accuracy of the result, quantitative assessment methods are also reviewed.

## 2.1 Laser scanner for data collection

Due to the fact that 3D laser scanners are getting much attention in gathering 3D data, there are a number of alternatives available in the market. 3D laser scanners are now available at different levels of specifications like range, measurement and accuracy at a variety of costs.

Early researches used a laser scanner by K2T Inc. (now Quantapoint, Inc.) to obtain 3D data for a close-range or partial surface reconstruction. Johnson and Hebert (1999) used it for synthetic item reconstruction (i.e. a rubber duck) while Stulp, *et al*. (2001) and Dell 'Acqua and Fisher (2002) use it to reconstructed a partial building interior with a single occlusion. This laser scanner was first developed by a group of researchers from Carnegie Mellon University also called K2T, before being changed to Quantapoint to imitate its business side (Quantapoint, 2011). At the same period, some research was being conducted using Perceptron, CYRAX and Riegl laser scanners. Whitaker, *et al*. (1997) and Castellani, *et al*. (2002) used Perceptron to reconstruct indoor scene and synthetic objects with occlusions respectively, whereas Gueorguiev, *et al*. (2000) and Allen, *et al*. (2001) used a CYRAX laser scanner to solve urban environment modelling. Han, *et al*. (2002) used Riegl laser scanner for both real scene and synthetic surface reconstruction.

More state-of-the-art laser scanners and mobile laser mapping systems are also being used to generate a more dense and accurate 3D data in recent times. Arayici (2007) used a higher specification of Riegl laser scanner to reconstruct building exteriors for built environment purposes. Leica laser scanners are used for synthetic data reconstruction by Yapo, *et al*. (2008), whilst Budroni and Boehm (2009) used it for reconstructing planar surfaces of a hallway and Brilakis, *et al*. (2010) used it for construction site modelling. Pu and Vosselman (2009) used StreetMapper mobile laser mapping system to reconstruct a model of Esslingen city in the Netherlands. A mobile laser mapping system is typically a laser scanner system mounted on top of a vehicle (car or van) which enables it to collect terrestrial data, usually for a large-scale urban outdoor application like highways and city modelling. Meanwhile, recent researchers from Carnegie Mellon University obtained their 3D data from a professional surveyor who uses a state-of-the-art laser scanner (Okorn, *et al*., 2010) (Adan & Huber, 2010).

As seen in the table, most of the researchers mentioned here are all using state-of-the-art 3D laser scanners, which are prohibitive to some (refer to Table 2.1). Due to this cost factor too, some researchers were depending on the data provided by the professionals, which create difficulties as they could not have access to more data to test their method. As mentioned in Tang, et al. (2010) in their review paper, one of the gaps in current research methods in creating 3D as-built models from laser scanner data is the lack of methods that are capable to process more than one environment. The majority of available methods have only been tested on one interior scene (Adan & Huber, 2010) (Budroni & Boehm, 2009) (Xiong & Huber, 2010) (Eich, *et al*., 2010) due to the difficulties in producing 3D interior datasets as it is costly to have the state-of-the-art 3D laser scanner. The lack of ability for the techniques to be applied to various different interior scenes will make them less robust and it is more appreciative if one could develop a general platform that can be used to produce 3D modelling of any interior scenery. Therefore, it is good to have a low-cost solution which can collect sufficient 3D data to represent existing building interiors.

| Laser scanner | Specifications | | | |
|---|---|---|---|---|
| | Scan rate | Scan area (°) | Range (m) | Price (USD) |
| RIEGL LMS-Z210 | 8000 pt/sec | 80 vertical,<br>360 horizontal | 800 | 21,000[*1] |
| CYRAX | 1000<br>pt/sec | 40 vertical,<br>40 horizontal | 100<br>(recommended max range 50) | 45,000[*1] |
| SICK LMS | 0.5 – 1.0 deg/sec | 180 | 80 | 7,000[*1] |
| SICK PLS[#] | 1 deg/sec | 180 | 50 | 2,000[*1] |
| K2T | 0.045 deg/sec | 360 azimuth,<br>63 elevation | Not available due to obsolescence | Not available due to obsolescence |
| Leica HDS3000 | Thousands – millions pt/sec | 270 – 310 vertical,<br>360 horizontal | 79 – 300 | 35,000 – 55,000[*2] |
| Perceptron P5000 | 0.24 deg/sec | 60 vertical,<br><br>60 horizontal | 40 | Not available due to obsolescence |

[*1]Approximate price as of November 2010, [*2]Approximate price as of July 2011

[#] Laser scanner used in this work. With added servo motor, the scan area is widen to 180° vertical and 180° horizontal

Table 2.1: Comparison of 3D laser scanner (Note: Prices obtained from available internet sources like online marketplace)

## 2.2 Data preprocessing

Before the point cloud data can be reconstructed to reveal its surfaces, it needs to be preprocessed first to ensure the data used represents the real conditions of the object of interest (or room area in this research). In this research, two preprocessing stages are being discussed - noise data removal and data registration - as both are the important steps in preprocessing 3D point cloud data before further reconstruction processes can being executed.

### 2.2.1 Noise data removal

Noise data needs to be filtered or removed before reconstruction can be made as they can contribute towards inaccurate modelling. Not all data provided by the 3D laser scanner is clean and ready to be reconstructed. SICK laser scanners for example, are known for producing noisy data. This is probably due to their specification which appeals to lower cost industrial-based applications.

To remove noise data, some researchers like Arayici (2007), Meadati (2009) and Brilakis, *et al*. (2010) used available commercial software to filter the data. Software like Revit and Polyworks are used especially by experts and professionals in 3D interior modelling development to remove unwanted data before further processes can be done. Although to have access to specific software to filter the noise data is an advantage, the cost of the software is prohibitive to some and this requires manual handling, which is very prone to erroneous removal of important data as one can remove important data when filtering the noise data.

In the meantime, some other researchers leaved out the process of removing noisy data. They assume clean, ready-to-be-processed data as this data is provided by the professionals, as it is prohibitive to have access to the state-of-the-art laser scanner due to cost. Among them are Okorn, *et al.* (2010), Stamos, *et al.* (2006) and Budroni and Boehm (2009). This is clearly not applicable towards all cases. One may claim that the data produced by the state-of-the-art laser scanner is perfectly clean, but they might have noise data that needs to be removed prior modelling.

Bajaj, *et al.* (1995) uses alpha shape (or α-shape) to define outliers from the data. α-shape is a method where it uses a predefined ball with a squared radius of α to determine the shape of a set of points. The ball will travel along the points to reveal the shape and the resulting shape revealed by α-shape depends on the radius of the chosen α. Quoting Computational Geometry Algorithms Library (2012) about α-shape analogy:

*'Let's say we have a tub of ice cream making up the space and containing the points as chocolate chips. Using a spherical-shape ice cream scoop, we carve out all parts of the ice cream block we can reach without bumping into the chocolate chips, hence we were carving out holes in the inside, resulting an object bounded by caps, arcs and points. A very small value of α (i.e. a very small scoop) will allow us to eat up all of the ice cream except the chocolate chips, whereas a huge value of α (i.e. a very large scoop) will prevent us even from moving the scoop between two pints since it's way too large.'*

Figure 2.1 shows a sample of 2D alpha shape. Although alpha shape works in his research, this method has not been tested towards removing noise data affected by clutter and occlusion, as Bajaj, *et al*. (1995) only used this towards synthetic items data which did not have any clutter and occlusions issues.

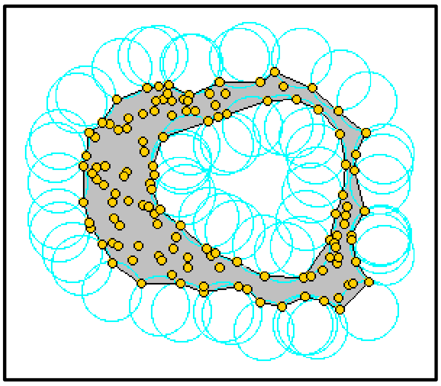


Figure 2.1: Alpha shape method, on 2D example, determines the shape of this points by rolling a predefined ball around them (Source: Computational Geometry Algorithms Library, 2012)

Meanwhile, Ali, *et al*. (2008) use binarization to remove noise data. Binarization is a process where a greyscale threshold is defined and applied to convert a greyscale image into a binary image, i.e. black and white image. From the binary image, the object of interest (in this case, windows as in Figure 2.2) can be detected. This method, however, can only be applied if one is using sensors that able to produce range or image data (i.e. camera or laser scanner that can generate range images data).

Figure 2.2: Binary image of a building to detect windows (Source: Ali *et al*., 2008)

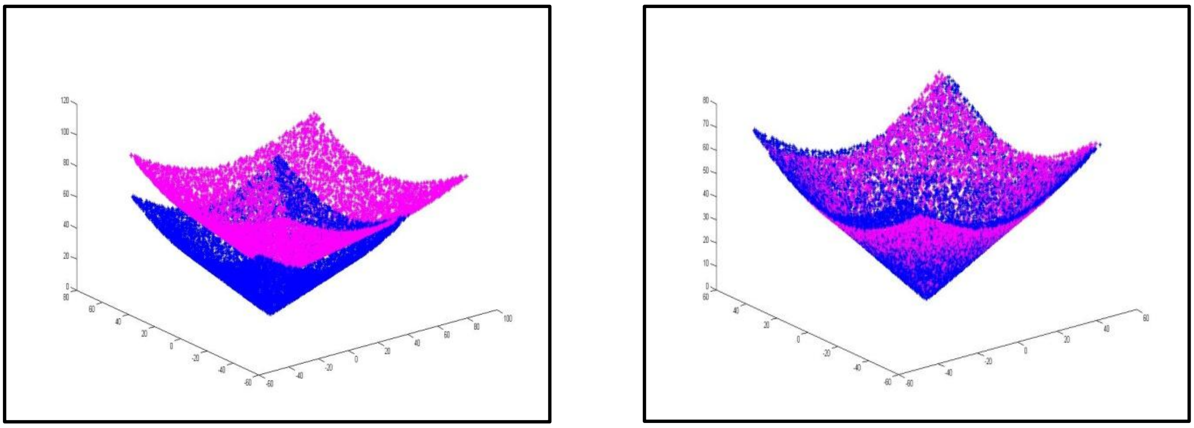
Some works, like in Adan and Huber (2010) perform manual data filtering processes before the modelling processes. The problem in manual data filtering techniques is the tendency to delete some relevant data (i.e. data representing the room structure) and this will contribute towards inaccurate modelling later on. Manual preprocessing is also a tedious, time consuming process, as users need to select the data carefully and check the result regularly to ensure correct removal of unwanted data.

### 2.2.2 Data registration

It is common when performing a surface reconstruction using laser scanner data to perform data registration prior to modelling, especially when dealing with bigger scale visualizations like buildings or life size monuments, as there will be more than one scan of data and they need to be registered together. Some registration methods are being considered during the data collection itself. This target-based registration method uses a 2D target with unique shape like a sphere or 'butterfly-figure' which it is placed around or actually on the object or environment of interest and this unique shape will be used as reference point in registering the data together before processing. This method is preferred by professionals who use a state-of-the-art laser scanner as usually an accompanying software package is available to register the data together through this method. For example, FARO and Z+F laser scanners have their own software called SCENE (FARO Technologies Inc., 2012) and LaserControl (Zoller + Froehlich GmbH, 2012). to assist user in registering the point cloud data collected by the respective hardware. As this type of data registration is conducted during the data collection, it will be discussed further in Chapter 4 on data collection processes. Due to the specialized target, this method can only be performed when one has access to the software package.

Apart from the above target-based registration, point cloud data is usually being registered by matching the input onto model data. This is usually being done when we have access to the original model data and would like to match similar input data with noise into it. People who have done this would usually like to test their registration method, by downloading the original model data from the database (like the Happy Buddha or Bunny by Stanford University). Then, noise will be introduced into the data (usually by inserting some Gaussian noise) to get noisy data. This noisy data will be used as the input to be matched with the original perfect model data to benchmark the developed registration method.

One of the well-known methods that use this principle is Iterative Closest Point (ICP). ICP was developed by Besl and McKay in 1992 to register two sets of data points together by minimizing the difference between the points. This is achieved by determining any transformation of the input data (due to translation or rotation process compared to the model data) and iteratively trying different transformations until the difference between the two set of data has been minimized. Figure 2.3 shows how ICP is being used to register data into the model. Among those who use ICP to register data together are Pu and Vosselman (2009) and Bosche (2010). However, due to its major limitation which it is prone to accumulative errors, many are now modify the original ICP, or combining it with other algorithms or doing both to produce several new methods. For example, Fitzgibbon (2001) combines ICP with Levenberg-Marquardt algorithm (LM) which claims to be more robust and generate faster results compared to the traditional ICP.



(a) (b)

Figure 2.3: ICP is used to register new data (in maroon) into model data (in blue): (a) original position of data before registration; (b) the registered data after 66 iterations (Source: Kroon, D.J., 2009)

Another method of data registration is feature-based. Here, similar features of two sets of data points are being used to register them together, and usually this method requires less overlapping points than ICP-based methods. Features that have been used are different in each case, for example, Whitaker, *et al*. (1999) and Pathak, *et al*. (2009) use the plane created from multiple data sets to register them together. As interior data points have planes representing surfaces like floors, these planes are used as the feature to match multiple data sets together before further reconstruction can be performed.

Rabbani, *et al*. (2007) developed a method to register point cloud data using features that normally exist within industrial sites. Features of geometric models like cylinders and spheres that are present in both data sets are being recognized and used to register the data together. By using these features, few overlapping points are needed to register the data compared to the ICP method which requires at least 25-30% of overlapping points (Rabbani, *et al*., 2007).

As some researchers used sensor fusion systems to collect data representing the object or environment of interest, this data can be utilized to register point cloud data together. Sensor fusion is a system which integrates two or more similar or different types of sensor and this data needs to be fused or rather processed together to produce the end result. There are a number of examples that use sensor fusion, and different types of input obtained from other sensors can be used to assist registration of point cloud data. For example, El-Hakim, *et al*. (1997) use a system which consists of a camera and a range sensor to collect interior data, and the images obtained from the camera are used to register the point cloud data together. While more recent research by the same author (El-Hakim, 2001) made use of information obtained from a dead-reckoning sensor which captures the location of the autonomous vehicle carrying a LIDAR, registers cloud data from the LIDAR data of historical sites.

## 2.3 Modelling the data

3D data modelling can be distributed into different sections, which depends on the type of application. For example, some works have been done to reconstruct surfaces of single objects like chairs, a lamp, facades, historical monuments and statues. These types of reconstruction need to consider the recreation of the surface texture as well, for example as highlighted by Wang and Oliveira (2002) and Breckon and Fisher (2008). As this research deals with building scene modelling and uses a low level of detail laser scanner, texture reconstruction is therefore out of the scope of the research and would not be discussed here.

At the beginning, researchers are more interested in reconstructing the outer surfaces, without considering any surfaces that are occluded by any objects in front of them. Results from modelling an interior will be just like a 3D rendered picture – no effort is conducted to perform reconstruction of planar surfaces with the entities separated. This is not suitable to be applied further for the applications (will be discussed further in Chapter 6), as most of them require separate handling of the surfaces' reconstruction to ease the overall functionality. Therefore, this section will discuss the surface reconstruction and methods in handling missing data due to clutter and occlusions separately as the later part is significant in producing idealized results, as the resulting model can be of benefited to professionals to aid their work.

### 2.3.1 Surface reconstruction

There are quite a number of methods available to reconstruct surfaces from 3D point cloud data, where most of them are statistical-based and surfaces are recognized and recreated using statistical models. Whitaker, *et al*. (1999) use weighted least square, while Hough transform combined with moving least square method has been used by Wang and Oliveira (2002, 2003). Both least square methods are based on the original least square, where a set of points are fitted approximately into either line, curve or surface. Figure 2.4 shows how least square is being used to fit surfaces onto a set of 3D points. While weighted least square approach averages the arithmetic means instead of assuming the same contributions from all points, moving least square produces a smoother interpolation compared to the weighted least square and is preferred for reconstructing 3D points. Meanwhile, Hough transform is often used for line (2D) and surface (3D) detection, where the detection work by determining the points' angle from the origin, and points who share the same angle will be verified as located on the same line or surface.

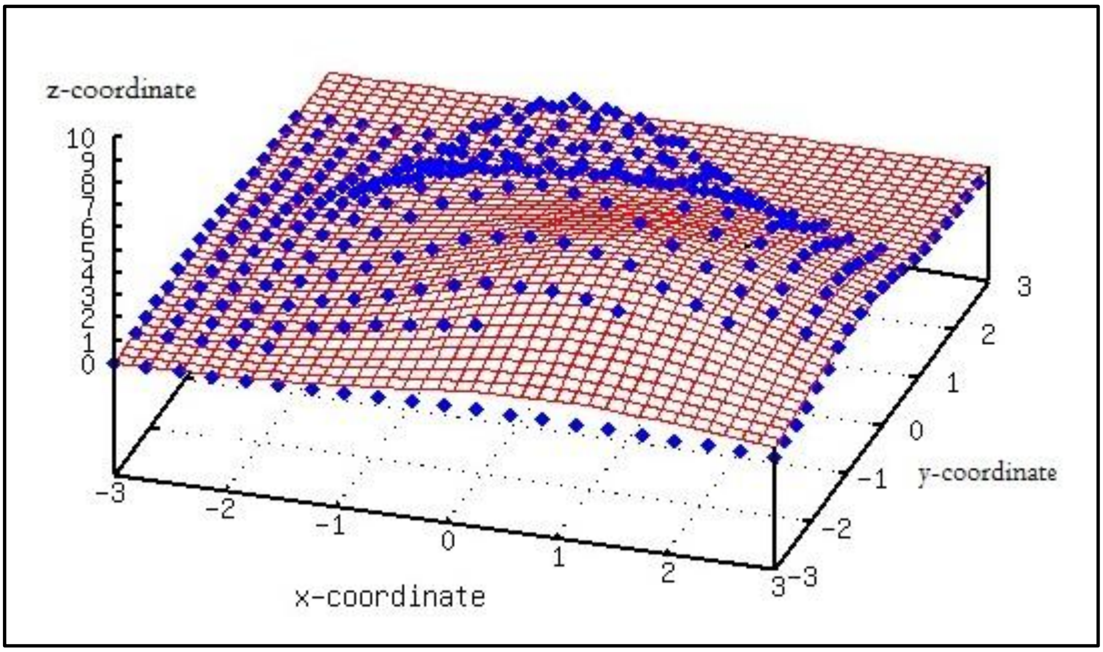



Figure 2.4: Fitting a surface onto a set of 3D points using least square (Source: OptimEFE, n.d.*)

Meanwhile, planar surfaces were represented by their volumetric information through voxelization by Adan and Huber (2010). Voxelization is a method to produce continuity of points by representing them in voxel, or volumetric pixel. From here, voxel can be segmented into respective surfaces by applying further classifications. Figure 2.5 shows an example of voxelization of smooth surfaces. Elevation information like heights and histograms were also being utilized to extract vertical and horizontal data before they can be categorized into

* OptimEFE [internet]. Available at: http://optimefe.sourceforge.net [Accessed 8 May 2012].

respective surfaces (Budroni & Boehm, 2009). A similar method is used by Okorn, *et al*. (2010) to develop floor plan modelling.

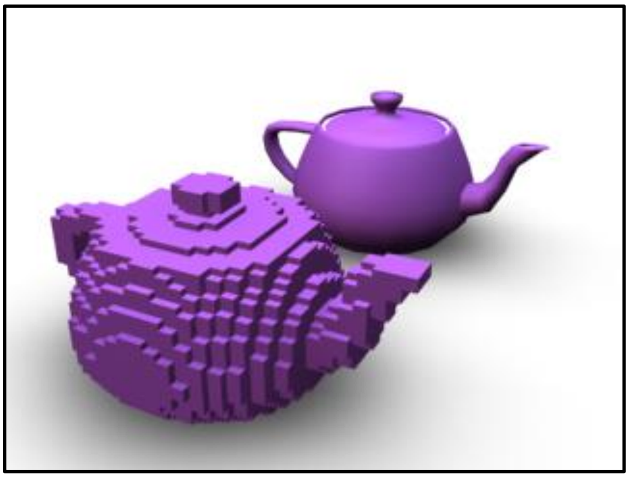


Figure 2.5: Voxel representation of a smooth teapot as on the right (Source: Mattausch, O., 2011*)

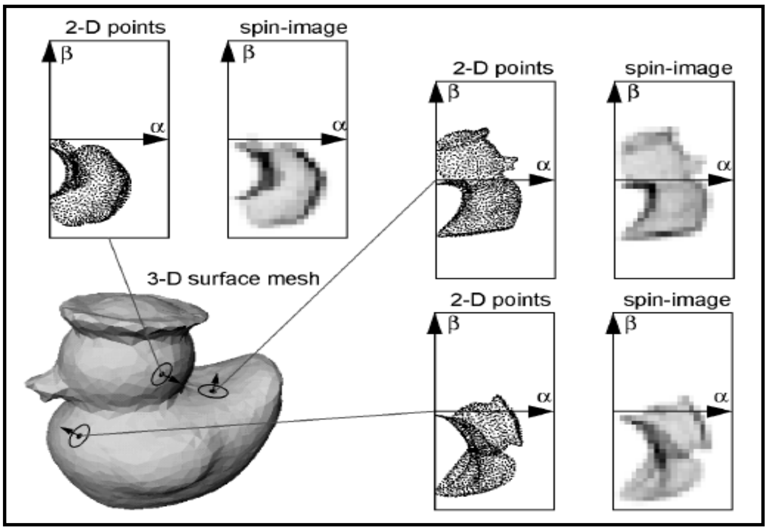
In the meantime, Eich, *et al*. (2010) use region growing algorithm to extract geometric data of a plane, where neighbouring points from a pre-defined seed points are being determined as to whether they belong to the same region by defining the similar criteria shared by them, and then this iterates until all points have been considered. Similar adaptation on region concentration are used by Sappa (2002) where a region connectivity graph is used while Stulp, *et al*. (2001) exploit depth discontinuity detection with fold edge details and cosine shaded image to reconstruct surfaces. Both rendering techniques (depth map and cosine shaded image) are being utilized to segment the points into respective surfaces.

Meanwhile, a probabilistic-based approach has been used by researchers in mobile robotics towards solving the Simultaneous Localization And Mapping (SLAM). Haehnel, *et al*. (2003)

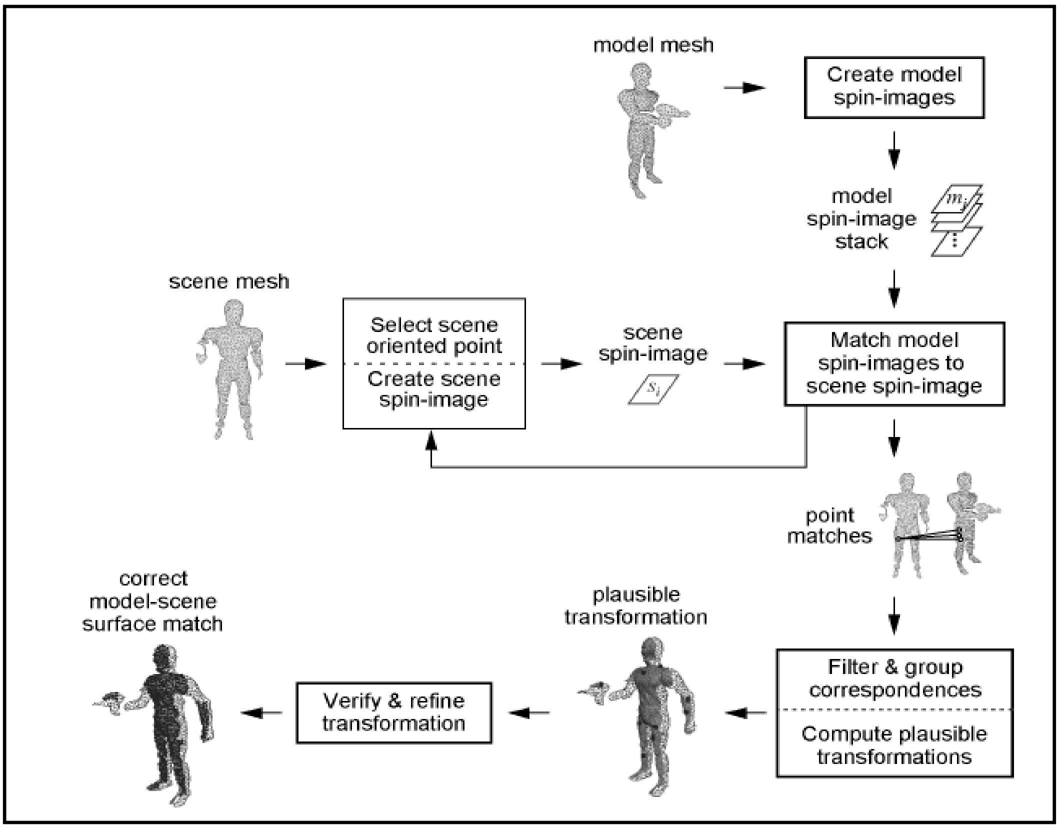
* Mattausch, O. [internet]. Available at: https://www.cg.tuwien.ac.at [Accessed 8 May 2012].

uses Expectation-Maximization (EM) method to produce a map from the laser scanner mounted on their robot. EM uses probabilistic models to segment data by iteratively fitting surfaces or planes towards the points. Other related methods like RANSAC and PCA are also being used by others to reconstruct the surfaces. RANSAC or RANdom SAmple Consensus is an algorithm that assumes outliers are parts of the data and will fit the data iteratively within the 'inliers' or required data. Meanwhile, Principal Component Analysis or PCA is a mathematical model that uses statistics to find patterns in the data. Elements like eigenvectors and covariance matrices were exploited to find the pattern of the points and fit them. Johnson and Hebert (1999) develop a method called spin images, and they use this with PCA to reconstruct surfaces of the object such as a rubber duck. Spin images is a method that can be used to reconstruct surfaces and recognize objects from point cloud data. Suppose there is a mesh model representing an object, and by applying a function to all vertices of the mesh, a set of points will be created. These points will be used to generate a set of images (i.e. spin images) and this set of spin images can be used to recognized the same object that has been occluded. Figure 2.6 summarizes the whole process of spin images. Cantzler, *et al*. (2002) use RANSAC for feature detection, and genetic algorithm to optimize the modelling.

Xiong and Huber (2010) combine geometry and statistical-based modelling methods of convex hull and conditional random field to classify planar patches. Convex hull reconstructs surfaces from a seed triangle developed from a set of points, and any points that are located at each side of the triangle will be searched and used to reconstruct new triangles. The triangles are then assimilated into the evolving polyhedron. The whole process will be repeated until all points have been considered. Figure 2.7 summarizes the process of convex hull.




(a)




(b)

Figure 2.6: (a) Summary of how spin images are generated from various vertices; (b) the overall process of surface reconstruction (Source: Johnson & Hebert, 1999)

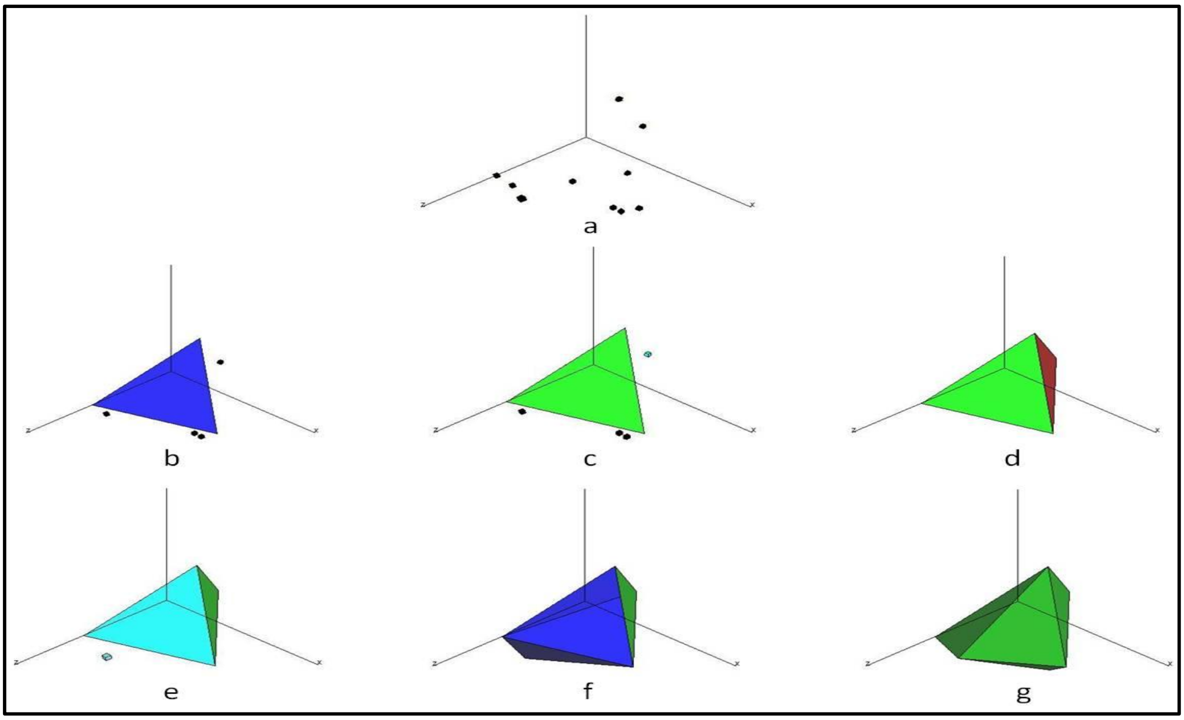



Figure 2.7: A summary of convex hull in 3D points: (a) the raw data; (b) the seed triangle which forms the basis of surface reconstruction; (c) a point in the right side of the seed triangle is recognized; (d) the point in (c) is used as the edge of a new triangle; (e) moving on to the next side where another point is recognized and be used to develop new triangle as shown in (f); (g) the final reconstruction representing all the points (Source: Lambert, 1998)

Apart from the above method, some professionals who are involved directly with reconstruction from 3D point cloud data are using commercially available software to process them. Arayici (2007) who is involved directly with built environment modelling, uses RiSCAN PRO software for point registration, 3D model editing and CAD extraction, and AutoCAD and Revit by Autodesk were used by architects like Meadati (2009) for data modelling. Meanwhile, Leica-based software such as Cyclone, Cloudworx and Geosystems were used by Brilakis, *et al*. (2010) to visualize the data for as-built modelling.

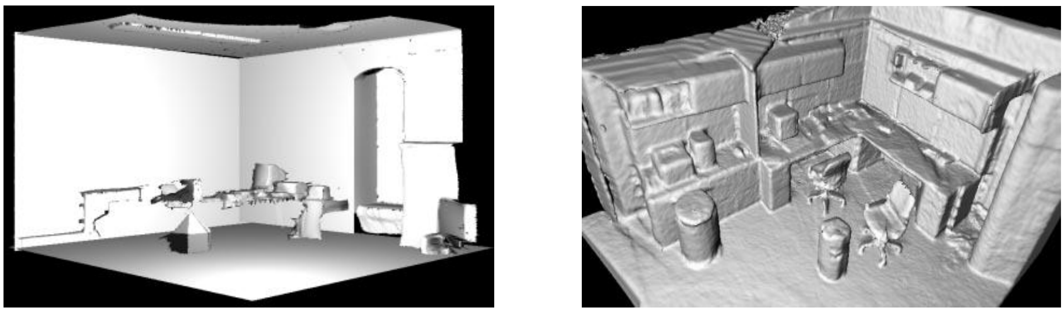
### 2.3.2 Handling missing data

It is now known that the process of gathering 3D point cloud data using a laser scanner would involve dealing with occlusion and clutter problems. Therefore, various researchers have come up with solutions to handle these and provide information on how to work out data that is missing or occluded due to the clutter.

Researchers in the late 1990s and early 2000s could only reconstruct outer surfaces from laser scanner data without solving the problem on how to reconstruct the occluded surfaces behind any clutter. The modelling results would be surfaces of any items or objects which exist in the scene combined together with the background producing smooth surfaces between them (refer to Figure 2.8 for samples). This kind of result did not bring any advantages to those relying on accuracy and measurement modelling in order to obtain any information from them, for instance architects and engineers who need to know the exact condition of an interior from the model.

Castellani, *et al*. (2002) used geometry estimation to reconstruct occluded lines, as shown in Figure 2.9. If the lines entering and leaving the clutter are straight with no angle between them, then it is assumed that it is a single straight line and a line is created to connect them. The same assumption is used in determining curves and joints – if two lines project out from the clutter at a certain angle, it is assumed that they intersect at a feature e.g. corner, therefore another curve will be used to join them. Meanwhile Sappa (2002) comes out with the method of handling missing data by using a geometry-based method of occluded surface recovery with crease edges. In here, all possible occluded regions will be determined by calculating their distances and crease edges will be recovered using the continuity method, as shown in

Figure 2.10. Adan and Huber (2010) identify occluded surfaces by using Support Vector Machine (SVM) and fill the holes by using an inpainting algorithm. SVM is a supervised learning method, which means it requires training examples to segment and classify data. Holes are identified using vectors and will be determined as to whether they need to be filled or not, since hole data due to the presence of windows and doors are expected and do not need to be filled. Holes due to occlusion are then being filled by an inpainting algorithm, where nearby patches of data are copied and used to fill the holes.



(a) (b)

Figure 2.8: Example of early surface reconstruction from laser scanner data. Notice that only outer surfaces were reconstructed, disregarding the occluded region (Source: (a) Han, *et al*., 2002; (b) Whitaker, *et al*., 1999)

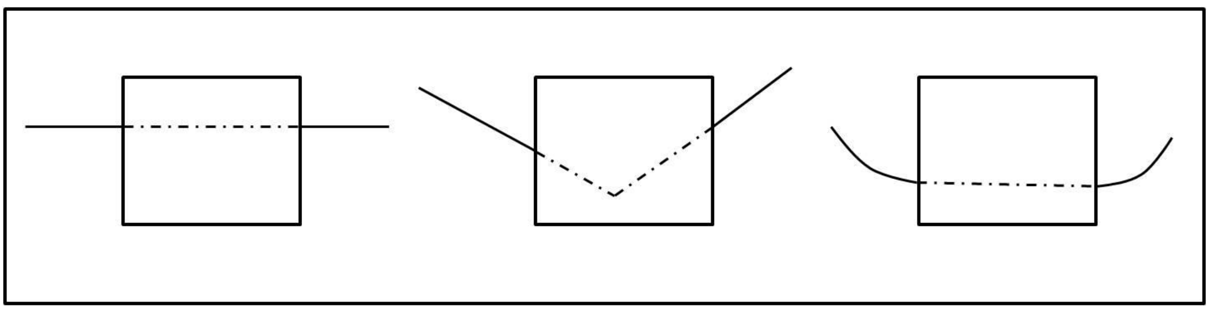


Figure 2.9: Some examples of geometry estimation made by Castellani, *et al.*, 2002, where the blocks represent clutter with lines or curve going through them

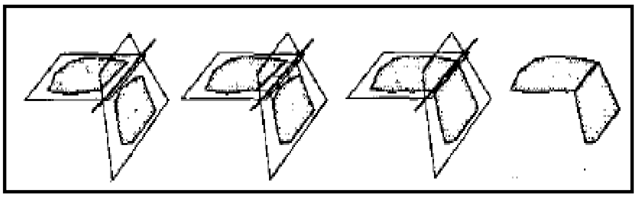


Figure 2.10: Recovering edges through continuity method (Source: Sappa, 2002)

Although the reconstruction results shown by Wang and Oliveira (2002, 2003) concentrate only on the outer surface (quite similar to that shown in Figure 2.8), they are also interested in recovering missing data from items or objects present in the scene. They use automatic segmentation to recover texture of a chair and a lamp of the indoor scene reconstructed from the 3D data. It is worth mentioning here the texture recovering method although this research will not go into depth into texture reconstruction to show the importance of occluded surface recovery.

## 2.4 Data interpretation

One of the ultimate aims of indoor scene surface reconstruction is to produce a model complete with labelling and mapping which carries semantic relationships between the entities within it. This is to ensure that the visualization intention of interior 3D modelling meets expectations and serves anyone who is involved directly or indirectly with these buildings.

But, the process of developing a semantic relationship map is not easy. The algorithm may not identify any entity automatically by just looking at the raw point cloud data. Some geometric and relationship modelling needs to be defined in order for the computation to recognize which points in the point cloud represent a particular feature. Since the process to produce semantic mapping from laser scanner data is quite new, object recognition from the same input shall be discussed here as some of the methods can be applied towards producing maps.

Verma, *et al*. (2006) have been using terrain and topology information to segment and detect 3D data that represents roofs. All these recognized data points shall then be geometrically fitted to ensure that the data did belong to a roof. But this method is only limited to flat roofs and cannot be used to detect non-flat roof, for example a dome, and inadequate or partial roof data. Meanwhile, Pu and Vosselman (2007, 2009) use an interesting segmentation technique to recognize windows from the exterior 3D laser scanner data. They extract windows using a hole-based segmentation, as most of the holes in the data represent the window location, and the method has achieve 90% recognition rate. However, false detections also occur in real holes in the wall, and some windows that exist in certain structures like dormer windows and extrusions were not detected.

Morphological operations are also being used to detect the region of interest before applying contour analysis and segmentation for windows recognition (Ali, *et al*., 2008). It is a process using dilation or erosion to enhance the border or outline of any region of interest, i.e. windows, by determining the connectivity of pixels. Brilakis, *et al*. (2010) use image segmentation with artificial neural networks to extract features of a column. They gather the data of construction sites using a laser scanner and use the above method to recognize the columns.

## 2.5 Quantitative assessment for point cloud data

Since the usage of 3D laser scanners has only been exploited in the last two decades, there are not many methods highlighted in measuring the accuracy of the developed model. Apart from that, the absolute ground truth that can be used by everyone in modelling building interior from 3D laser scanner data is not here yet, compared to a more mature method like stereo vision. Ground truth is the exact, original data that represents the object of interest at its location, and be used to compare results obtained using other methods to see whether it has achieve the correct representation. For example, in stereo vision, a lot of original disparity images and maps representing various scenes are being posted online together with their stereo pictures (see http://www.vision.ee.ethz.ch/datasets/index.en.html or http://iris.usc.edu/Vision-Users/OldUsers/bowu/DatasetWebpage/dataset.html). From here, other people who would like to test their disparity algorithm can use the same stereo pictures and compare their disparity results with the ground truth (i.e. the real disparity images as provided at the same source). Due to the big size of 3D laser scanner data, plus issue related to copyright privacy (information in public domain), it is difficult to make ground truth or datasets of point cloud data representing building interior available online. Hence, it is quite complicated to develop a method to determine quantitative assessment of the generated model.

However, in modelling synthetic items for example, researchers now have started to design various methods to verify the quantitative assessment of their results. Early research like Johnson and Hebert (1999) compare their results by showing the performance against the percentage of occlusion and clutter, and their method of using spin images in recognizing the synthetic object shows that the recognition rate decreased with the high clutter and occlusion percentages. While Mian, *et al*. (2006) modify Johnson and Hebert's definition of clutter and occlusion before comparing their recognition rate with the percentage of clutter and occlusion. Apart from that, other factors like processing time and different methods of 3D point cloud processing are also used to determine the best method in processing the 3D laser scanner output.

Due to the unavailability of a general ground truth that can be used by everyone in processing 3D point cloud data, some researchers have developed a manual method to compare their results' performances. Castellani, *et al*. (2002) used a manual measurement method to determine the modelling accuracy with ground truth, where some element of measurement like number of occlusions for each object in their model are being verified by hand. Meanwhile, others developed their own ground truth manually to provide a platform in evaluating the results. For example, Ali, *et al*. (2008) developed a ground truth manually to compare their window detection modelling results, and Okorn, *et al.* (2010) have utilised the usage of commercial software to produce a ground truth for 2D floor plan modelling from 3D laser scanner data and compare the results with their method of reconstruction.

In the meantime, some researchers have taken the quantitative assessment route by publishing results of various methods of processing 3D data and compare their results based on diverse factors like processing time, quality of modelling, complexity and hardware. Tarsha-Kurdi, *et al*. (2007) highlight that the quality of roof modelling using two different methods of RANSAC and Hough transform are dependent on the point cloud, complexity and the dimensions of planes. Here, Hough transform can only detect the roof when it is represented by sufficient number of points, but at the same time, it is a time consuming process and it is not easy to make the whole process fully automatic. RANSAC at the same time can only produce 70% detection, while the extended version of RANSAC increases the detection rate to 85%. Time has also being used as the measurement factor to evaluate different methods of plane detection (Pathak, *et al*., 2009). They tested a variety of plane detection methods – renormalization, approximate least square, eigenvector perturbation problem and exact maximum likelihood – and justify the quality of results using squared Mahalanobis distance and recorded the processing time. Some methods can generate results in less than 1 second, while the exact maximum likelihood problem can only produce the result in 15 seconds, thus the offline route is recommended. Different types of laser scanner used could also create different results as mentioned by Scott, *et al.* (2010). They have shown that the Markov localization method produced a good quality map (manually measured) in timely efficient manner compared to others, but this method could also under performed when being used with a different laser scanner, due to its differing accuracy and repeatability and thus, these will affect the whole data supplied to them.

## 2.6 Current issues with laser scanner data modelling

Although there is a significant advances in modelling from 3D laser scanner data research as mentioned above, due to the demands and its importance, there are still some gaps and holes within it. Others are also using data provided by the professional and assume that this data is clean and ready to be processed, without taking into account any preprocessing stage. Apart from that, some perform the preprocessing method manually and this will affect the time and complexity of the whole 3D point cloud data reconstruction. In registering point cloud data, most available methods require a lot of overlapping points in data that needs to be registered, for example ICP, and therefore limited to registering new data into an available model data. Meanwhile, feature-based registration developed by Rabbani, *et al*., (2007) uses geometric primitives to register data, which may not exist in all data sets. On the other hand, some of the methods are producing results in hours, rather than ideally in few minutes or seconds. As timing is very crucial, professionals like architects and engineers could not tolerate waiting for hours in order to get fundamental results which may need some further alteration. Additionally, with a lot of interior structures are becoming more complex due to modernization in architectural design, none of the methods have been used to model a complex geometrical structure. Most of the researchers, indeed, have tested the method only towards one simple and sparse interior, like a normal box shape structure.

Tang, *et al*. (2010) in their review paper discussed related methods that have been developed to create 3D as-built models from laser scanner data. Apart from that, the authors also mentioned some technology gaps that haven't been dealt with by previous research:

- **Modelling non-ideal geometrical structure**

  Some of the methods produced are limited to modelling simple geometrical structures of interior scene, i.e. box-shape rooms (Adan & Huber, 2010) (Xiong & Huber, 2010) (Eich, *et al*., 2010) (Okorn, *et al*., 2010). While there is a trend towards developing more complex geometry and structures in architectural applications, the developed technique must be able to consider the modelling of these non-ideal (i.e. difficult), complex geometrical structures to make them more usable and robust.

- **Handling real environments with clutter and occlusions**

  Not many methods developed by others are capable of modelling real environments which have clutter and occlusion issues. Several methods are only capable of modelling interiors with nearly zero clutter, for example, developing a model of an empty hallway or corridor (Budroni & Boehm, 2009) (Nuechter & Hertzberg, 2008), while early research was either reconstructing surfaces behind occlusion for a close-up view (Dell 'Acqua & Fisher, 2002) (Stulp, *et al*., 2001) or reconstructing outer surfaces without filling in the missing data due to occlusions and clutter (Han, *et al*., 2002) (Whitaker, *et al*., 1999).

- **A quantitative assessment method to evaluate model accuracy**

  There is a critical gap in knowledge or practice as no literature has come out with a method to provide quantitative accuracy measurement for the developed model, apart from Okorn, *et al*. (2010), but his proposed method is only limited to 2D floor plan. As people are only interested in judging the quality of a model based on visualization (the model looks fine as long as it is visually right), not much work has been done to develop a quantitative assessment technique to evaluate model accuracy. However, this is important if the model is to be used by professionals or experts in assisting their job.

- **Automation of 3D as-built BIM development**

  Tang, *et al*. (2010, pp.12) mentioned in his paper that the needs of automation in creating 3D as-built BIM is *'still in the very early stages'*. However, as experts are more likely to depend on the available software to process the point cloud data, manual work is still an issue (refer to Section 1.2 on limitations of 3D modelling using laser scanners). To have an automatic method to process the interior data would be immensely beneficial, nonetheless it is still in the premature phase as a lot of work and effort needs to be done in order to realize this.

To summarize current gaps on the available methods, Table 2.2 mapped the methods for collecting and processing point cloud data together with their limitations. Based on these limitations and insufficiencies, it is recognized now that this research is of worth and needs to be done.

| Process | Author/s and Hardware / Method | Limitation |
|---|---|---|
| Data collection | Johnson & Hebert, 1999<br>Stulp, *et al.*, 2001<br>Dell 'Acqua & Fisher, 2002 } K2T | Cost, have not been tested to collect full room data |
| | Whitaker, *et al.*, 1997<br>Castellani, *et al.*, 2002 } Perceptron P5000<br>Budroni & Boehm, 2009<br>Brilakis, *et al.*, 2010 } Leica HDS3000<br>Han, *et al.*, 2001 - Riegl LMS-Z210 | Cost |
| | Gueorguiev, *et al*., 2000<br>Allen, *et al.*, 2001 } CYRAX | Cost, have not been tested indoor |
| | Pu & Vosselman, 2009 - StreetMapper Mobile Laser Mapping System | Cost, cannot be used indoor |
| Noise data removal | Arayici, 2007<br>Meadati, 2009<br>Brilakis, 2010 } Software | Cost, manual process |
| | Okorn, *et al*., 2010<br>Stamos, *et al.*, 2006<br>Budroni & Boehm, 2009 } Assume clean data | Risky as not all data supplied by professionals are without noise data |
| | Bajaj, *et al.*, 1995 - $\alpha$-shape | Have not been tested on data with clutter and occlusions |
| | Ali, *et al.*, 2008 - Binarization | Need to have access to range data and respective images |
| | Adan & Huber, 2010 - Manual process | Risky as may have remove important data |

| Process | Author/s and Hardware / Method | Limitation |
|---|---|---|
| Data registration | Pu & Vosselman, 2009<br>Bosche, 2010 } Iterative Closest Point (ICP) | Limited to registering new data to model data |
| | Fitzgibbon, 2001 - ICP with Levenberg-Marquardt (LM) algorithm | Limited to registering new data to model data but require lesser overlapping points compared to ICP |
| | Whitaker, *et al.*, 1997<br>Pathak, *et al.*, 2009<br>Rabbani, *et al.* (2007) } Feature-based registration | Manual process, some of the features are not available in all cases |
| | El-Hakim, *et al.*, 1997<br>El-Hakim, 2001 } Hardware-based (sensor fusion) | Need to have access to more than one sensor which may lead to higher processing time and computational complexity |
| Surface reconstruction | Whitaker, *et al.*, 1999 - Weighted least square | High processing time (hours), not automatic, did not handle missing / occluded data |
| | Adan & Huber, 2010 - Voxelization | Not automatic, tested to sparse interior only |
| | Wang & Oliveira, 2002, 2003 - Hough transform and moving least square | Not working on open surface / boundaries, not automatic |
| | Budroni & Boehm, 2009<br>Okorn, *et al.*, 2010 } Elevation data | Tested only to sparse interior |
| | Eich, *et al.*, 2010<br>Sappa, 2002<br>Stulp, *et al.*, 2001 } Region growing | Limited to certain reconstruction (shape / close-up), wireframe reconstruction |
| | Haehnel, *et al.*, 2003 - EM | Highly computational method |
| | Johnson & Hebert, 1999 - PCA & spin images<br>Cantzler, *et al.*, 2002 - RANSAC | Have not been tested on interior data (tested towards synthetic item data only) |
| | Xiong & Huber, 2010 - Convex hull & conditional random field | Tested only to sparse interior |

| Process | Author/s and Hardware / Method | Limitation |
|---|---|---|
| Handling missing data | Castellani, *et al*., 2002<br>Sappa, 2002 } Geometry estimation | Have not been tested on interior data (tested towards synthetic item data only) |
| | Adan & Huber, 2010 - SVM & inpaiting algorithm | Requires training examples |
| Semantic mapping | Verma, *et al*., 2006 - Terrain & topology information<br>Pu & Vosselman, 2007, 2009 - Hole-based segmentation<br>Ali, *et al*., 2008 - Morphological-based<br>Brilakis, *et al*., 2010 - Image segmentation & neural network | Limited to one type of object recognition only (flat-roofs, windows, columns) |
| Quantitative assessment for point cloud data | Okorn, *et al*., 2010 | Compare with results obtained using a commercial software which may not be accessible to everyone |
| | Scott, *et al*., 2010<br>Pathak, *et al*., 2009<br>Tarsha-Kurdi, *et al*., 2007 | Compare results of various methods, may not be accessible to everyone |
| | Johnson & Hebert, 1999<br>Mian, *et al*., 2006 | Comparison of results with percentage of occlusion and clutter only |

Table 2.2: Issues in currently available methods in collecting and processing point cloud data, especially for interior

# Chapter 3

# Survey Methodology: Making Statistical Inferences

*"At all times it is better to have a method"*

- Mark Caine[*]

As seen from Chapter 2, there is a need to develop a suitable method to collect and process 3D laser scanner data before a 3D interior modelling can be generated. This is due to the limitations of current methods that are not capable in reaching this research's aims and objectives, as reviewed in Chapter 2. But, before a suitable method can be developed and conducted, there is a need to get more information on the current situation in using 3D laser scanner to develop 3D building interior modelling. This is because of the development of this research area which only began in the late 1990s, hence, not so much background on the current situation can be obtained, apart from several reference books which only concentrate on the development of Building Information Modeling (BIM) itself, not 3D interior modelling as a whole.

[*] BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 1 November 2012].

It is important to know of what has happened in this research area. As it is emerging, a lot of solutions have been proposed to overcome any disadvantages or limitations of current techniques. By recognizing the trends, suitable methods can be proposed and developed to overcome these limitations, as the outcome of this research is to provide valuable and helpful solutions to related professionals.

In order to gather all the information on the current situation, the most suitable method to perform is by using a survey. A survey is a method that has been proven in originality, discovery and validity of data, where usually factors such as time, effort and money need conciliation (Gillham, 2008). This survey should be concentrating on interviewing professionals (both experts and potential experts) and those who have been involved in using laser scanners to develop interior modelling directly or indirectly as they are the current and potential users whom may use the outcome of this research in the future. In this survey, individuals were selected among three categories of people namely: those who are familiar and have used the method (referred to as the experts); professionals that aware of the method but haven't used it yet; and people who are not aware of the method (both referred to as potential experts). The findings can be used to motivate, justify, inform and support this research.

This chapter will concentrate on the survey method itself - from designing the questionnaires to the selection of professionals and processing the outcome to find out what are the current scenarios in this research area. All the whole survey was conducted using interviews and indirect communication through telephone and email contact. Results obtained from this survey will be used as a guidance in developing a suitable solution to overcome current limitations and disadvantages.

## 3.1 Survey preparation

### 3.1.1 Designing the questionnaire

The questionnaire, is to be designed in order to find out what are the present situations in developing the 3D modelling representing building interiors using 3D laser scanners, which includes:

- Background of respondents. This is important to classify the group or type of respondents which could also influence the survey outcomes
- The awareness of the existence of 3D laser scanners and their usage, as this technology is only recent and not everybody is informed with its development.
- Recent methods in developing interior modelling, both hardware and software, to see what are their limitations and disadvantages.
- Applications of interior modelling

The draft of the questionnaire is then being distributed among 2 people, one from the specialist who involved in related research area, while another one to non-specialist, to pilot the questions. By doing this, the questionnaire can be improved to ensure it covers all the important aspects that are needed. In addition to that, responses from this pilot study can be used as a guidance to redesign the questions to make sure the respondents understand the questionnaire whilst being informed from the viewpoint of potential responders. After all the feedbacks from this pilot study have been considered, necessary amendments have been made to the questionnaire before it can be distributed to the potential respondents. The questionnaire that has been used to collect the information can be found in Appendix A.

### 3.1.2 Finding the respondents

Based on the literature review as well as related readings, there are several applications that are currently being associated with 3D interior modelling using laser scanners, which includes AEC and historical building preservation (Tang, *et al.*, 2010) (Vosselman & Maas, 2010). Therefore, the targeted respondents for this survey would be people from these industries.

According to Vosselman and Maas (2010), terrestrial laser scanning can be divided into several applications. Hence, the selection of respondents would be the people who are currently working in this area, especially related to interior modelling. Table 3.1 summarizes all the potential professionals:

| Applications | Areas | Professionals involved |
|---|---|---|
| Engineering (building extraction, reconstruction of industrial sites, structural monitoring and change detection, corridor mapping) | AEC / FM / Forensic | • Surveyors<br>• Civil engineers<br>• Mechanical & Electrical (M&E) engineers<br>• Architects<br>• Facility / project managers<br>• Geospatial intelligence |
| Cultural heritage | AEC / FM | |
| Mobile mapping (indoor and outdoor) | AEC | |

Table 3.1: Summary of potential respondents for this survey

Since indoor mobile mapping applications (e.g. SLAM) are mostly being done by researchers (professionals often offer outdoor mobile mapping solutions and services, such as road and railroad-track based systems), therefore this application will not be included in the survey. All these professionals were then being recognized and contacted based on information obtained from the internet as well as previous contacts (meeting during conferences, personal contacts).

## 3.2 The respondents

After potential respondents have been recognized, several contacts have been made among related companies and firms to be in the sample answering the survey. Altogether there were 18 companies that have been contacted:

- Surveyors companies - 6
- AEC / Architect firms - 5
- Estates / Facility Management companies - 3
- Historic Environment Advisers - 2
- Professional institutions / associations - 2

From these companies, 3 (one association, one historic environment adviser and one surveyor company) did not contact back and one professional institution refused to participate, making the response rate 78%. From this 14 companies, there were 19 individual respondents taking part in the survey, as in Table 3.2. As they already covered all the respective professionals in the relevant applications and areas (as suggested by Vosselman and Maas, 2010), the number of samples are appropriate enough to generate valid and convincing results that can be used to guide and motivate the overall research. Summary of the respondents' background can be found in Figure 3.1.

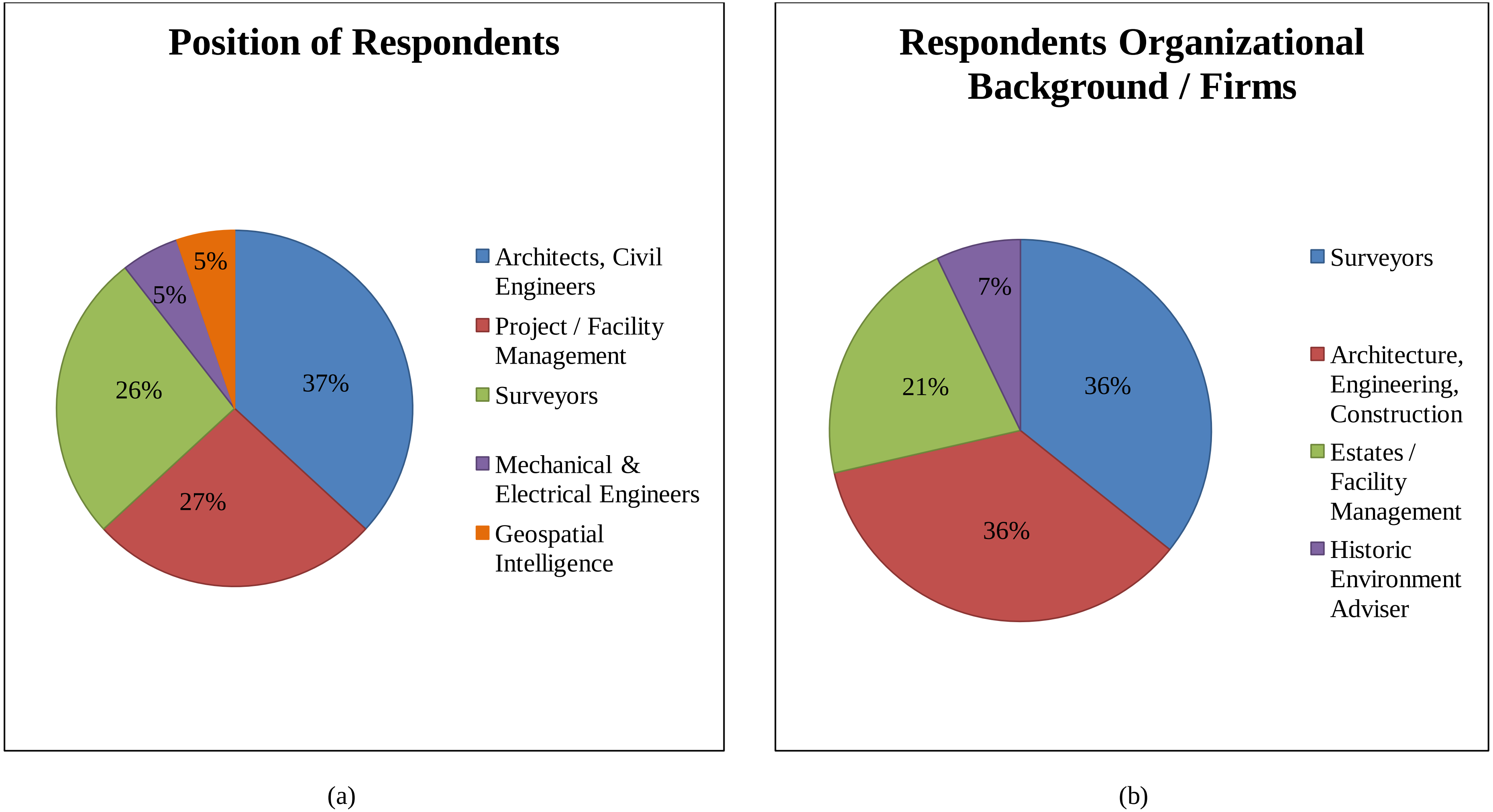



Figure 3.1: Survey respondents' background: (a) position held by respondents in this survey; (b) company or firm where the respondents work

| Companies / Firms | Positions | Gender |
|---|---|---|
| 5 Surveyor companies: | | |
| • Surveyor A | 1 surveyor | Male |
| • Surveyor B | 1 surveyor | Male |
| • Surveyor C | 1 surveyor | Male |
| • Surveyor D | 1 surveyor | Male |
| • Surveyor E | 1 surveyor | Male |
| 5 AEC / Architect firms: | | |
| • AEC / Architect firm A | 2 architects | Both male |
| • AEC / Architect firm B | 1 M&E engineer | Male |
| • AEC / Architect firm C | 1 architect | Female |
| • AEC / Architect firm D | 1 architect | Female |
| • AEC / Architect firm E | 1 civil engineer | Male |
| 3 Estates / Facility Management companies: | | |
| • Estates / FM company A | 2 managers, 1 architect | 1 male and 1 female manager, 1 male architect |
| • Estates / FM company B | 2 managers | 1 male and 1 female |
| • Estates / FM company C | 1 civil engineer | Male |
| 1 Historic Environment Adviser company | 1 geospatial intelligence, 1 project manager | Both male |

Table 3.2: Details of respondents

## 3.3 Results and discussions

Before the respondents were surveyed, they were asked whether they are experts or potentially experts by asking about how well they know about the method. The respondents have been asked to answer the survey, and as the interview can become more interesting, open-ended questions were also being asked on existing, traditional methods of producing interior models or drawings in order to figure out their disadvantages. The existing, traditional method here refers to manual measuring work (using measurement devices like tape measuring or laser range finder) and transferring those readings into drawings using CAD software. Questions on the 3D modelling from laser scanner data for building interior methods are also being asked to investigate its limitations. The findings about both existing traditional methods as well as the method chosen for this research (3D modelling of building interior using laser scanner data) are summarize as in Figure 3.2 and 3.3 respectively.

Due to the limited literature and as the technology is still emerging, some respondents like architects and engineers from smaller construction firms are still not aware about the usage 3D laser scanner and its capability of collecting 3D data that can generate a 3D interior modelling. These respondents can be classified as the potential experts and it consists of 47% from the total samples and the remaining 53% are the experts (samples who are familiar and have used the method). In discussing about the disadvantages of existing traditional methods, respondents who have direct communication with non-experts (non-professional people or public who use the experts' skills) agree that the lack of visualization of the existing method is the major disadvantage of this method. Most of them are the project / facility managers who deal with non-experts as well as surveyors who need to supply data to the related public. These limitations are also being highlighted by professionals currently working in BIM in their books (Kymmell, 2008) (Smith & Tardif, 2009).

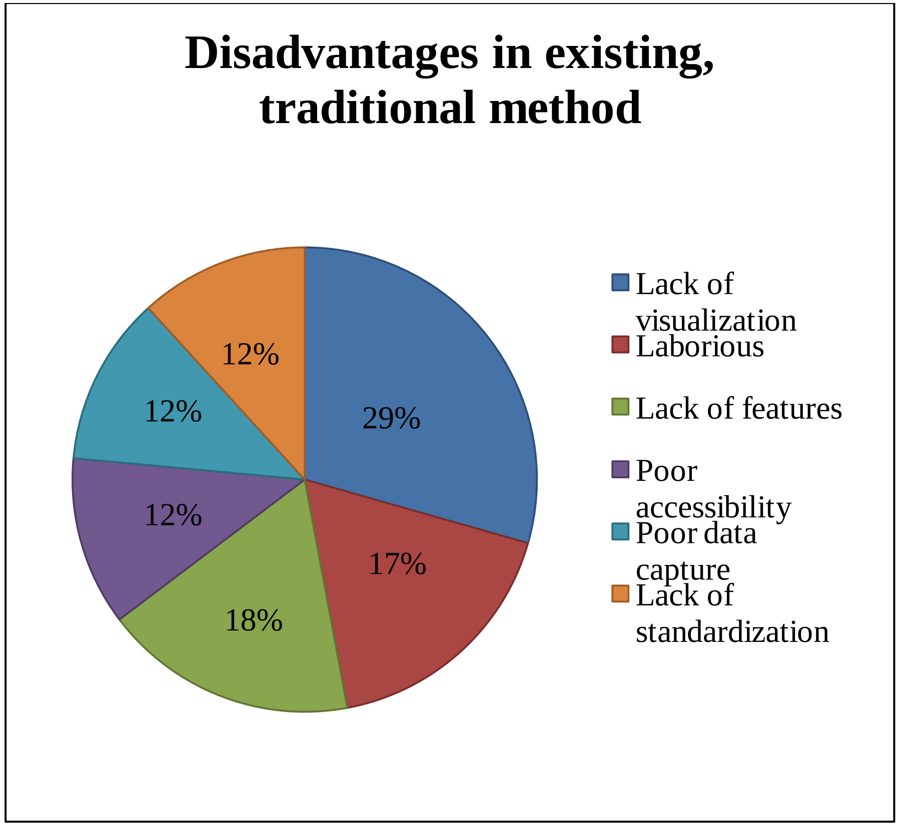



Figure 3.2: List of disadvantages of existing, traditional method in producing building interior drawing

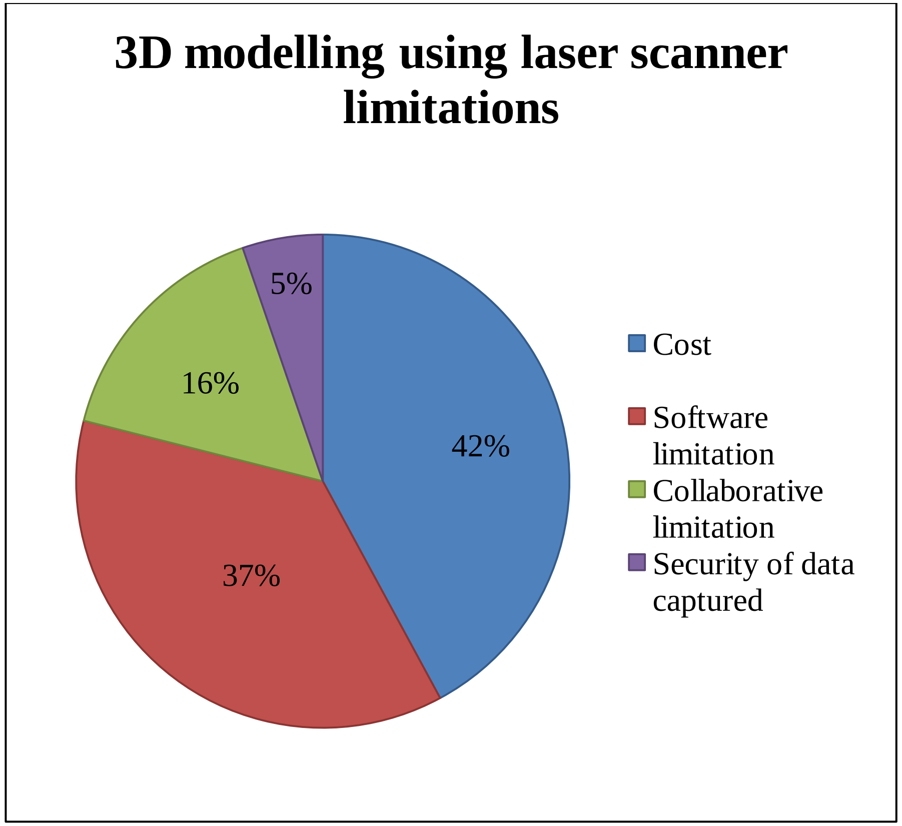



Figure 3.3: Current limitations of 3D modelling for building interior using laser scanner data

Meanwhile, experts who have to go to the site and collect the interior data (architects and surveyors) agree that the laboriousness of the task and data capture factors are the disadvantages of the existing method, as it is tedious, time consuming and requires a lot of manual effort. Professionals who work with facility management and maintenance organisations agree that the current methods have accessibility issues, especially when they have to deal with different software packages to access the same information, since CAD-based software records the drawings for the interior but facility management-based software has the information about space and facilities within them. Features and standardization issues are among the factors that need to be overcome or dealt with by professionals, who use the existing method as a standard for FM-based software where information is tabular and lacks much detail. There is no specific standard between different software packages, so when professional refer to a particular room or location, the lack of a standard referencing system leads to misunderstanding and confusion. These limitations were also being mentioned in FM books (Sule, 2009) (Park, 1998) (Booty, 2009).

The next part of the survey, which asks about the current limitations in using laser scanner data for building interior modelling, are specifically being asked towards professionals who are familiar and have used the method i.e. the experts. As a result, 80% of respondents, agree that cost is the important factor that affects the usage of this method. Meanwhile, 70% of the experts voted that the current software that is capable of processing 3D point cloud data, has some limitations including the need for manual processing, lack of ability to handle occlusions and clutter problems as well as large data handling issues, and also its insufficiency in data accessibility, as one needs to have access to the same software to open the model. Experts who have dealt with various laser scanner manufacturers and different surveyors have chosen collaborative issues as one of the limitations, as different hardware comes with its own data format and processing software, and so far there is no standard platform developed to handle this within the industry. A surveyor who has used this method has also mentioned about security issues, as he has problems with sharing the data with his clients, and currently using the web is not secure enough to ensure the confidentiality of the data. Apart from that, the enormous size of point cloud data produced by the state-of-the-art laser scanners makes it difficult to produce a dataset available for general or research purposes.

## 3.4 Summary

This chapter has contributes towards one of the main findings in this research, which is a review of existing techniques in producing models of building interiors, plus additional information on current usage of laser scanners from 19 related professionals. These professionals are individuals identified during conducting this research who use interior 3D models or could use the models such as architects, surveyors, AEC engineers, facility managers and geospatial intelligence.

One of the main reason that motivates towards performing this research is the lack of information to find current limitations of using laser scanner for generating 3D interior modelling. As a summary, Table 3.3 highlights the features offered by the commercial software such as Revit and Pointools, as shown in the "offered" column, compared with the needs of professionals as uncovered by the survey (as in the "required" column). Therefore, this research would be concentrating on how to handle the limitations currently "offered" by the software by developing a solution "required" by the professionals.

Methodology and processes developed by this research are the best combination to solve these software limitations, which includes 3D data collection, data preprocessing, data modelling and interpretation as well as data assessment. A new process of data surfacing shall also be introduced in this research and its significant, along with other data processing methods, shall be discussed further in Chapter 5. Meanwhile, Chapter 4 will highlight on the data collection method, which is essential as current solutions are high in cost and may be prohibitive to some (refer to Table 2.1).

| Offered | Required |
|---|---|
| • Manual process | • Automatic* |
| • Library dependant | • No library needed |
| • Individual file format | • Laser scanner file format (ASCII) |
| • High density with complete data required | • Can handle missing data |
| • High processing time | • Almost real-time# |
| • High in cost | • Low-cost |
| • Requires CAD knowledge | • No CAD background needed |
| • No semantic information | • Semantic features included |

*Prior knowledge of interiors needed

# Processing time for SICK PLS 101 laser scanner data

Table 3.3: Offered vs. required - summary of current software's limitation and the comparison with this research

# Chapter 4

# Hardware: Collecting 3D Data of Building Interior

*"I'm always collecting emotions for future reference"*

**-** Harlan Howard[*]

In developing a method to produce building interior models, having a suitable hardware to gather the data will evidently assist the process of the reconstruction, furthermore not all sensors are capable of producing 3D data. Choosing an inappropriate sensor to collect the 3D data may lead towards a longer time in collecting data, plus would lengthen and increase the processing time, which could also produce imprecise modelling. Besides, not all sensors are capable of collecting and generating 3D data and for those which can, they will come with various specifications like range, resolution, processing time and robustness that need to be considered.

3D measurement systems can be divided into two categories – active and passive. 3D laser scanners, which operate on either time-of-flight (pulsed laser) or phase measurement techniques, as well as triangulation range finders are among the active range sensors, while

[*]BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 14September 2011].

stereo is being treated as a passive method because it does not give out any form of energy unlike LIDAR which gives out light. Another existing method in interior modelling is photogrammetry, which works on the same principle as stereo with the addition of geodetic information, and has been used widely especially in heritage conservation. Although triangulation-based range sensors can be considered as one of the first range imaging methods used in robotics (Hebert, 2000), it is not suitable to be used in interior modelling, due to its short range (refer to 'operating range' column in Table 4.1), which limits the system's capability to capture the whole scene of the interior. This type of sensor is usually being used to collect synthetic items data, like artefacts and small objects, and thus, triangulation-based laser scanners are out of the context of this research and shall not be discussed further. Table 4.1 shows the type of laser scanners with their usages and typical specifications.

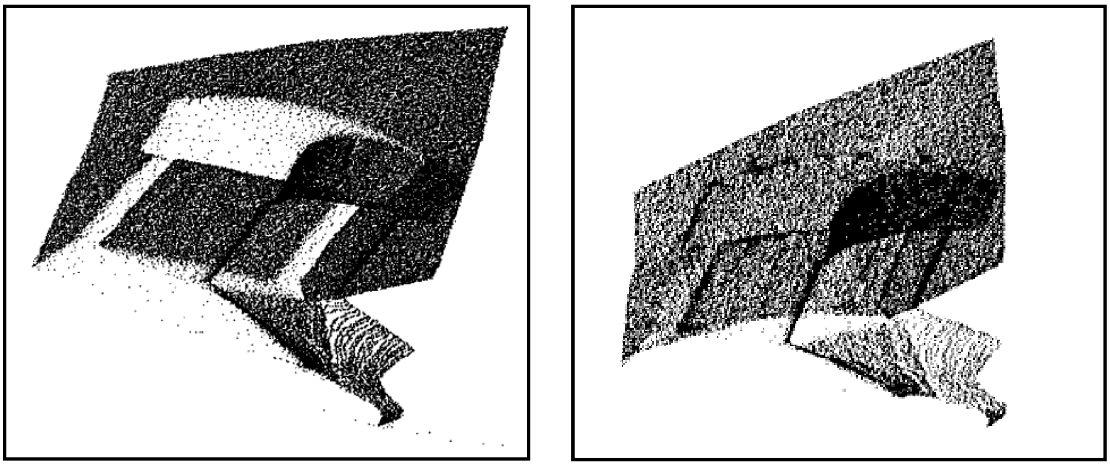
| Scanning system | | Use | Typical accuracy / operating range |
|---|---|---|---|
| Triangulation-based artefact scanners | Rotation stage | Scanning small objects | 50 microns / 0.1m-1m |
| | Arm mounted | Scanning of small objects and small surfaces | 50 microns / 0.1m-1m |
| | Mirror / prism | Scanning small objects surface areas *in situ* | Sub-mm / 0.1m-25m |
| Terrestrial time-of-flight laser scanners | | Suitable for survey of building façade and interiors resulting in line drawings (with supporting data) and surface models | 3-6 mm / 2m-100m |

Table 4.1: Laser scanners and their specifications (Source: Barber, *et al.*(2006) cited in Jones, ed. (2007), p.7)

This chapter will start off by discussing the usage of several sensors towards collecting and producing 3D data, especially for building interior purposes. Although other applications have already been gaining benefit from 3D data to aid various processes of work, such as industrial tasks like manufacturing, metrology and inspection, gathering 3D data of building interiors has only started to get serious attention around ten years ago, especially after BIM was introduced in the late 1990s. While there are quite a number of sensors that are able to support all the industrial applications mentioned above, the emphasis here is on sensors with suitable attributes for collecting 3D data of building interiors. Early attempts saw people fusing two or more, similar or different types of sensor to gather 3D data, like photogrammetry. A single 2D sensor usually would not be able to produce 3D data due to the lack of depth information, which is a necessity in 3D. Thus, it needs to be combined with others, for example stereo vision (two cameras fused together) to retrieve the 3D information. A background on the 3D laser scanner used in this research will also be highlighted here, and being a low-cost, low-level laser scanner, some challenges need to be handled in order for the laser scanner to perform as needed in collecting building interior data. The overall process on how to collect the data will also be mentioned, as well as some contributions made to the hardware part of the research.

## 4.1 Ways to collect 3D interior data

Early research in building interior modelling was more into analyzing indoor scenes (related with partial or close-up view - refer to Figure 4.1 for more information) and solving mobile robots' navigation and mapping (which was done in 2D before). Some work fused similar or different types of sensors (e.g. camera, 2D laser scanner) to obtain 3D data. Due to the fact that 3D laser scanners are getting much attention recently in gathering 3D data, a lot of manufacturers are now involved in developing them. They are now available commercially at different levels of specification like range, measurement and accuracy at a variety of prices. Table 4.2 summarizes the chronological journey of various sensors in collecting 3D building data.



(a) (b)

Figure 4.1: An example of early work in reconstructing surfaces behind occlusion, where in this case the interest surface is a partial or close-up view of a wall behind the chair: (a) the 3D point cloud data; (b) the resulting reconstruction (Source: Stulp, *et al*., 2001)

### 4.1.1 Fusing similar and different sensors

Sensor fusion is a term used to refer to the usage of two or more sensors in one system or solution. The data collected by all the sensors needs to be ‘fused’ (or processed) together to achieve a desired result which may not be achieved with one sensor or the sensor's price may be prohibitive. For example, fusing two cameras together, which is also known as a stereo system, can be used to obtain depth information that is needed in generating 3D data.

| Year | Proceedings | Sensors |
|---|---|---|
| 1885 | Photogrammetry for cultural monuments documentation was established by Albrecht Meydenbauer after years conducting research in measuring from photographic images (Albertz, 2001) | Photogrammetry (stereo and geodetic system) |
| 1957 | The first analytical plotter was introduced by the Finnish Uki Helava, a measuring system able to process stereo photos using computers, replacing analogue instruments (Lemmens, 2011) | Photogrammetry |
| Late 1950s | Laser to replace radio waves as a medium for ranging systems, which yields into the first laser range system (Beraldin, *et al.*, 2010) | Laser scanner |
| 1977 | Nitzan, Brain and Duda started to considered lasersto provide intensity or range data in 3Dpartial or close-up indoor scene analysis (Hebert, 2000) | 3D laser scanner |
| 1980s | State-of-the-art LIDAR first developed for airborne surveying due to the deployment of GPS, which led to other types of state-of-the-art LIDAR (LiDAR UK, 2012) | LIDAR |
| 1995 | The first commercial digital photogrammetric system called ZEISS Phodis ST available on the market (Albertz and Wiedemann, 1995) | Digital photogrammetry |
| | Indoor scene 3D model was developed using a laser range finder on a mobile robot for navigation and verification from its range images (Sequeira, 1995) | 3D laser scanner |
| 2000 | Researchers from Carnegie Mellon University created 3D mapping for mobile robotics using two 2D laser scanner (Thrun, *et al*., 2000) | Two 2D laser scanners |
| | Murray and Little pioneered the usage of stereo in 3D mapping for indoor mobile robot navigation, and has inspired others to use the same method for 3D indoor modelling in late 2000 (Olufs and Vincze, 2010) | Stereo |
| 2001 | 3D data of building interior collected using 3D laser scanner fusing with digital photogrammetry (El-Hakim, *et al*., 2001) | A 3D laser scanner and digital photogrammetry |
| 2002 till present | More interest shown in indoor modelling using state-of-the art laser scanners, while modelling using stereo peaks around 2010 | Various |

Table 4.2: Chronology of 3D interior modelling (Due to the possibility of military applications on this type of work, it is highly likely that there is some unpublished work)

**Stereo vision and photogrammetry**

A stereo vision system works by placing two cameras in parallel, with a separate distance (as in 'baseline' in Figure 4.2) and both cameras will capture an image of interest at the same time. Both left and right images are then used to calculate the disparity (the difference of locations of matching pixels in both images) to produce a depth map, which can give the 3 dimensional entity for that particular scene. The resolution and ambiguity of the data depends on the baseline, i.e. the distance apart of both cameras, where larger baseline will allow the system to identify the location of distant objects more accurately.

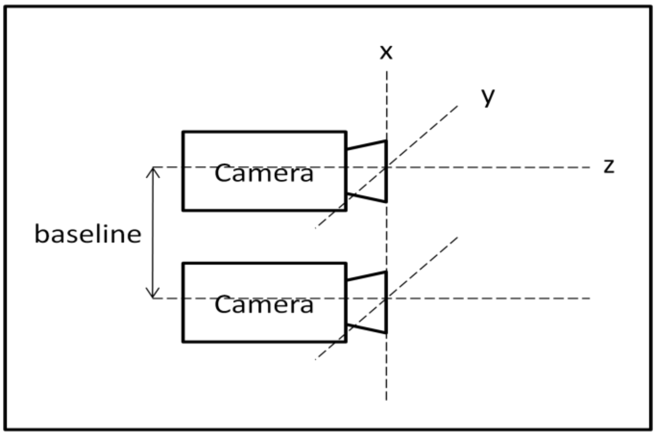
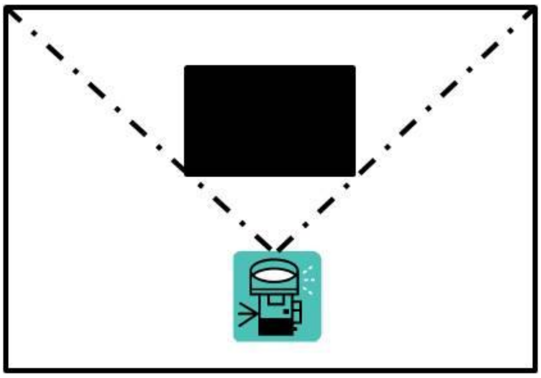
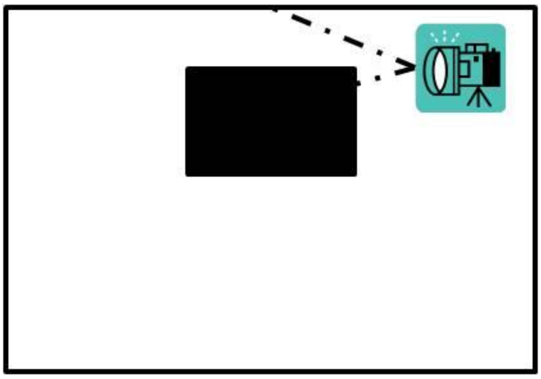



Figure 4.2: The idea behind a stereo vision system – two cameras located in parallel with a distance (baseline), which resembles human's vision

Stereo vision can be considered as one of the oldest methods in solving computer vision problems, and all the literature covering it is too vast to be discussed here. However, the use of stereo in modelling building interiors is not that enormous, and that may be due to several factors – first, the huge amount of computational work that is required, as dozens of correlation operations are needed for each pixel (Hebert, 2000). Secondly, it needs a lot of images at slightly different locations of the same scene to reconstruct the model, which is time consuming. Thirdly, as most interiors have clutter and occlusion issues, a stereo vision system is not suitable to handle this problem, as it needs to capture the best images representing the occlusions to reconstruct the affected surfaces, as shown in Figure 4.3, where the location of the camera as in (a) cannot capture the surface behind the black box - it needs to be placed as in (b). That is why stereo has only been recently used to model building interiors, but with some limitations. It is only to be used to reconstruct outer surfaces with data missing due to occlusions and clutter.

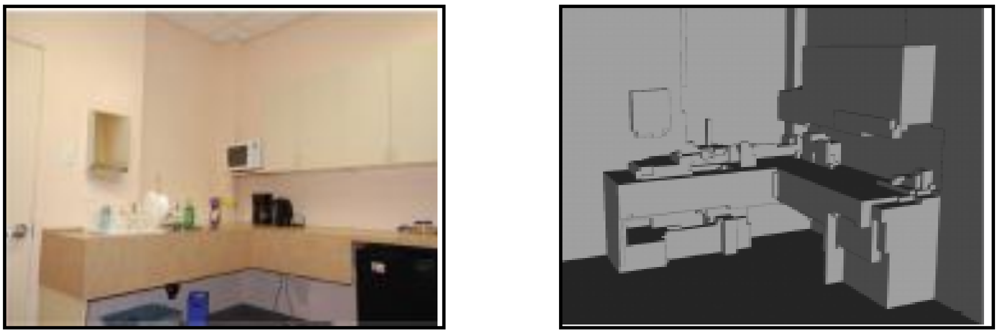


(a)



(b)

Figure 4.3: The importance of camera's position to capture occluded surface behind the black box



(a) (b)

Figure 4.4: Sample of result from Furukawa, *et al.* (2009): (a) the image of the interest kitchen interior; (b) the resulted reconstruction from the image in (a). Notice that the result is similar to the early work in surface reconstruction from laser scanner data as shown in Chapter 2 (refer to Figure 2.8) where only outer surfaces were reconstructed, disregarding the occluded region (Source: Furukawa, *et al*., 2009)

Although there were quite significant developments of mobile robotics using stereo vision in late 1990s, these systems have not been tested in indoor environments, and stereo usage in 3D indoor modelling was only starting to be considered in 2009.In 2010, Olufs and Vincze claimed that the increased usage of stereo in indoor modelling perception in 2009-2010 was due to the pioneer work made by Murray and Little in 2000, which uses real-time stereo to develop 2D grid maps for mobile robot navigation. More work using stereo in 3D modelling can be found in Furukawa, *et al*. (2009) and Krishnan and Krishna (2010). There is also some complete stereo vision systems available on the market, for example Point Grey's Fire Wire stereo system (Point Grey, 2012) which allows one to use stereo without having to install two cameras and worrying about calibration and setup.

Due to the increase of interest in the use of stereo or multi view images in 3D indoor modelling, recently, Autodesk (the company behind AutoCAD and Revit – mentioned in

Chapter 2) has launched a beta version of Project Photofly (now called 123D) (Autodesk, 2012), that allows users to create a 3D model of any scene from multiple images. Users need to take multiple images around a full 360° of a scene or object (ideally the 360° need to be divided up equally into many viewing angles, e.g. every 10°) and upload them to the software, named 123D Catch that will create a mesh model and a 3D model of the scene or object. While this can benefit some applications like 3D surface reconstruction of artefacts or a synthetic object, it is still lacking some important factors like the inability to reconstruct surfaces behind occlusion and clutter for modelling an interior scene, which makes it unsuitable for reverse engineering applications like 3D as-built or FM. This is due to the software only being able to create a model of just outer surfaces of the scene, without handling missing data due to occlusion and clutter (similar to early surface reconstruction work as mentioned in Chapter 2, refer to Figure 2.8). Therefore, this result did not bring any benefits to those who would like to use the interior model for accuracy and measurement modelling like architects, engineers and managers where they sometimes need a record of the exact structure from the model. Figures 4.5 and 4.6 summarize on how this software works. Table 4.3 highlights on the guidelines as advised by Autodesk to users who would like to use the software successfully.

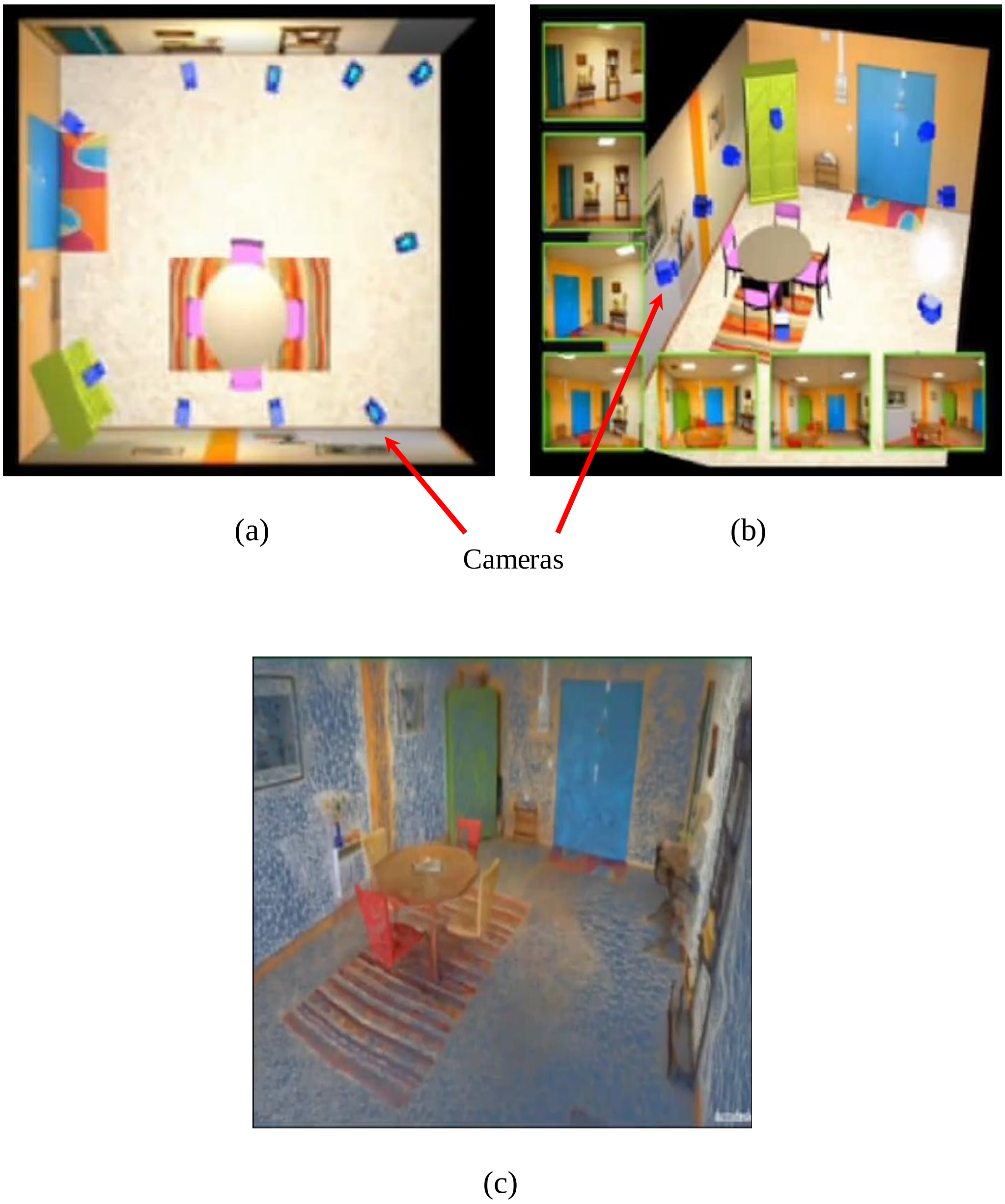



Figure 4.5: (a) Autodesk's suggested camera location (shown in blue cubes) to gather interior images; (b) sample of images from various camera locations; (c) the 3D model produced by 123D Catch software using these images (Source: Autodesk 123D, 2012*)

* Autodesk 123D [internet]. Available at: http:// www. 123dapp.com/catch/learn [Accessed 12 February 2012].

(a)

(b)

Figure 4.6: Users need to plan the accessibility of the target to create an ideal model: (a) it is advisable to get front and top view of the model at varying angles; (b) a sample of images taken from varying angles of an object from side and top views (Source: Autodesk 123D, 2012*)

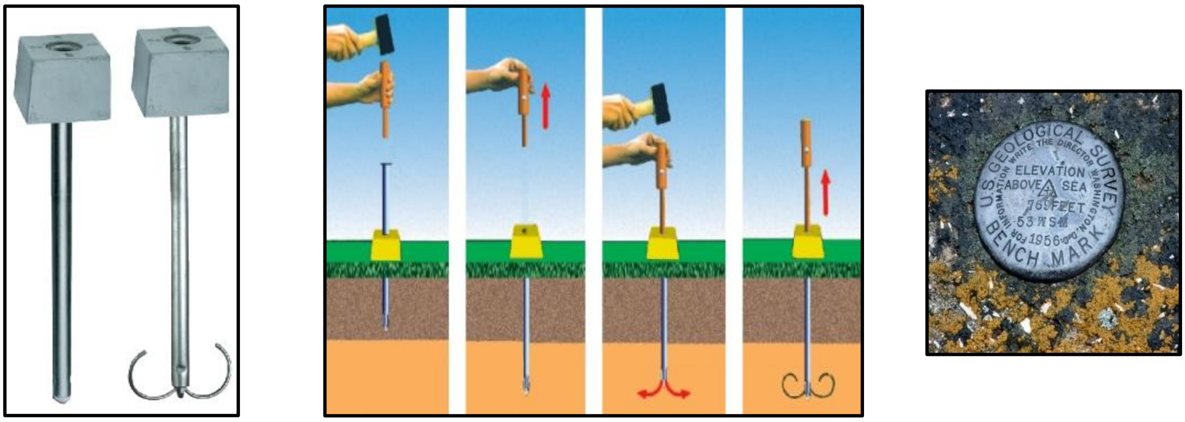
1) At least 50% overlapping images
2) Need to have 360° accessibility to front and top view
3) Static objects (objects cannot be moved)
4) No transparent, reflective or glossy objects
5) Consistent lighting – no camera flash
6) Enough images must be taken to cover occlusion (self / other)

Table 4.3: Guidelines for 123D Catch users (Source: Autodesk 123D, 2012*)

Meanwhile, in archaeological preservation, photogrammetry has been used widely in capturing and recording interiors of historical buildings. Photogrammetry uses stereo images, which overlap with each other, obtained from two cameras placed at a distance. But instead

* Autodesk 123D [internet]. Available at: http:// www. 123dapp.com/catch/learn [Accessed 12 February 2012].

of using disparity to determine the 3D coordinates, photogrammetry uses geodetic information to establish precise measurements between these images and relate them with any other models. This geodetic information is obtained by placing some station markers on the ground (refer to Figure 4.7) and its 3D coordinate values will be recorded. However, experts who would like to place a station marker nearby a monument or historical buildings for their conservation work need to get approval from the appropriate organisation, for example Scheduled Monument Consent requirement as in the UK (English Heritage, 2009). Due to this intricate process, it is more sufficient to use Global Positioning System (GPS) to obtain the Ordnance Survey National Grid (OSNG) values (Blake, 2007). Figure 4.8 summarizes on the details of using digital photogrammetry for building architecture applications.




(a) (b) (c)

Figure 4.7: Station marker usage: (a) anchor station marker; (b) how to place an anchor station marker on the ground (Source: SCCS Survey, 2012[*]); (c) station marker in the US (Source: Land Surveyor Directory and Surveying Guide, 2012[*])

[*] SCCS Survey [internet]. Available at: http:// www. sccssurvey.co.uk/ [Accessed 9 March 2012].

[*] Land Surveyor Directory and Surveying Guide [internet]. Available at: http:// www. landsurveyors.com/ [Accessed 12 March 2012].

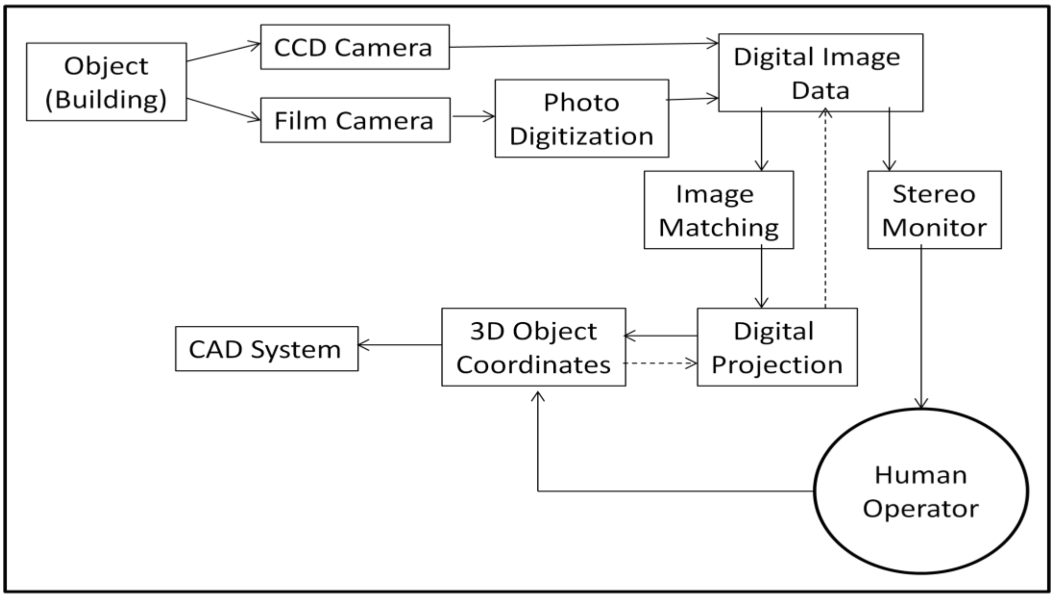



Figure 4.8: Digital photogrammetry process for building architecture application (Source: Albertz & Wiedemann, 1995)

**Fusing other sensors**

Apart from stereo vision, early researchers fused other types of sensor to collect 3D data of building interiors, due to their restricted resources a single sensor capable of producing 3D data was either prohibitive or the technology at that time was inadequate for their needs. Sensors like 2D laser scanners were being fused together to obtain data around occlusions and behind clutter, while others fused laser scanner data together with camera images, as laser scanners can collect more detailed data in a geometrical complex areas, which images cannot provide. However, one must be prepared to handle computational cost due to sensor fusion as various types of data from different sources need to be processed before results can be obtained.

### 4.1.2 Using 3D laser scanners to collect 3D data

Beraldin, *et al*. (2010) stated in his article saying that the time-of-flight measurement systems started off using radio waves known as RADAR (RAdio Detection And Ranging), which all begin with the works by Heinrich Hertz in the late 1880s. It was then replaced by lasers with its imaging ability at higher range resolutions, since lasers (which initially had infrared wavelengths) have shorter wavelengths than radio waves (refer to Figure 4.9). Different usage of this type of measurement requires different specifications, however they worked on the same theory that uses radiated electromagnetic energy for ranging. 3D laser scanners also known as LIDAR (LIght Detection And Ranging in Europe) or LADAR (LASER Detection And Ranging in USA), but due to the fact that LIDAR was first used extensively for airborne scanning, early researchers are more comfortable in referring LIDAR as airborne laser scanners, while 3D laser scanners are for terrestrial or ground-based applications, although both are cross related and can be used to define each other.

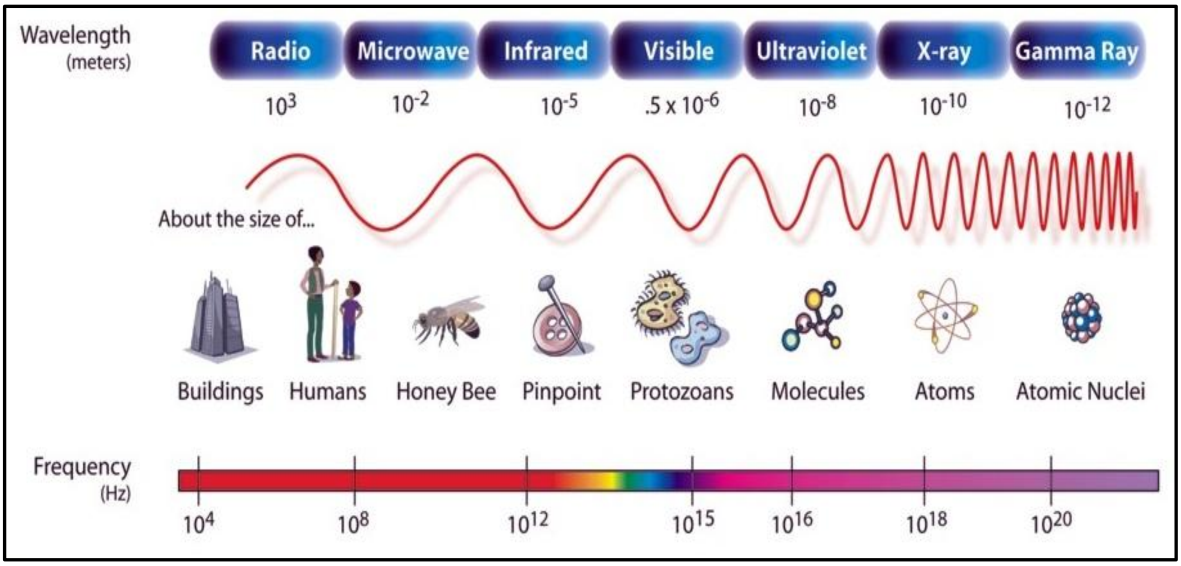



Figure 4.9: The electromagnetic spectrum. Since infrared has shorter wavelength than radio, it has higher resolution (Source: NASA, 2012*)

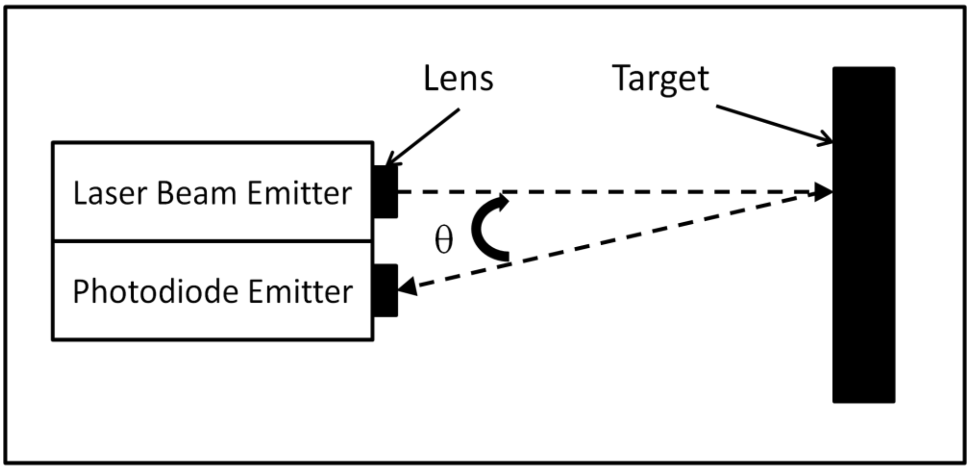



Figure 4.10: Basic principle of time-of-flight operation

* National Aeronautics and Space Administration (NASA) [internet]. Available at: http://mynasadata.larc.nasa.gov/ [Accessed 10 March 2012].

Figure 4.10 shows the basic principle of time-of-flight laser operation. In here, the distance, *d*, of the object from the laser can be determined using the equation:

$$d = \frac{c \times t}{2} \tag{4.1}$$

where $c$ = speed of light

$t$ = time the light pulse takes to travel to the target and return

Practically, the angle $\theta$ in this figure is very small and can be neglected, as it has no effect on the accuracy of the measurement. The coherent light or laser produced by the emitter operates at the speed of light, and that has enable the system to take up to a millions of points per second generally, which yields a high density of data. Another method used by time-of-flight laser scanners to determine the distance is the phase shift measurement, where the distance is calculated by comparing the phase shift between the emitted light wavelength and the received light wavelength.

**SICK PLS 101 laser scanner**

SICK proximity laser scanner (PLS) 101 is an industrial-based, time-of-flight optical sensor which uses infrared laser beams to scan its surroundings. When it is operating, it emits very short light pulses. Whenever the light pulse hits a target, it will be reflected back to the sensor. The distance of the target from the scanner will be calculated by determining the time between sending and receiving the light by an 'electronic stopwatch' built inside it. There is a uniformly rotating mirror inside the scanner. By determining the mirror angle every time it receives a reflected light pulse it can also detect the direction of the target. Both the distance and direction will be used to determine the target's precise position in 3D (x, y, z-direction).

Originally, the scanner moves in a 2D horizontal semicircular plane acquiring 1 point per degree, as shown in Figure 4.11. The user can select any scan angle up to maximum of 180° horizontally. Figure 4.12 (a) shows the condition of the laser scanner used in this research, which is mounted on a mobile platform with 45 cm height above floor to allow portability. By mounting a servo motor on the side of the laser scanner (refer to Figure 4.12 (a)), it will allow the sensor to scan a hemispherical area in a single operation, as shown in Figure 4.12 (b), and this took about 3 minutes to do. Table 4.4 highlights some of the scanner's specifications.

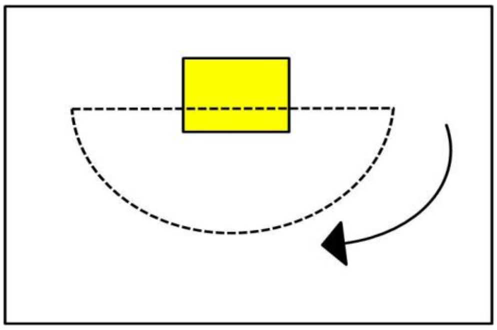
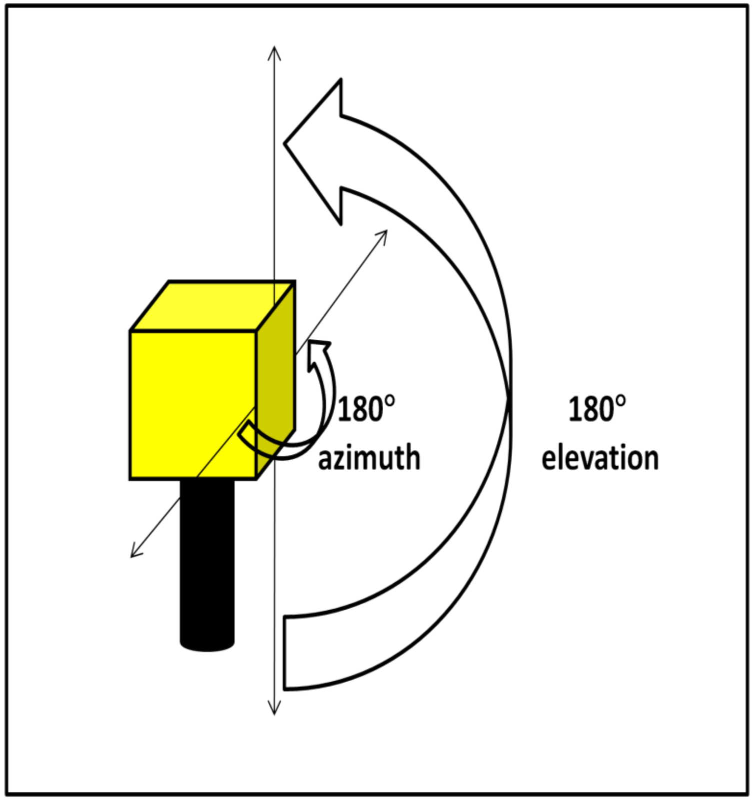


Figure 4.11: Top view of SICK PLS laser scanner, showing its scan area. It scans up to semicircular plane horizontally


(a)




(b)

Figure 4.12: (a) SICK PLS 101 laser scanner; (b) the servo motor mounted below the scanner allows it to scan up to a hemispherical area in a single operation

| | |
|---|---|
| Measuring range | Maximum 50m |
| Scan area | Maximum 180° |
| Measuring error | ± 50mm |
| Response time | 80ms |

Table 4.4: Specification of SICK PLS 101 laser scanner (Source: Abdul Shukor & Young, 2011a)

Due to the nature of this laser scanner which is typically used for industrial applications such as for measurement and quality inspections, there are some considerations that need to be taken care of when using this to collect interior data:

- **Low resolution**

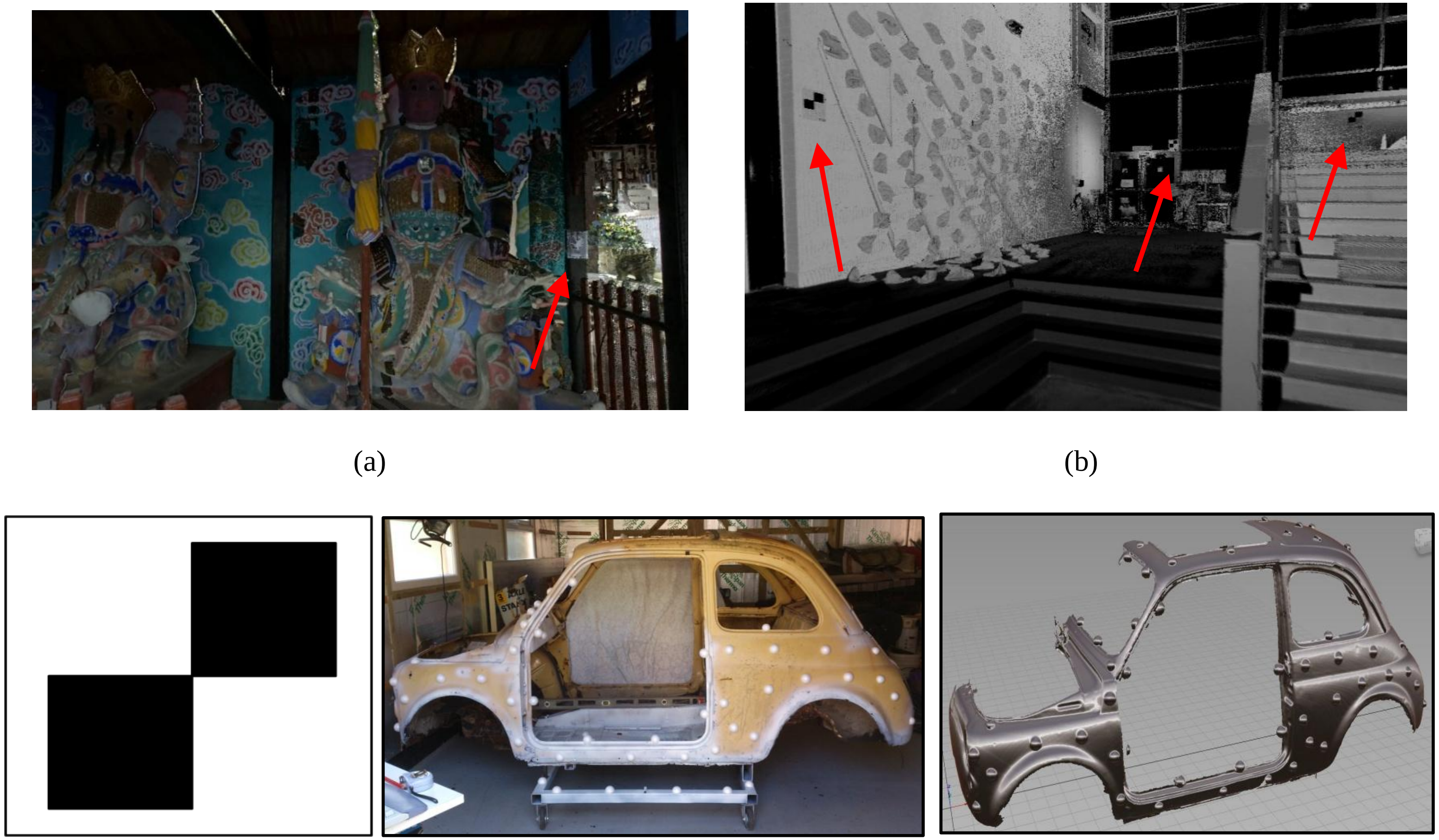
  Being one of the first of its kind industrial-based laser scanner, this SICK PLS 101 does not provide as high density of point cloud data as a current state-of-the-art laser scanner. However, the resolution provided by it is sufficient enough for the scope of this research.

- **Coverage area**

  The laser scanner can only gather 3D data within 180° area, compared to 360° coverage provided by the modern laser scanners. It is normal for a measurement system to be used outside its coverage area, and this is where the data registration method plays its part. This important task is about integrating the input while considering the coordinate system in which the data is being used. In photogrammetry for example, professional surveyors will use the station markers as mentioned above to combine the images together, as the geodetic information representing these images are there to be used. Airborne-based laser scanners are also using the earth coordinate system or frame to register the data. A modern laser scanner could face this problem too, especially when collecting data representing a huge environment, for example a building exterior or an enormous outdoor site like Stonehenge in Wiltshire, UK. When this happens, a target with a unique form like a sphere or 'butterfly-shape' will be placed within the scanner's range and the laser scanner software will merge and combine them together when processing the data. Figure 4.13 shows the scanning process at Stonehenge by one of the surveyor's company in the UK. Figure 4.14 shows some of the target templates used by various laser scanner manufacturers and an example of the usage. Apart from the viewing angle, the SICK PLS 101 laser scanner has shorter measuring range of 50 meters. But, as the time taken to collect the data is within a reasonable duration, plus while others are also using markers and targets for precision, the coverage angle issue does not bring any impact in performing this research. Based on the average size of a typical large room which is within the maximum range of this laser scanner, thus this issue does not affect the overall work of this research.


Figure 4.13: Scanning Stonehenge using 'butterfly-shape' and sphere shape target (Source: Greenhatch Group, Ltd., 2010[*])

[*]Greenhatch Group, Ltd. [internet]. Available at: http://www.greenhatch-group.co.uk/ [Accessed 23 June 2012].



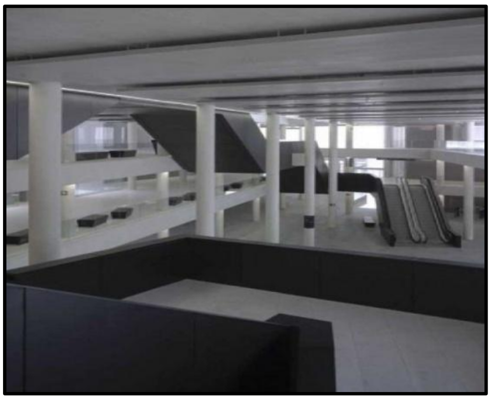
(a) (b) (c) (d) (e)

Figure 4.14: Example of 2D targets used to register 3D laser scanner data: (a) a picture of sphere used as a target in registering data of an ancient building; (b) a unique shape used as targets to register interior data; (c) the target template used in (b); (d) spheres were placed around object of interest; (e) result of (d)

## 4.2 Building interior data collection

Collecting 3D information representing a real world environment is a challenging task as one cannot control their surroundings. In building interiors, for example, the complexity of structure plus the existence of various equipment and furniture will create shadows, occlusion and clutter issues. As it is highly unlikely to have an empty area, especially when dealing with in-use space, the sensor needs to be placed accordingly in order to collect relevant data that is able to be used to overcome these issues.

(a)



(b)

Figure 4.15: Some examples of complex geometry structures in building interiors: (a) a sample of modern minimalist design for a home (Source: Juvandesign, 2012[*]); (b) model of a complex interior in Spain (Source: HomeConceptDecoration.com, 2012[*])

[*] Juvandesign [internet]. Available at: http://www.juvandesign.com/ [Accessed 16 January 2012].

[*] HomeConceptDecoration.com [internet]. Available at: http:// www. homeconceptdecoration.com/ [Accessed 16 January 2012].

### 4.2.1 Methodology

From the beginning of this research, the laser scanner is used to collect data representing a partial interior of a room. Several interiors were selected and scanned, initially consisting of an empty space with no clutter and occlusion, then a sparse room with minimal clutter and finally a bigger room with a lot of clutter, occlusions and a complex structure. Here, the term "sparse room" represents a cubic structure of a room (box-type) with plain objects (for example bin or box) that would create simple clutter and occlusion problems. The laser scanner was set to scan and collect 3D point cloud data of these rooms in a hemispherical range of view. This step is important as this can be used to test the workability of the hardware, as well as to measure the performance of individual techniques and the overall modelling process (data collection, preprocessing and reconstruction) in terms of time and rapidity.

The second stage of data collection continued with collecting full data of a whole room. From literature review as well as comments obtained from related people in respective industries, modelling of a full room is important and will be considered as a stepping stone towards relevant applications such as 3D as-built model creation and facility management. Thus, rooms with clutter and occlusions as well as complex structures are chosen to test the performance of the algorithm. Due to the fact that most interiors come with complex structures, this factor is taken into consideration when choosing the location of the room. However, since the range of the laser scanner is only limited to 180°, two important steps have to be made to ensure the accuracy of the data collected – the viewing angle range of the laser scanner as well as the location to place the laser scanner before collecting the data, which is discussed below.

It is worth mentioning here again the definition of complex indoor environment term used in this research. In this research, the “complex indoor environment” not only signifying real interiors with clutter, but also with complex geometry construction or composition. These aspects are taken into considerations as they typically represent the common scenario of any interior.

### 4.2.2 Results and discussions

In general, it takes about 3 minutes for the SICK PLS 101 laser scanner to collect 3D data with the hemispherical view. This laser scanner is used to generate several data sets, both for training and testing the algorithm, within a two stage process. In stage one, half and partial room interior datasets were collected. At first, an empty room is chosen as the interior, then two items (small cylindrical bin and square paper recycling box) were placed in the same interior to create a sparse interior. Then, partial data of a very complex interior, which consists of an intricate structure as well as presence of furniture and various equipment, was chosen to be collected. Table 4.5 below summarizes the data collected for the respective interiors at the first stage.

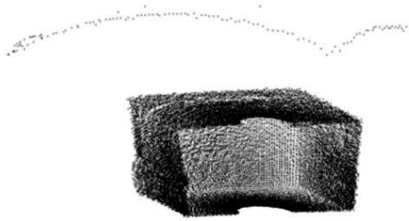
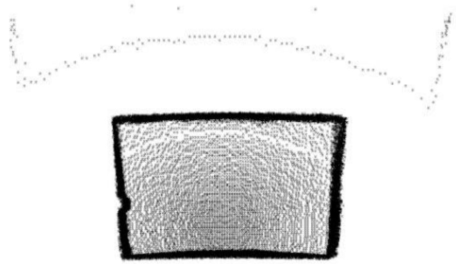
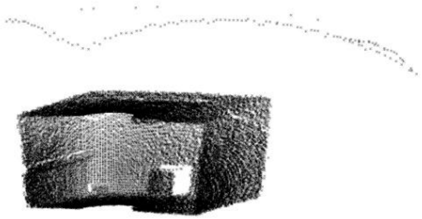
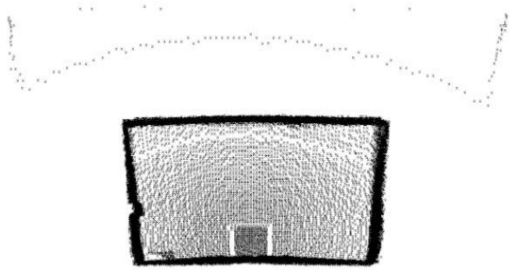
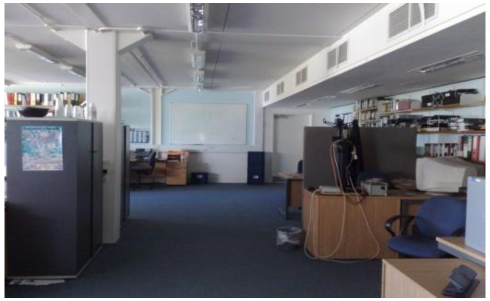
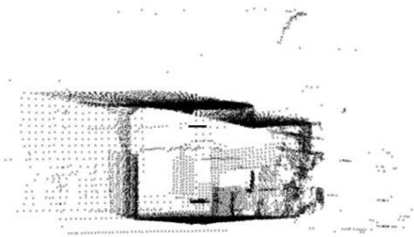
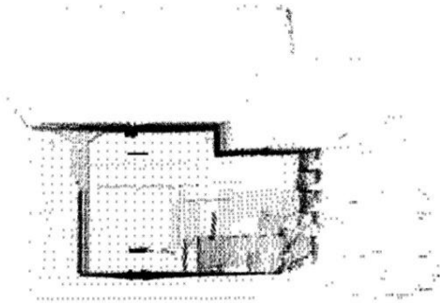
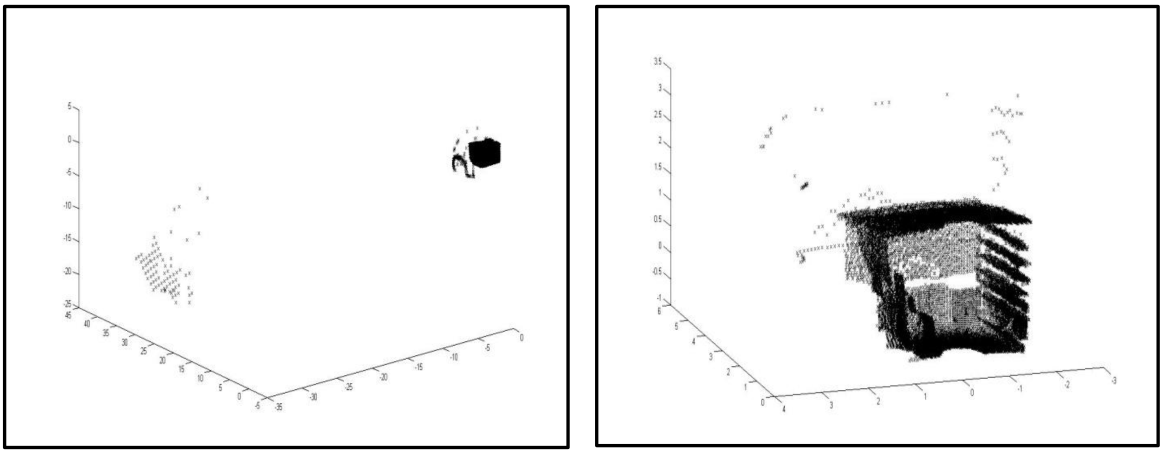
| Room type | Figure of the room | Raw data collected by laser scanner | 2D view (front) of raw data |
|---|---|---|---|
| Room 1: Empty (5 datasets collected for training and testing) |  |  Dataset 1 - 25,470 points |  |
| Room 2: Sparse (1 dataset collected) |   |  Dataset 2 - 25,470 points |  |
| Room 3: Complex interior (1 dataset collected) |  |  Dataset 3 - 21,719 points |  |

Table 4.5: Data collected at the first stage using SICK PLS 101 laser scanner

After realizing the importance of modelling and visualizing the whole interior, second stage of data collection is conducted where here, data representing the whole interiors were taken. Several indoor scenes representing complex interiors were chosen to assess the algorithm in producing 3D visualization of building interiors. Figure 4.16 and 4.17 show the selected interior.

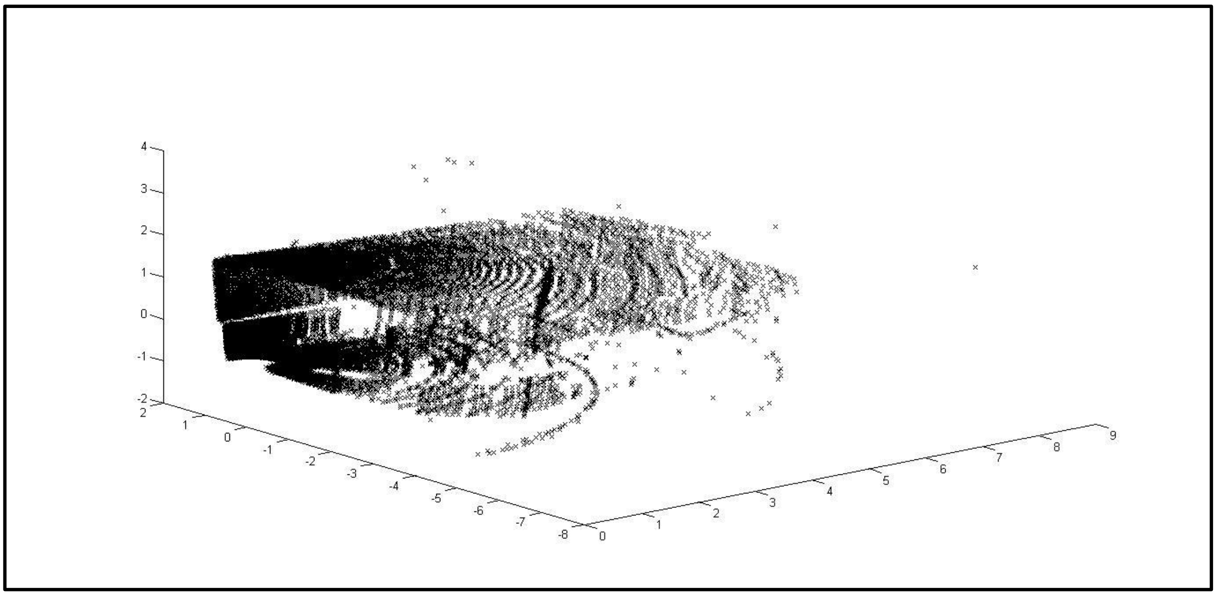
(a)



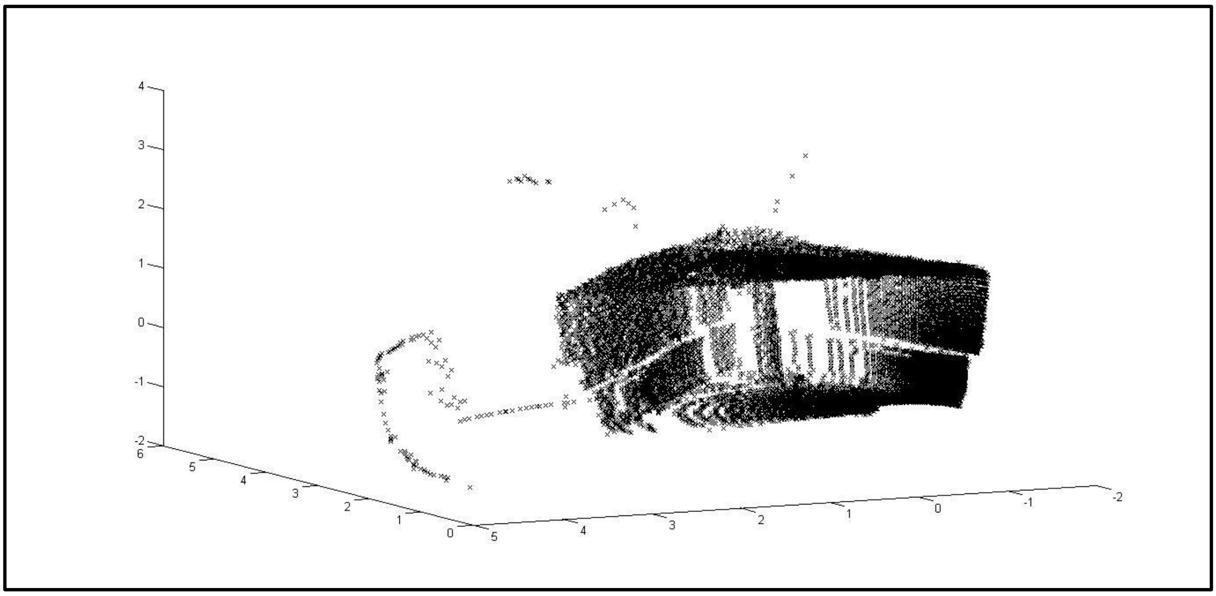
(b)

Figure 4.16: (a) The chosen complex indoor environment, Room 4, used to generate 2 datasets for training and testing; (b) first and second hemispherical raw data of Dataset 4 from the above interior of 50,777 points

(a)



(b)



(c)

Figure 4.17: (a) Room 5, which generate 2 datasets for training and testing; (b) and (c) First and second hemispherical raw data of Dataset 5 (50,364 points) from Room 5

To collect data of a full room, there are a variety of potential locations to mark the place of the laser scanner. Table 4.6 summarizes these choices and highlights on the comparisons drawn on the assessment of each possible mark location:

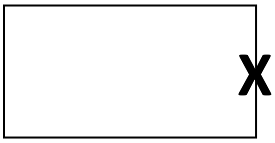
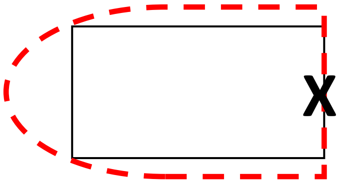
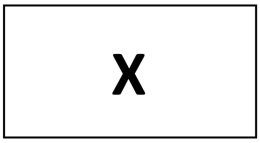
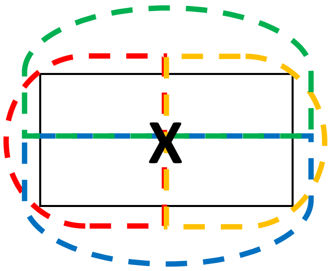
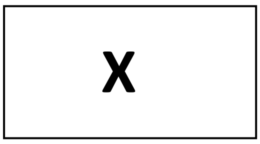
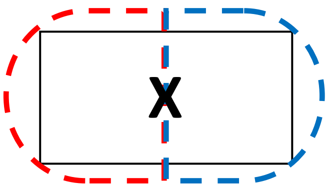
| Location mark | How scanning works | Assessment |
|---|---|---|
| 'Against a wall'<br><br> | <br> | First location is to put the laser scanner by one of the walls. Although this can avoid data registration issues, it may not work as expected especially with a long and highly clutter room, as in the case mentioned in Figure 4.18 below. |
| '4 scans in a central location'<br><br> | <br> | When placing the scanner in the middle of the room, it can be programmed to scan into 4 quadrants as shown in the red, blue, yellow and green lines. However, this may lead to higher computation time as more data needs to be processed for registration. |
| ' 2 scans in a central location'<br><br> | <br> | This is the chosen location, as by scanning the room in two halves, it would allow all surfaces to be scanned and at the same time, less data needs to be processed |

Table 4.6: Summary of potential location of laser scanner in collecting interior data

Based on the above assessment, the 2 scans in a central location is the preferred choice. Although 4 scans or 3 scans could also collect all the data representing the whole interior, they do have limitations:

- Higher collection time compared to 2 scans as more data scanning are needed
- Higher data collected means higher computation complexity method needed to process and register all the data together, which also leads to higher computation time

- Although they have more percentage of overlapping points compared to 2 scans, these datasets still could not be registered together using existing registration methods like ICP (reviewed in Chapter 2), as ICP is only limited to registering new data into model data only
- The 2 scans method chosen to collect the data is compensated by the novel data registration method developed in this research

However, there are some challenges that need to be faced. Since the laser scanner can only collect data within 180° view of range and mounted on a low 45cm high platform, several conditions need to be taken to ensure the correctness of the data. The following circumstances are taken into consideration when deciding where to put the laser scanner:

- **Station markers**

  Photogrammetry combines stereo images with geodetic information to obtain the 3D information. Surveyors who used photogrammetry would find out the geodetic information of the place of interest using the existing station markers (like in the US, as in Figure 4.7 (c)) or by securing a clear marker, like the one in Figure 4.7(a) and (b) (English Heritage, 2009).As technology grows, this geodetic information is now obtained using recording the GPS location instead. This geodetic information can be used to match and register images together, as the information is permanent. In using a state-of-the-art laser scanner, images as in Figure 4.13 and 4.14 are used to register point cloud data together. In this research, a station marker is being placed to ensure the exact same location is being used to place the laser scanner when it is physically turned 180° to collect the second half of the interior data. As it works in a hemispherical view of range, it needs two scans to collect the data for the whole room if it is being placed at the centre of the room. Initial investigation placed the laser scanner at one of the walls, but due to the low resolution, the data representing the furthermost surface (the furthest wall) is inadequate and could be mistakenly defined as "noise data" by the preprocessing algorithm. Figure 4.18 shows an example of this, where the first attempt to carry out a full scan of Room 3 which is 18.1 metre in length, is not doing what was expected, as very few points were collected to represent the furthest wall, as indicated in the red circle. This may lead to the system mistakenly removing these points as noise. Furthermore, as the room is full of clutter, not all walls can be detected as the scanner's viewability has been blocked by this clutter (as in the green circles). Throughout conducting this research, an ‘X’ is being placed on the floor or carpet to mark the station markers, i.e. the location of the laser scanner.

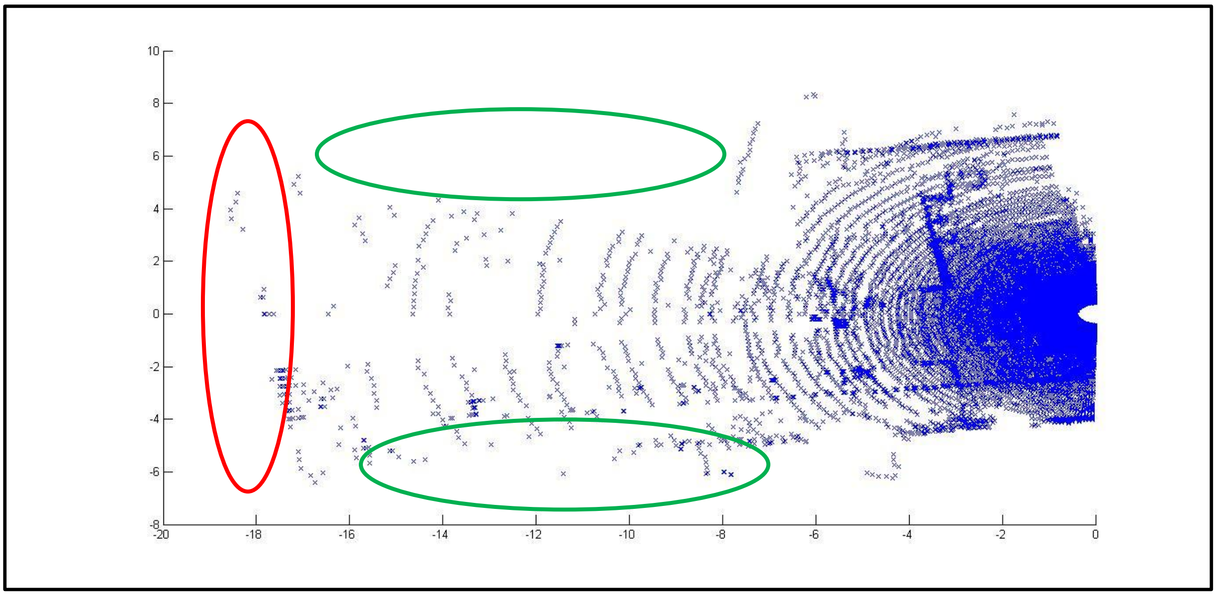



Figure 4.18: The initial data representing Room 3 when the laser scanner is placed against a wall. Red circle shows the furthest wall, while green represent the side wall

- **Viewability or lines of sight of the laser scanner**

  The decision on where to put the laser scanner is also being influenced by the viewability from the laser scanner itself. This step has to be taken into account even though one is using a state-of-the-art laser scanner, as some complex interior elements like a pillar or the structural geometry of the building may block the visibility of the laser scanner, i.e. its many lines of sight that may generate thousands or millions of data points which represent all the surfaces. In this research, as the laser scanner used is mounted at a fixed height, the operator can also estimate the view by observing the room from the laser scanner's position and height. Figure 4.19 summarizes this condition, where the corner of Room 5 and surfaces of wall in another interior which uses a state-of-the-art laser scanner were not collected properly. Therefore, the laser scanner needs to be placed accordingly to ensure it can collect as many points representing any surfaces as possible.

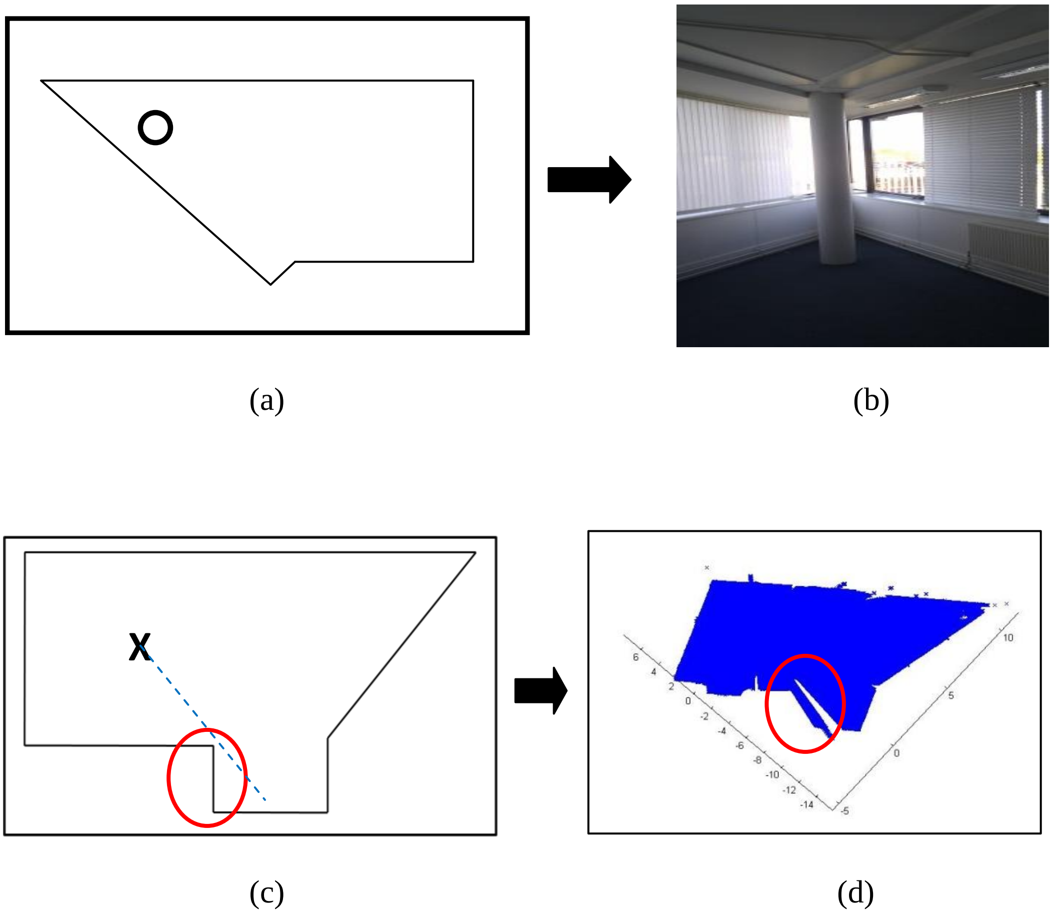



Figure 4.19: Layout of rooms with complex geometry structure used in this research: (a) and (b) Room 5 with a pillar nearby one corner; (c) layout of another interesting interior, where if the scanner is being placed at the 'X' mark, it will not able to collect data to represent the wall as in the red circle, with the blue-dashed line represent its line of sight; (d) the collected data with location of the laser scanner as in (c), where the red circle denotes the missing surface

## 4.3 Summary

In this chapter, a low-cost solution for 3D building interior modelling has been proposed, which yields into a number of significant contributions. The laser scanner used to collect 3D data of building interiors in this research is far more cheaper compared to the modern laser scanner, as it cost around £2,000 compared to £20,000 for a modern model (see Table 2.1). A more state-of-the-art laser scanner is a lot more expensive to buy or even to rent, which is prohibitive to some. Although there are stereo vision systems, which can be considered as a low-cost method to collect 3D data, but, to date, this system still cannot be used for building interior reverse engineering. Stereo cannot handle missing data due to occlusion and clutter, therefore the final end model yields only an outer surface reconstruction, which is very prone to modification and alteration. Some examples of the outer surface reconstruction final model developed using camera images can be referred in Figure 4.4 and 4.5.

As more developers are building complex interiors, using a low-cost laser scanner in these buildings can also bring an added advantage compared to the more modern laser scanners. A low-cost laser scanner, which usually comes with a lower resolution, is sufficient to collect data on a building interior, within the context of this research. State-of-the-art laser scanners with high resolutions will create a massive file size of data to represent any interior, regardless of whether it is full of clutter or not, whereas surface modelling is the main focus in this research, and this is adequate for various applications as mentioned later in Chapter 7. Data which has been produced by the modern laser scanners are mainly 2GB in size in average, compared to 2MB data provided by SICK PLS 101 laser scanner. This huge size leads to higher computation time needed by the algorithm to process the data, as the algorithm that will be mentioned in Chapter 5, does compensate with the low-cost, low-level laser scanner.

Many practitioners may not be aware that different modern laser scanners come with their own programme to collect the data, and this will lead to the issue of standardization. Data format standardization is one of the main issues in modern terrestrial laser scanners at the moment, due to the fact that different modern laser scanners produce different types of data format as they use their own software to collect the data. A low-level laser scanner can only produce data in simple text file format, often referred to as ASCII, and the algorithm has been designed to read this type of data. As this format can be produced by every single type of modern laser scanner, this system can be a universal solution and shall not be a problem for the algorithm to be used with any laser scanner's data. To highlight the importance and needs of the ASCII data, English Heritage, a British government body responsible for preserving cultural heritage, has asked every contractor that works with them to supply the data in this format for recording purpose (Bryan, 2011) (Purslow, 2012).

One of the gaps in this research area is the unavailability of 3D building interior dataset. Thus, by having this low-cost, low-level system, one can have unlimited access to produce various building interior datasets, without having to worry about the size and format of data.

This chapter has discussed the hardware available and the hardware used in this research, the next chapter (Chapter 5) will highlight on the algorithm developed to process the data provided by all the scanners this research has used.

# Chapter 5

# PreSuRe Algorithm: 3D Modelling and Mapping of Complex Interiors

*"Another feature that everybody notices about the universe is that it's complex"*

- Seth Lloyd[*]

It has been known that a good system does not only depend on the correct selection of hardware used, but also the algorithm or mathematical modelling method chosen to process the data. Choosing the correct computational method to process 3D point cloud data of a building interior in producing its 3D model is one of the challenges that must be handled properly in order to ensure the accuracy and significance of the digital representation.

There are several reasons why a new algorithm is needed in this research. Although there is related software that is currently available in the market to process the data, they come with quite a few of limitations, based on the survey conducted among experts and professionals who have experience in using this type of software in the past. As mentioned in Chapter 3, these limitations include full manual work, poor in clutter and occlusions handling, as well as

[*]BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 19May 2011].

managing large data sets. As these software packages are user dependent, a lot of interactions are needed from time to time when processing the data, making it a laborious, highly skilled and time consuming work.

Apart from the above, there are some gaps in knowledge and technical aspects of the current methods of processing point cloud data that need improvement, which has been mentioned in Chapter 2. Most of the developed methods have only been used to model sparse interiors, without being tested on non-ideal geometric structures, as well as real indoor environments with clutter and occlusions. Also, the methods haven't been extended to new environments before, making it only suitable to develop a 3D model of one specific interior that they use to test the algorithm. In addition to that, no quantitative measurement method has been developed to measure the accuracy of the model, and this is important to aid experts and professionals in conducting their work.

This chapter is the continuation from the previous chapter, where it will highlight on the development of PreSuRe algorithm to process data collected by the hardware mentioned in Chapter 4. The next chapter (Chapter 6) will concentrates on the verification and validation of the results. All the results produced using this algorithm can be extended further towards several existing and potential applications and will be discussed further in Chapter 7. The entire algorithm mentioned here is being developed using MATLAB 7.8.0, in 2.4 GHz Intel(R) Core(TM) i5-2430M CPU with 8 GB RAM.

## 5.1 Overview of PreSuRe pipeline

PreSuRe algorithm is the acronym of the important processes in this research and derived from **Pre**processing, **Su**rfacing, **Re**construction, in addition to the 'SuRe' from as**SUR**anc**E** of measurement, which is also included. As there are quite a sufficient number of algorithms developed to process building interior's point cloud data, this research is aimed at developing a new algorithm pipeline in producing the 3D model. Figure 5.1 below summarizes the PreSuRe pipeline representing the overall algorithm.

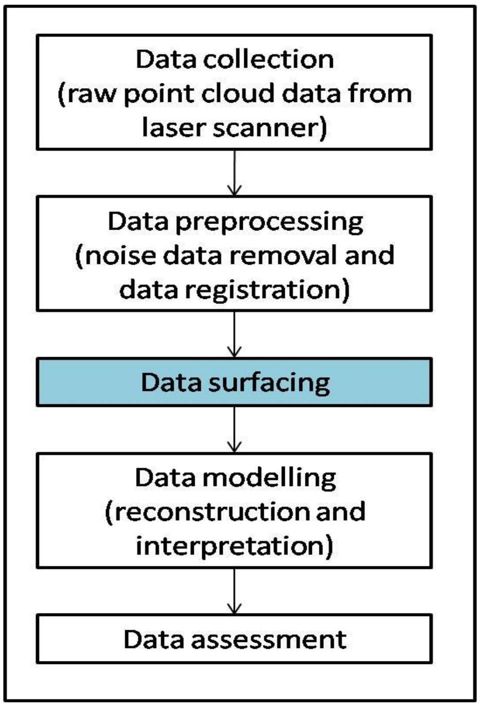



Figure 5.1: Pipeline for the algorithm developed in this research

In this research, a new process called data surfacing (as highlighted in blue in the above figure) has been introduced to produce a new pipeline in processing the data. In PreSuRe pipeline, the 3D point cloud data collected by SICK PLS 101 laser scanner, will be preprocessed first to remove the noise data using the histogram method, and for full room data collected by the laser scanner, separate scans need to be registered together. A novel method for data registration will be used and shall be discussed in this chapter. After that, instead of directly being reconstructed as previous methods do, data surfacing is conducted to remove data representing clutter using the ball fretting method. As the scope of this research is to reconstruct geometrical structure of an interior, the introduction of data surfacing to remove data representing clutter is important as it is likely can interrupt the surface reconstruction process afterwards. After all the surfaces have been reconstructed by a computational geometry technique, a process to visualize and map them will be done as this feature is important before it can be used in several applications. As one of the gaps identified in this research area is the lack of a quantitative measurement method, the model will be assessed to ensure the correct accuracy has been achieved.

## 5.2 Data preprocessing

Before the data can be processed to produce the 3D model representing the building interior, it needs to be preprocessed first (hence the name preprocess means – a method of prior data processing, i.e. modelling). The data preprocessing stage of PreSuRe consists of two parts – noise data removal and data registration. Prior to preprocessing, the data obtained from SICK PLS 101 laser scanner needs to be inverted appropriately, due to the placement of the laser scanner on the mobile platform that has been rotated 90° from its original setting (refer to Figure 4.12 (a)).

### 5.2.1 Noise data removal

It is a common thing for any measurement system to produce noise in the raw data collected. The level of noise is due to the specification of the system itself that comes from what range and measurement accuracy the system may have. However good the system is in collecting and measuring data, it will always produce noise data and this has to be taken into consideration when designing a suitable algorithm to produce the desired output. Although some previous work (Okorn, et al. 2010) (Stamos, et al. 2006) assume clean, ready-to-be-processed data provided by professional organisations, it will be shown later that the data obtained from state-of-the-art laser scanner (in this case, a Z+F laser scanner) also has noise, therefore this process should not be neglected.

Noise that is caused by the electronic components within the measurement system due to different specifications is being referred to as white noise. Components inside the 3D laser scanner can be one of the sources that yields into generating noise, like the lens, mirror and laser (Sun, et al., 2009). Apart from this white noise, there are other things that may lead into the creation of noise, and this is mostly due to the usage of the laser. Since the laser beam works in straight lines, it can hit several things in one direction which can yield more than one reflected signal. This can happen due to several reasons like when the laser hits the edge of an object. In this case, the laser will scan two different locations, both the object and the background, and the system will generate an average position thus making the points representing the object wrongly being placed. Scanning transparent objects like glass for example would also create the same issue as the signal will come from the object as well as any object that happens to be behind the glass. A moving laser scanner could also create noise, as this could develop vibration that can disturb the laser while scanning the environment. This applies to the SICK laser scanner used in this research, as it is mounted on a servo motor to make it move and collect data hemispherically.

During the early period of conducting this research, all noise data was removed manually using some features available in the software. This method is a knowledge-based technique, where prior information on the area of the room was used to remove noise data. All data situated outside the range of the room's area was defined as noise and thus was removed manually.

But, as this way of noise data removal has also being implemented and offered by commercial software packages, it is now a requirement to produce an automatic method to remove this unwanted data. In addition to that, manual preprocessing techniques will have the tendency to delete some relevant data (i.e. data representing the room structure) and this will contribute towards inaccurate modelling later on. Manual preprocessing is also a tedious, time consuming process, as users need to select the data carefully and check the result regularly to ensure correct removal of unwanted data.

This research has developed an automatic technique to remove noise data from 3D point clouds representing building interiors. It adapts the histogram method that has been used widely in image processing to represent an image by its pixel intensity value. A histogram is a bar chart and in image processing, it is used to show the distribution of an image's pixel intensity values, where the value can be utilized to perform any further process towards the image, like image enhancement and analyzing. Figure 5.2 shows an example where histogram is used in computer vision to show the frequency distribution of intensity values within an image.

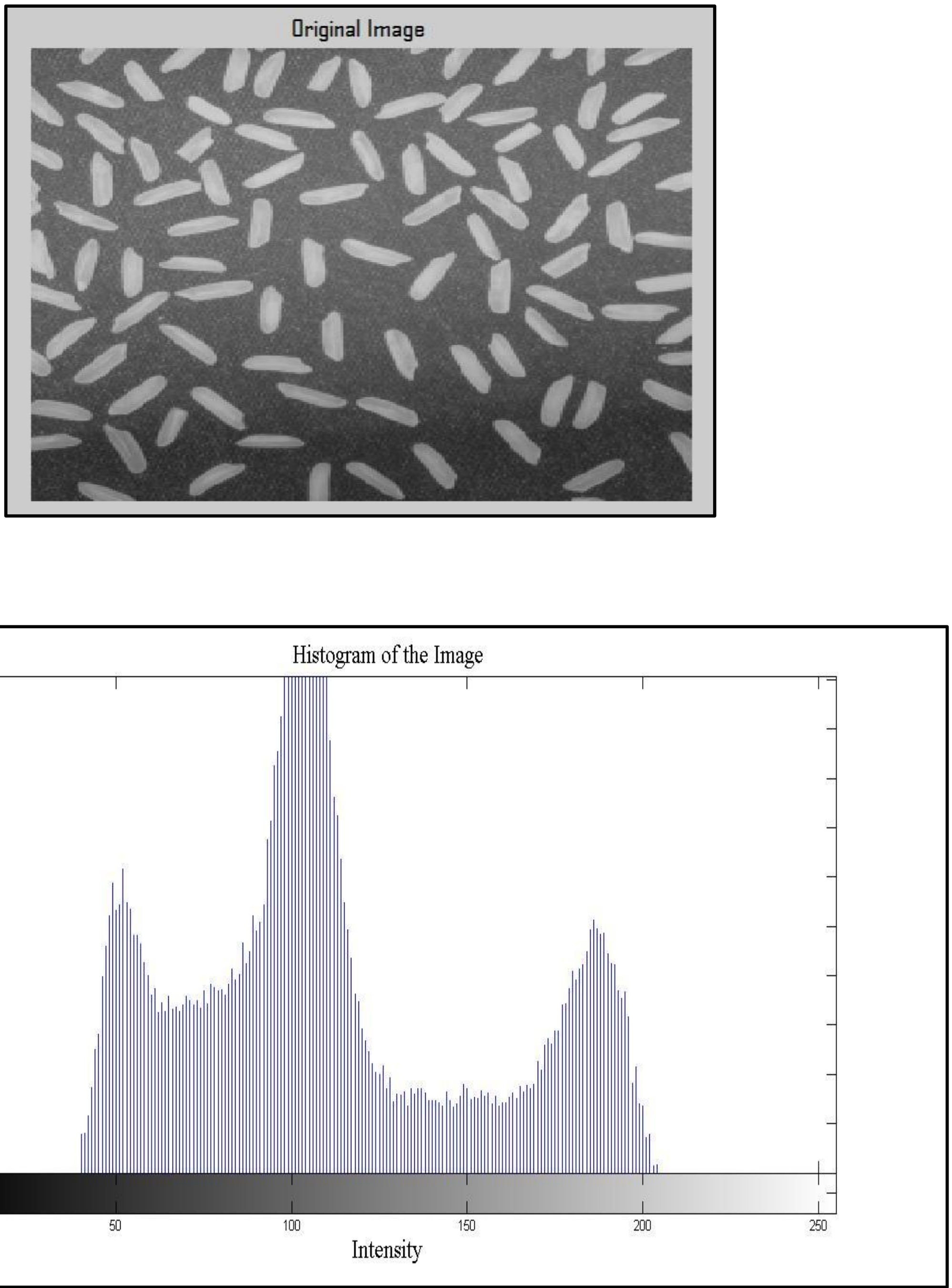



Figure 5.2: Example of histogram representing a grey-scale image shown above it

A histogram can be used to calculate and represent any value as needed. For example, a histogram has been used by Okorn, et al. (2010) to represent voxel values of important entities in an interior. The entities can be recognized using the voxel values and their approximate location based on the height. Figure 5.3 shows the height measurement against frequency of voxel counts. From this information, the location of the entities can be estimated and unnecessary things like equipment (lights and floor) can be removed, as the work is focusing on finding surfaces for floor plan modelling.

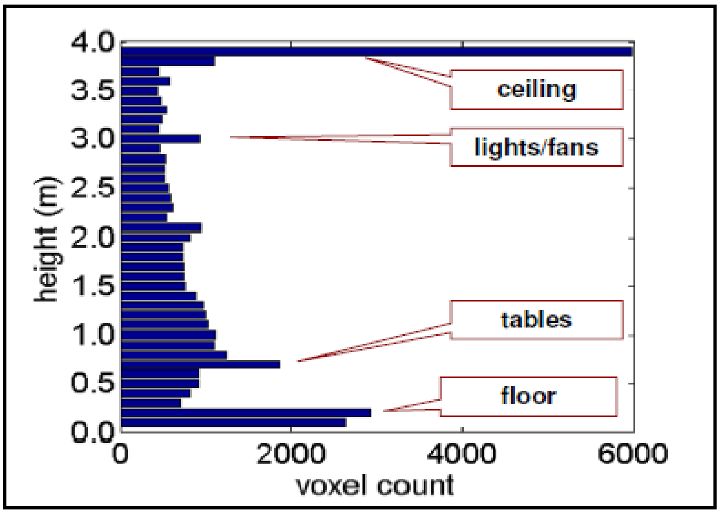



Figure 5.3: The vertical histogram used in Okorn, et al. (2010) to represent entities in interior

(Source: Okorn, et al., 2010)

In this research, a histogram technique has been adapted to remove unwanted noise data from raw data obtained by the laser scanner. Two histograms, one in XY plane and the second in XZ plane are used to represent raw data which corresponds to points that signify both important and unwanted data (i.e. noise). As the unwanted noise data has a sparser point cloud compared to the required data, and furthermore this noise is situated at a notable distance from the important data (i.e. outliers), so will have lower frequencies in the histogram. By calculating the average frequency, any points with a below average frequency are removed automatically. The same process is then repeated in XZ plane where the room is sliced into vertical planes. By using this algorithm, the majority of noise is removed and the "clean", important data is then ready to be reconstructed. But for the data of a full room collected by the SICK laser scanner, it needs to be registered first (Room 4 and Room 5 datasets). Figure 5.4 shows how the noise removal process works in this research.

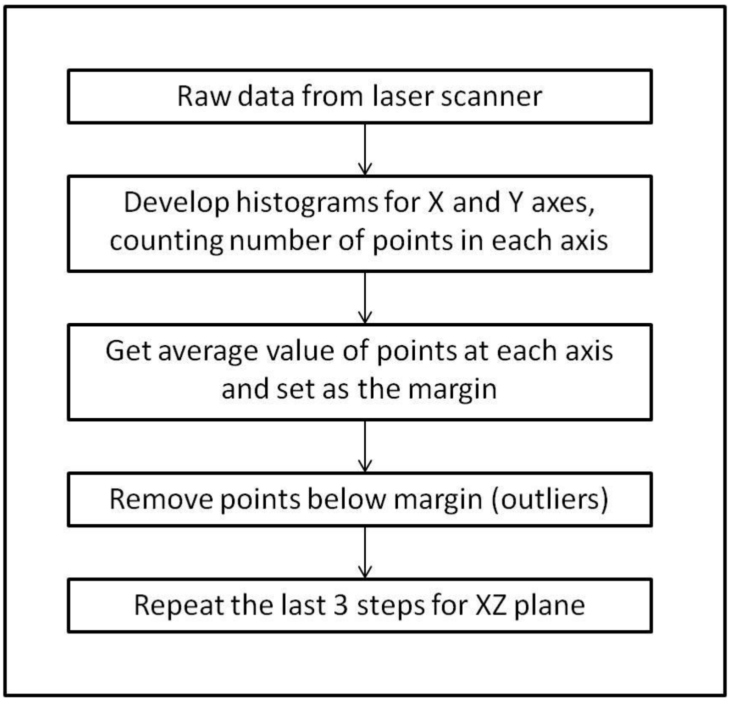



Figure 5.4: Noise data removal algorithm used in this research, adapting histogram method

An example of how a histogram works to remove noise data can be seen in Figure 5.5 to Figure 5.9, where it shows the noise data removal algorithm executed on Room 3 data. Further histogram can also be applied towards YZ plane, but, this process will not remove any more significant noise thus not required. A sample on how unnecessary this third histogram can be seen in Figure 5.10.

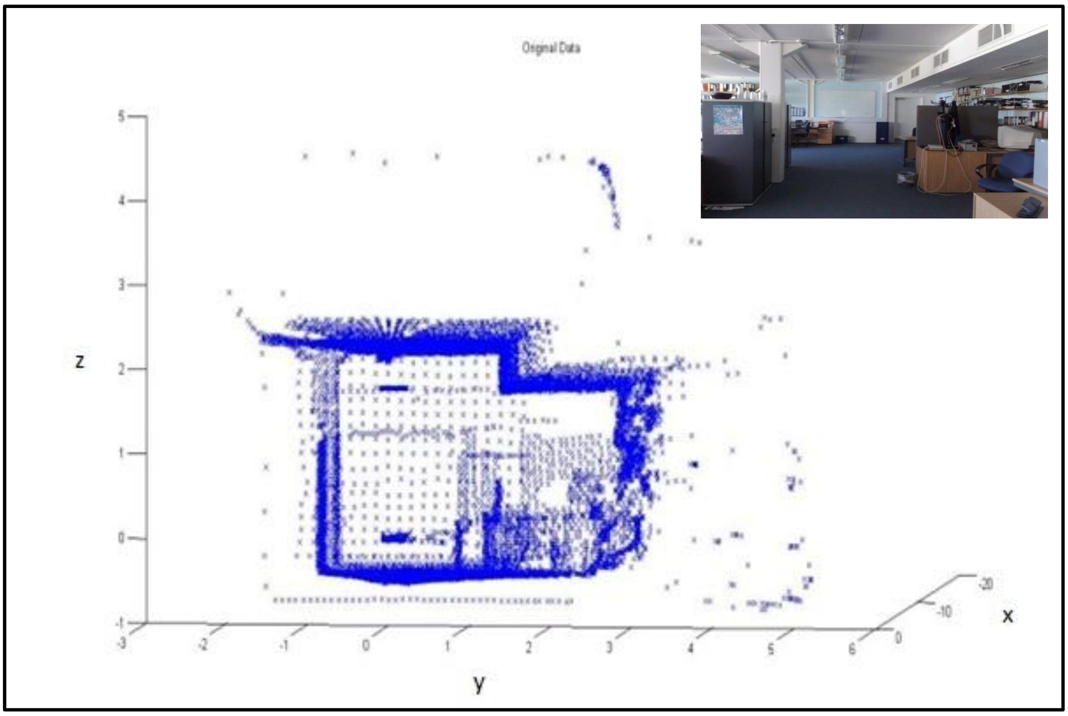



Figure 5.5: Raw data of Room 3 as collected by the laser scanner, ready to be cleaned

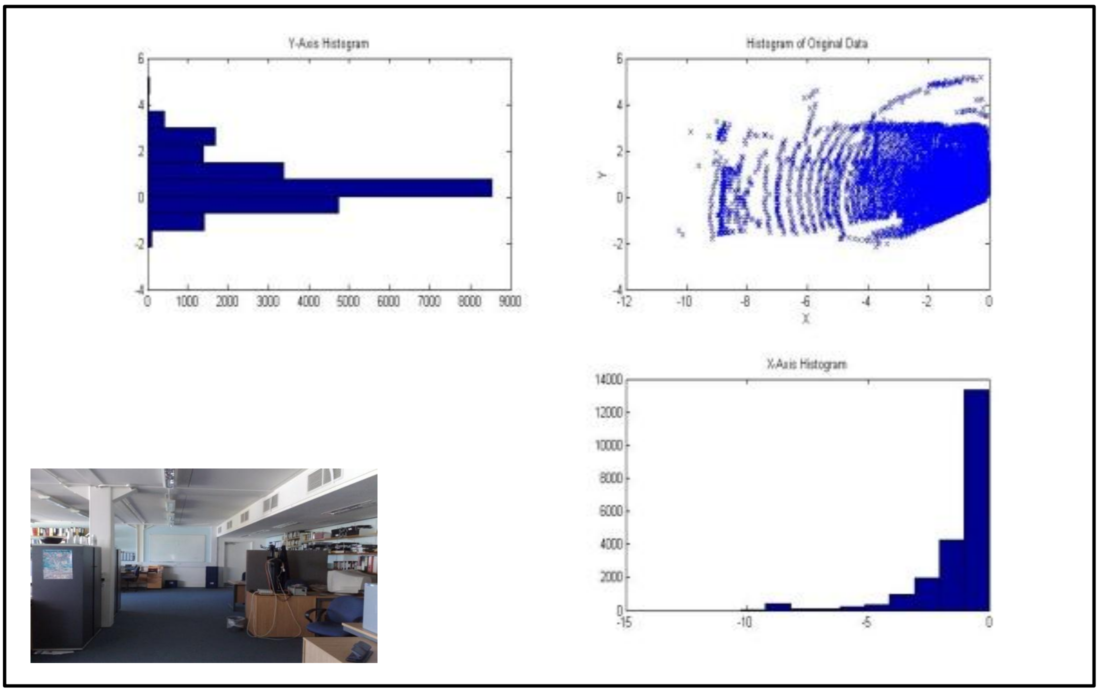



Figure 5.6: Histogram of XY plane of the raw data, counting the number of points in each axis. By calculating and setting the margin as the average value, outliers can be removed

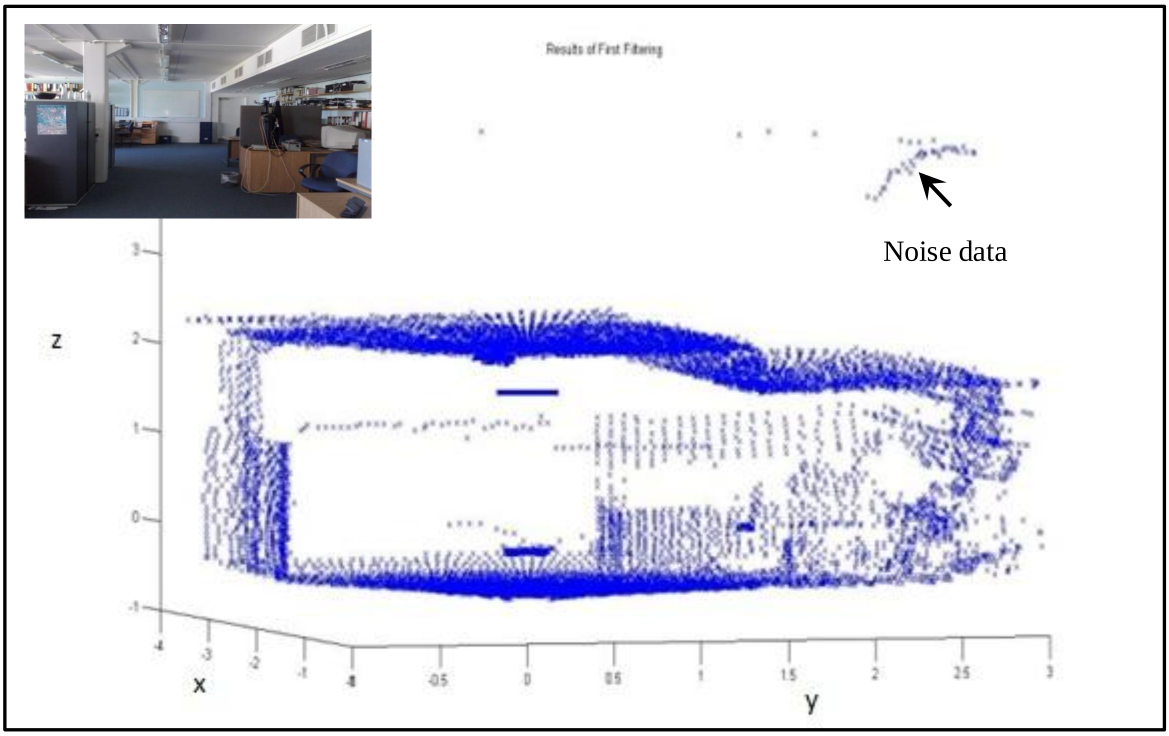



Figure 5.7: Result from the XY noise removal, note that there is still some noise data, hence second histogram is conducted

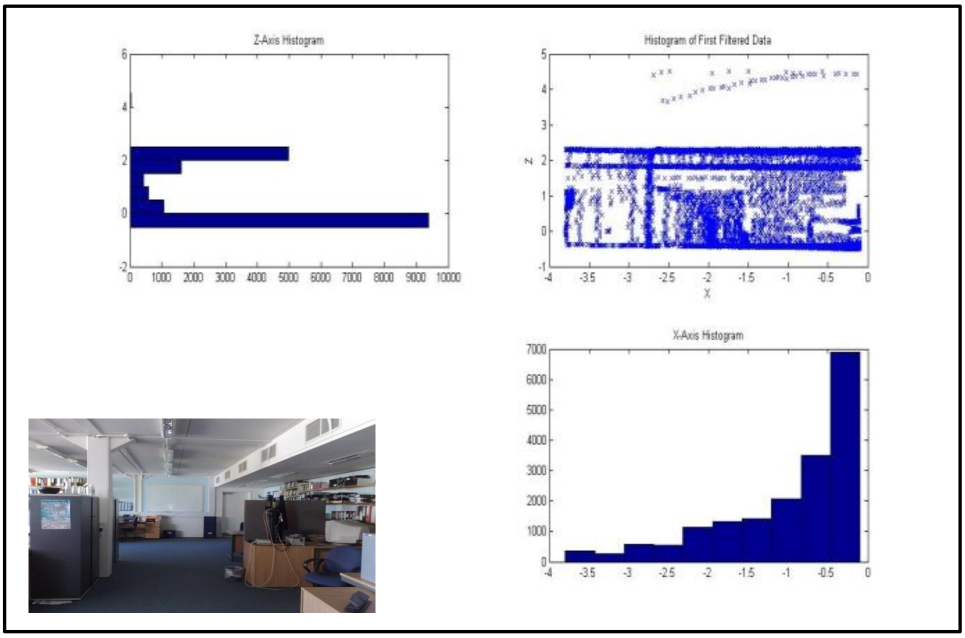



Figure 5.8: Second histogram of XZ plane is created. Noise is being removed using similar approach as the first histogram

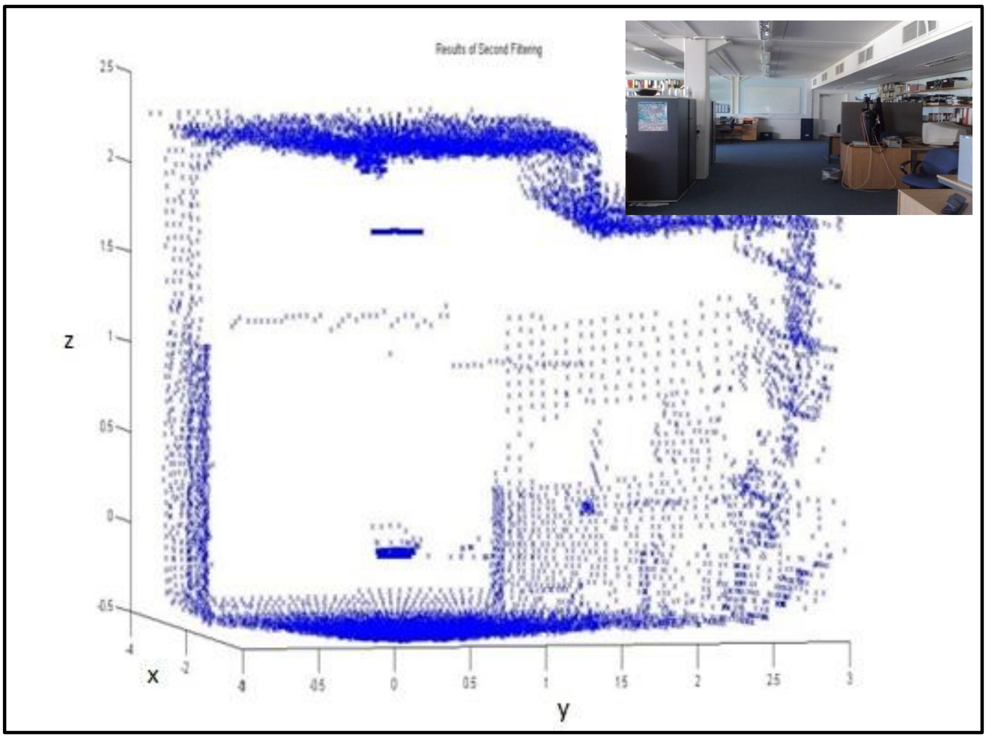



Figure 5.9: Clean, ready to be reconstructed data

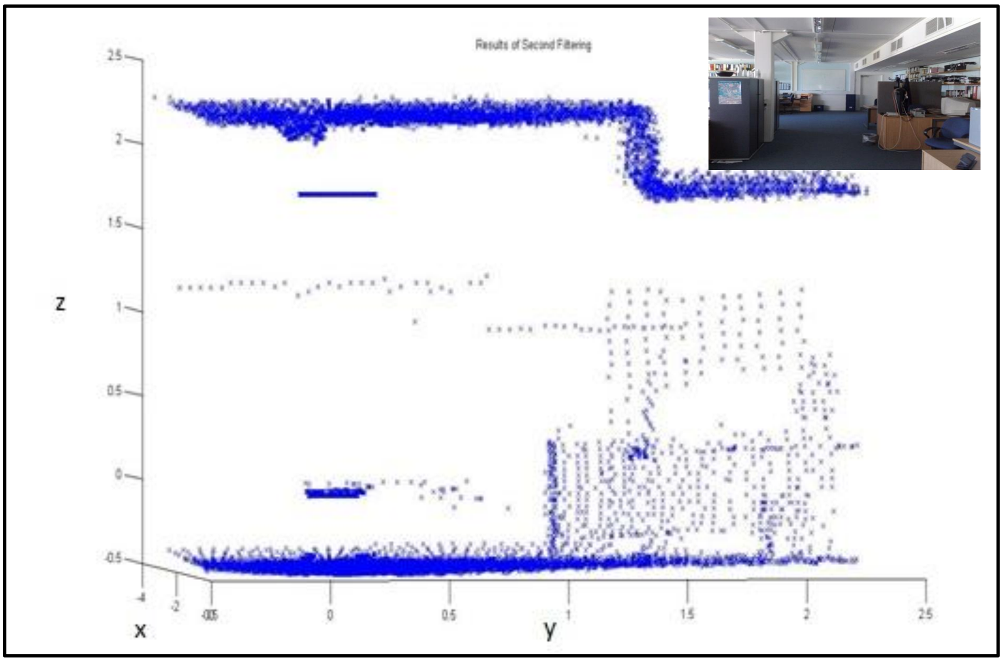


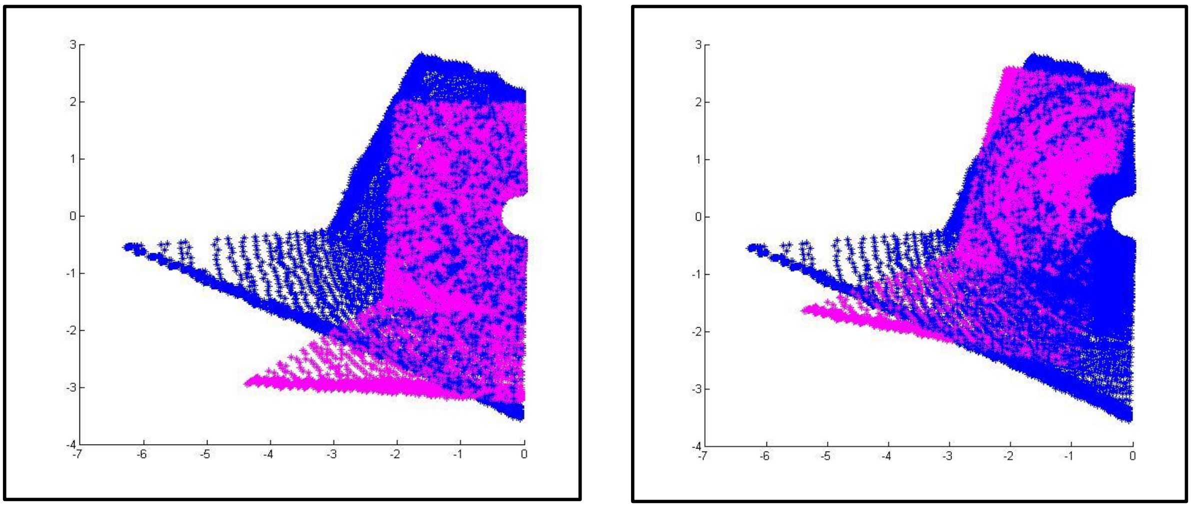

Figure 5.10: Result of applying a third histogram for YZ plane, it will only removed required data thus not needed

### 5.2.2 Data registration

As mentioned previously in Chapter 4, the SICK PLS 101 laser scanner has a limitation when collecting 3D point cloud data, as it can only gather the data in a hemispherical area. Thus, it needs to be turned around to collect another set of data to represent a whole interior. When the laser scanner is being placed in the middle of the room, two datasets will be obtained representing the whole room in two halves. To ensure the same position is used to place the laser scanner, a cross is taped onto the floor to mark its location. All these steps are taken to ensure the correct position of laser scanner when collecting the data. It is motivated by the same process taken during conducting photogrammetry to obtain data, as mentioned in Chapter 4, where station markers and GPS coordinates are used to ensure the correct position of the system which will be used to register the images together later on. As accuracy is important in this research, the above processes are considered as necessary whenever data representing a full interior is collected.

Although all the necessary actions as mentioned above have been taken to ensure the same location of the laser scanner is used, a data registration method is still needed. This is to make sure that when the two sets of data are combined, the data correctly represents the interior. As accuracy is one of the important elements in developing this model, having an extra step of data registration is an advantage to ensure consistency in producing a correct model.

Data registration is an important research area by itself. A lot of methods have been developed to handle data registration. However, most of the available methods are applied to synthetic objects (see Chapter 2), where new scanned data is registered onto model data from previous scans. Here, people will have data representing any object, and whenever a new set of data is collected for that same object, this registration method is used. This approach can work well when there is a great number of overlapping points in new data and the existing model data. This is because the algorithms will try to find commonality of area profiles between two sets of data. Obviously the greater the overlap, the more likely an algorithm will find similar connecting points. Figure 5.11 shows how this typical registration method works.



(a) (b)

Figure 5.11: How a typical data registration method works, where the algorithm tries to register / match new data (in magenta) to existing model data (in blue). Note that it needs a large percentage of overlapping points: (a) shows an original view of the model with new data overlaid; (b) Resulting model after applying a data registration method, in this case the Finite ICP method (Kroon, 2009)

Before a new data registration was developed for PreSuRe, a number of existing registration techniques have been reviewed and some of them were tested using interior data collected by the SICK laser scanner, with 3.6% overlapping points. Table 5.1 summarizes the reviewed methods along with their limitations.

| Method | Limitation |
|---|---|
| Randomized with Poisson method (David 3D Solutions, 2011) | Works better in registering curve surfaces |
| Absolute orientation quaternion (Horn, 1986) (Wengert& Bianchi, 2008) | Limited to registering new data to model data, and both needs to be in the same size |
| Iterative Closest Point (ICP) (Besl & McKay, 1992) (Bergstroem, 2006) | Limited to registering new data to model data |
| ICP with Levenberg-Marquardt (LM) algorithm (Fitzgibbon, 2001) | Limited to registering new data to model data but require lesser overlapping points compared to ICP |

Table 5.1: Summary of existing data registration methods

Due to the lack of data registration methods to combine two sets of data together where there are few overlapping points, this research has developed a new technique to register data collected in two hemispherical areas in order to create a full room data. As most of the interior space (room) has at least one straight wall, this wall can be used as the side wall when considering where to locate the laser scanner. As this wall should be a straight line when both sets of data are to be combined together, this data registration method can be used to ensure this condition is met, by calculating any angle of difference between them and rotating one side of the data to create the straight wall. The developed method used here in this research will automatically calculate the angle of difference that occurs between the straight surfaces and rotate one set to register them together. However, the selected interior must have a straight wall in order for this registration method to work, but, as mentioned above, most of the interior space will have at least one straight wall, thus the method should not have a problem to be used with the majority of interiors. More information on this limitation will be discussed in Chapter 8.

To explain more on how the method works, let's assume A is the first half data collected of an interior and B as the second half. Both sets of data need to be cleaned first and B needs to be inverted to represent the real interior. This is because the laser scanner is turned around to collect the second hemispherical data, which makes the starting point parallel with the previous one (i.e. left wall in the first scan will be the right wall in the second scan) and thus the second scan needs inversion. To register both data sets, A and B need to be plotted together in 2D (XY plane - ignore the Z values first) and the angle between them can then be determined. First, the upper most surface (i.e. a straight side wall) with the highest Y value will be identified and the algorithm will recognize two points representing the same surface in both A and B. As the Y value represents the side wall where the laser scanner is located, obtaining the highest value of Y will represent the straight wall or side wall that has been used as the reference wall and it can be manipulated to determine the correct registration has been achieved or not. Let $(x_1,y_1)$and $(x_2,y_2)$ be the points representing the side wall (i.e. a line in 2D) of A and likewise $(x_3,y_3)$ and $(x_4,y_4)$ for B. The angle, $\theta$, between them can be calculated by:

$$\theta = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right) - \tan^{-1}\left(\frac{y_4 - y_3}{x_4 - x_3}\right) \tag{5.1}$$

From here, a rotation matrix, $R$, can be created and be applied to all points in B to determine the newly registered data:

$$R = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.2}$$

Figure 5.12 summarizes how this data registration method works, and Figure 5.13 shows the sample of results of the method applied to Room 4 data.

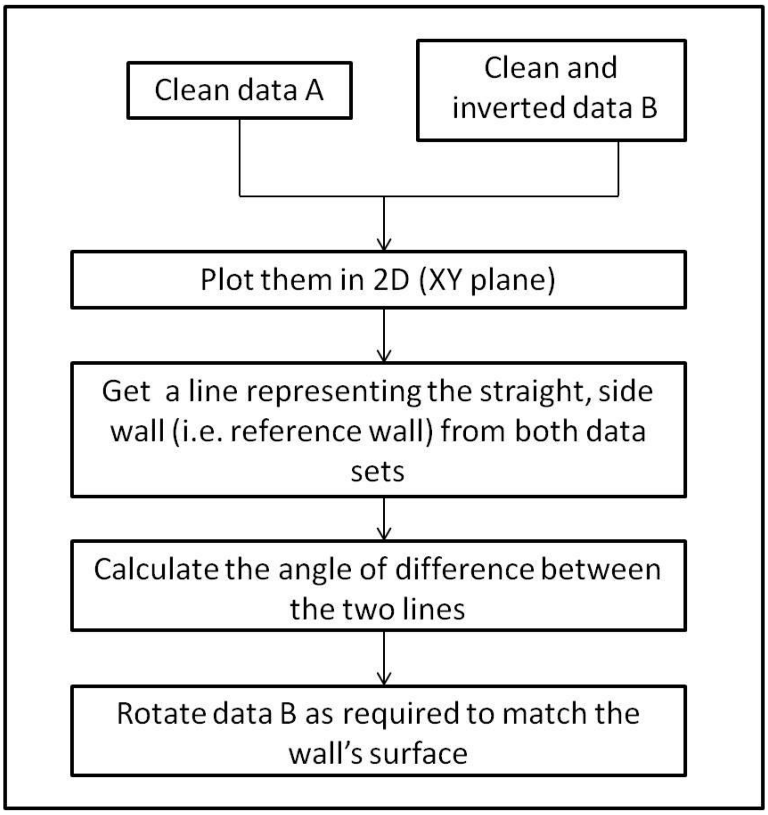
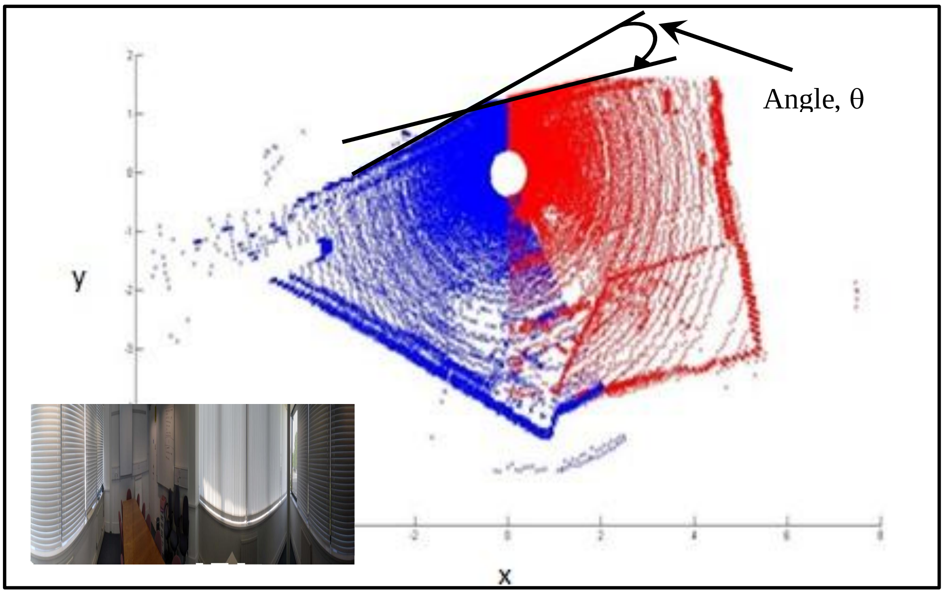
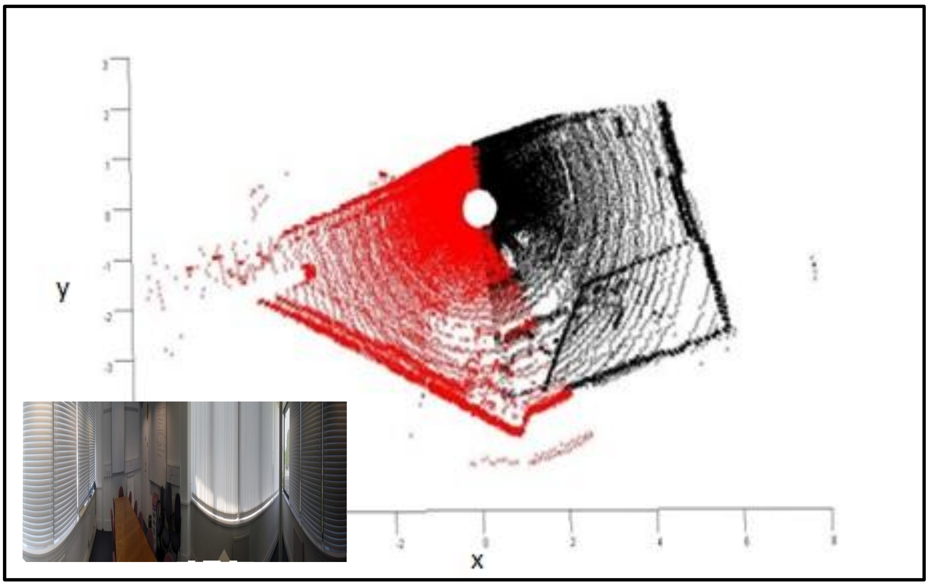



Figure 5.12: Data registration algorithm developed in this research




(a)




(b)

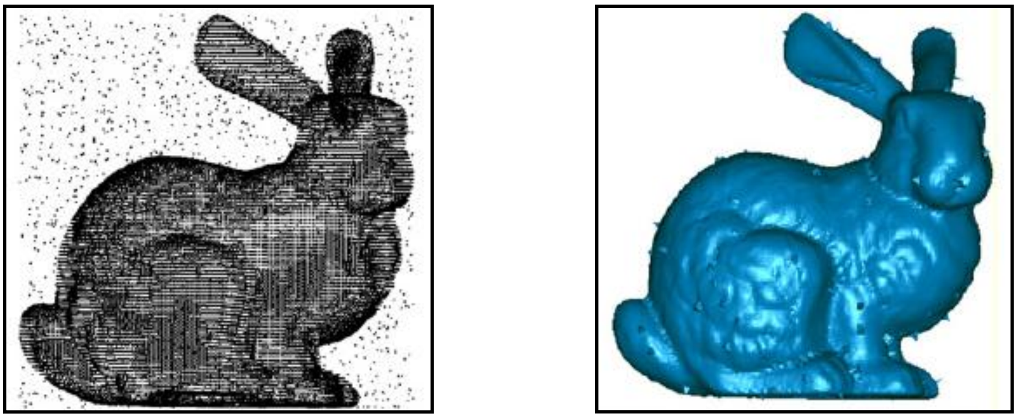
Figure 5.13: (a) Original data of Room 5, where the data in red can be assumed as A and blue for B; (b) result of data registration algorithm applied to B, with the angle of difference between the two sets of side wall points (as indicated by the black arrow in (a)) is calculated to rotate the other half data, B, (now shown in black) for registration

## 5.3 Data surfacing

The scope of this research is to model important structure within an interior. This model is to help professionals and experts in recording and maintaining the interior, which is important in various applications as mentioned earlier in Chapter 2. As most in-use interiors are fully equipped with furniture and related equipment (i.e. clutter), it is better to have an algorithm that is capable of removing all the clutter before structural reconstruction can begin.

Due to the above reason, a new stage of data surfacing is being introduced in PreSuRe as a method to remove all clutter that may exist in an interior. By removing the clutter, the remaining data can be used to reconstruct surfaces without having too much disturbance from unnecessary clutter data. This removed clutter can then be used to calculate the percentage of clutter present within an interior.

In this research, a method called ball fretting is being adapted to remove the clutter. Ball fretting algorithm has been developed by Giaccari (2009) based on ball pivoting method by Bernardini, et al. (1999) to reconstruct point cloud data of synthetic items. Previous research has used this method to model higher levels of detail in the reconstruction of various synthetic items, especially complex objects like statues, sculptures and carvings, where there is a lot of detail present which needs to be recovered. Figure 5.14 shows an example of a result of applying the ball pivoting method which in this case is used to highlight details of a statue.

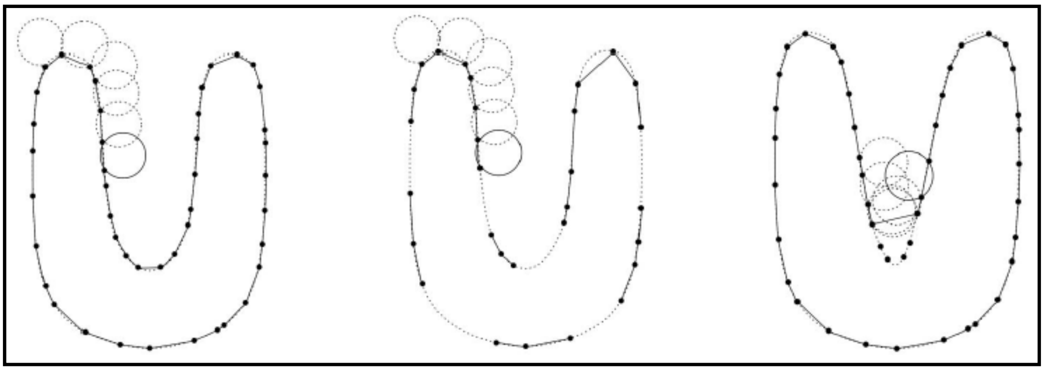


(a) (b)

Figure 5.14: Reconstructing surfaces from noisy Stanford Bunny data using ball pivoting: (a) Original noisy data; (b) The reconstruction outcome (Source: Angelo, et al., 2011*)

Figure 5.15 shows how the ball pivoting algorithm works in 2D. With a predefined radius, the ball connects all points with edges that are within its reach while rotating / pivoting (hence ball pivoting algorithm) along them. All the edges will be connected together using a triangle mesh to produce surfaces. The ball in this algorithm carries out the surface reconstruction task by creating a seed triangle first, which is developed when the ball touches three points. Then, from this seed triangle, the ball will start pivoting around an edge until it meets another point to create another triangle, and repeats this process until all reachable edges have been considered. Next, another seed triangle is generated to start reconstructing another set of edges until all points have been selected (Bernardini, et al., 1999).

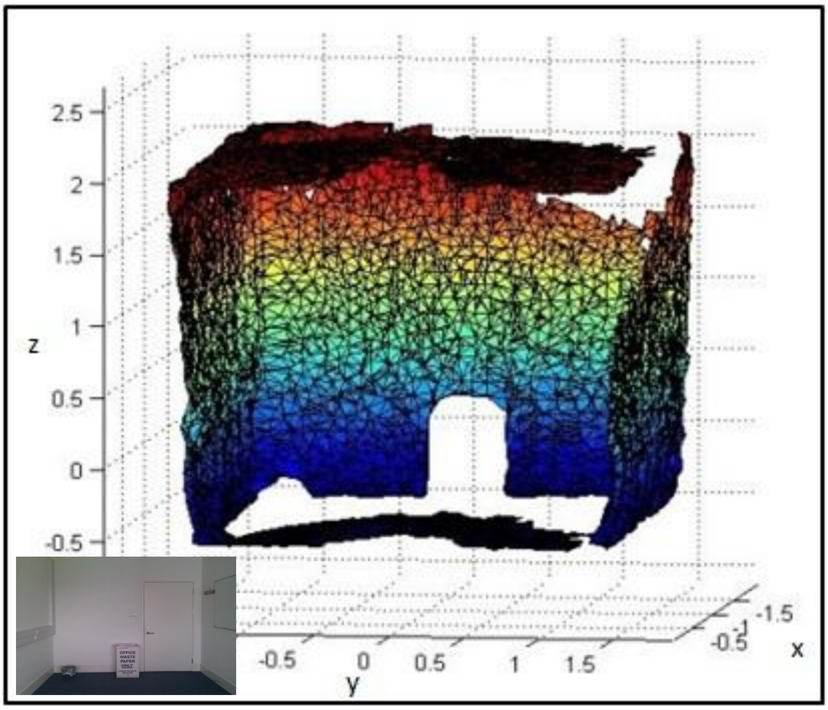
* Angelo, L.D., Stefano, P.D. & Giaccari, L., 2011.A new mesh-growing algorithm for fast surface reconstruction. *Computer-Aided Design*, 43, pp.639-650.



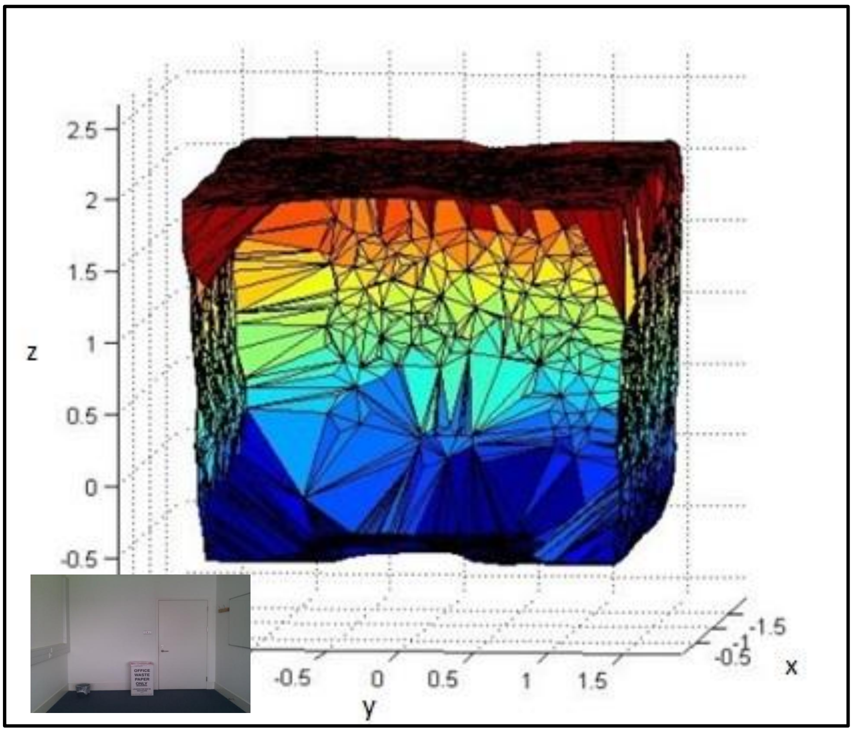
(a) (b) (c)

Figure 5.15: Ball pivoting algorithm in 2D: (a) the ball rotating / pivoting and connecting the points with edges; (b) holes will be created for low density points; (c) importance of selecting the correct ball radius - if it's too big then the ball can't reach the point at the shallow end (Source: Bernardini, et al., 1999)

In this method, the radius needs to be identified carefully as it depends on the point density of the input data, *S*. According to Bernardini, et al. (1999), the ball's radius, $\rho$, should be cautiously selected so that *S* has sufficient point density to avoid the ball passing through the surface without touching relevant points. As previous research used this method to reconstruct surfaces in detail (i.e. to highlight the details that exist in the object of interest), this research has been using the same method to do the opposite, as it is used to remove clutter in an interior (i.e. to get rid of the details). Although it has been suggested for the user to repeat the same process using a ball with larger radius to reconstruct surfaces with different point densities, this cannot be applied towards the scope of this research, as the goal is to remove clutter compared to others who are using this to emphasize any details. In PreSuRe, the ball has been defined with a radius, $\rho$, equal to 0.1, while the radius is set to 0.3 when surfacing data of a full, complex interior, as in Room 5. This may due to the big area of the room (a meeting room), compared to others which are quite small (e.g. office area for one person).


2.5
2
1.5
1
0.5
0
-0.5
z
-0.5
0
0.5
1
1.5
y
-1.5
-1
-0.5
x

(a)


2.5
2
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0.5
0
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z
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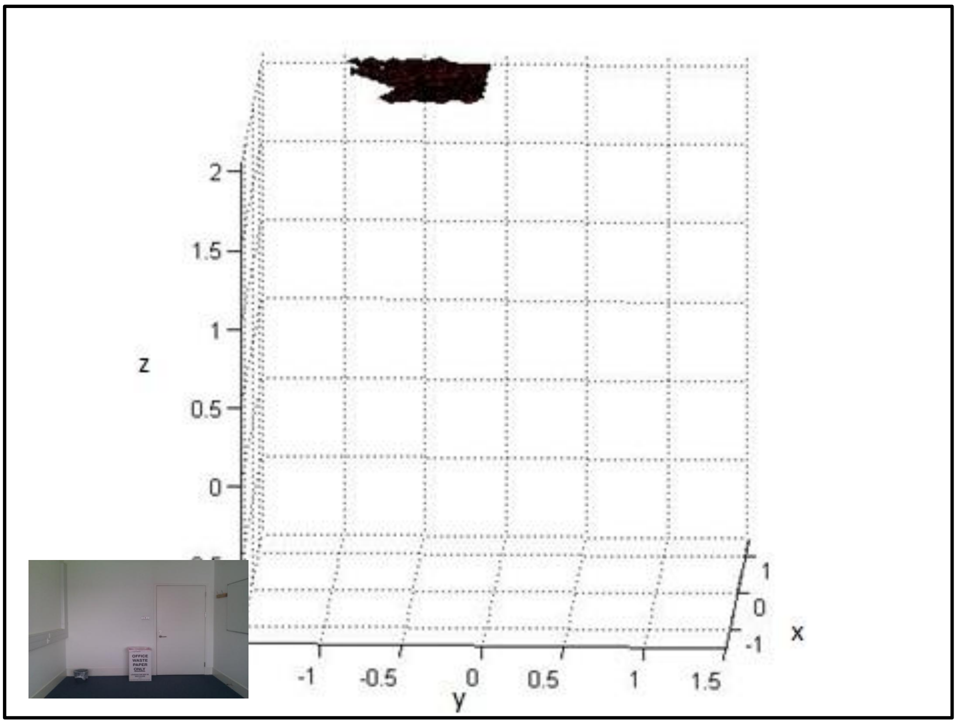
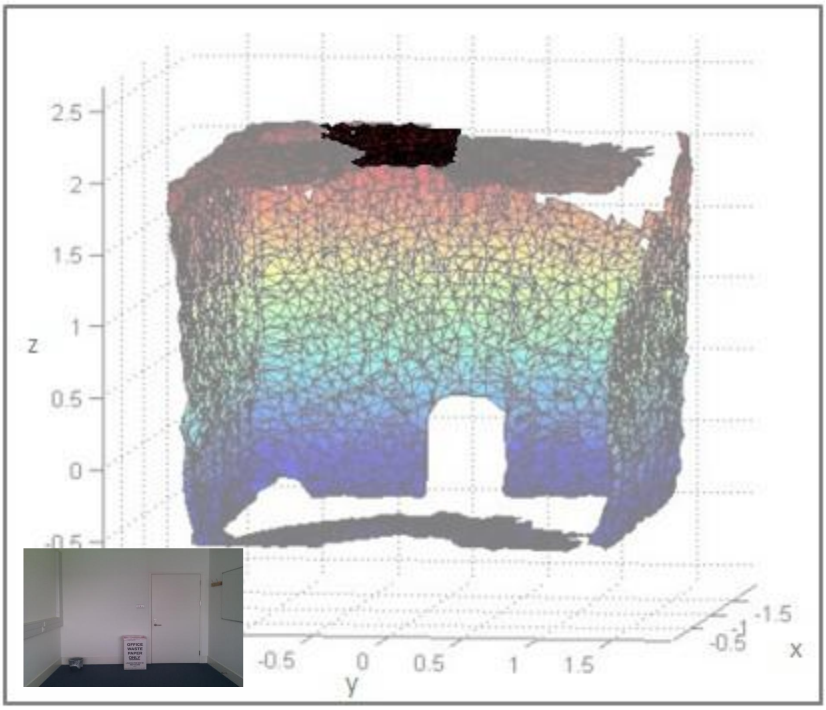
-1
-0.5
x

(b)




(c)

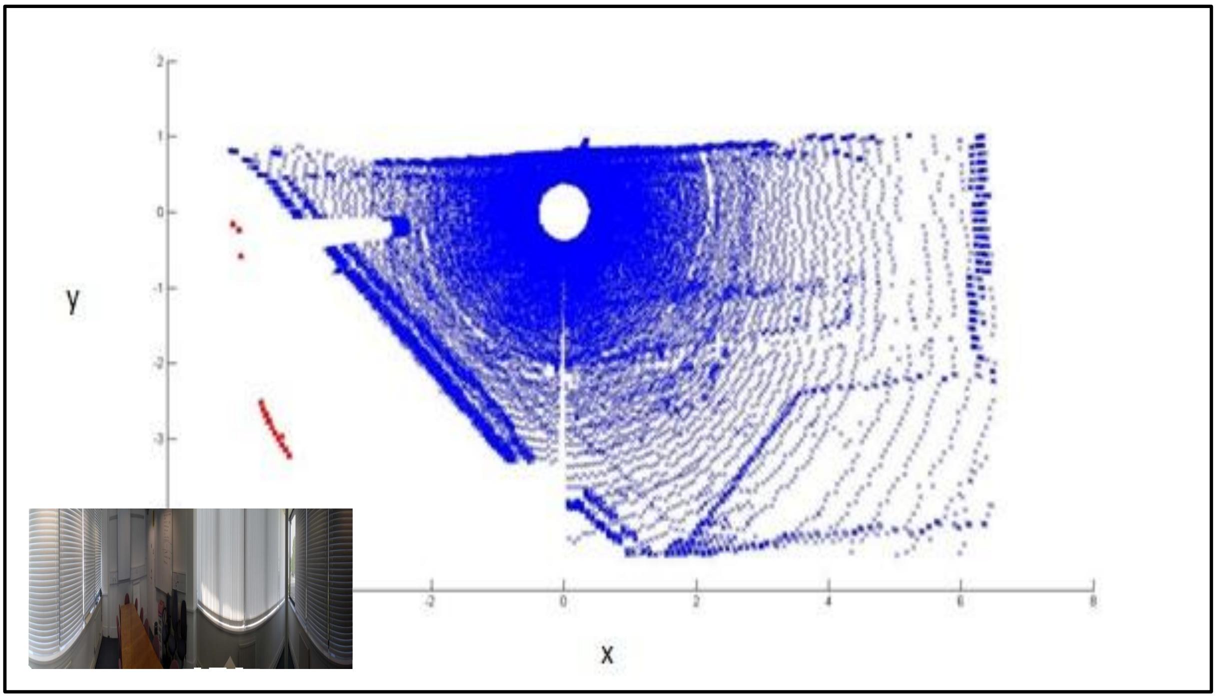



(d)

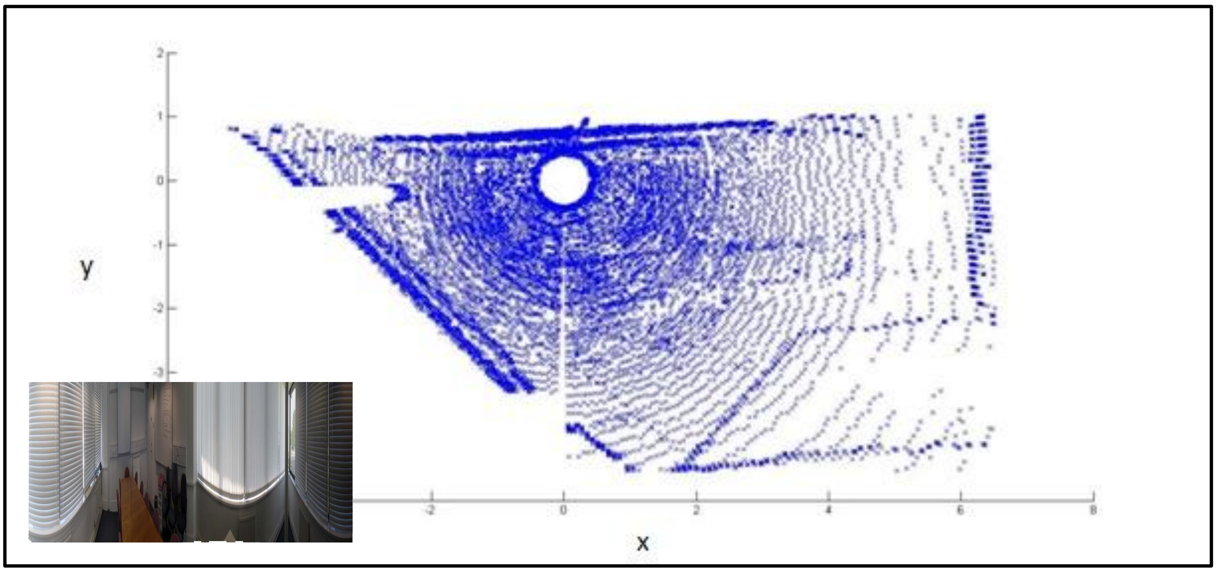
Figure 5.16: (a) Radius ($\rho$= 0.1); (b) Radius ($\rho$ = 0.5); (c) and (d) Radius ($\rho$ = 0.05), where (d) shows the location of the mesh

Figure 5.16 shows differing ball radius values applied to the same scan data of an interior and its impact towards removing clutter. In this case, data of Room 2 is processed to view the effects. In (a), the radius has been set to 0.1, which is the correct ratio towards the input point cloud data density, thus by applying the ball pivoting algorithm, the clutter has been removed but retaining the important surfaces like wall, floor and ceiling. Choosing a bigger radius ($\rho$ = 0.5) makes the clutter become absorbed (integrated) into the room's structure. Here, the bins are now parts of the wall's surface. Meanwhile, in (c) and (d), by applying a smaller radius ($\rho$ = 0.05), everything is removed except data with higher density, which is part of the ceiling, is reconstructed.

Apart from removing the clutter, the ball fretting technique used here in data surfacing is also important as it could be used to remove noise data that may still be present after noise data removal, especially towards interiors with complex geometrical structure. As the histogram method, which is used in the noise data removal here in this research, works best in a sparse room, therefore by using ball fretting, noise data, which may still exist, can be removed to give an acceptable model. Figure 5.17 (a) shows the result of data preprocessing for Room 5 which has a complex geometrical structure and its data surfacing result as shown in Figure 5.17 (b).




(a)




(b)

Figure 5.17: Room 5 data: (a) result of data preprocessing with small amount of noise (in red) still present; (b) result of data surfacing which also removed the noise

## 5.4 Data modelling

After the necessary clutter has been removed in the data surfacing, the remaining data resulting from it can now be reconstructed in the data modelling and mapping process to produce the 3D visualization of the interior. In here, several methods have been combined to generate the 3D model and map of the selected indoor environment.

The challenges to produce a 3D model and map of interiors are to overcome the occlusion issue as well as the relatively low specification of the laser scanner used in this research. Occlusion often creates missing data due to clutter, therefore the selected method to model and map the data needs to handle this situation. Regarding the specification of the laser scanner, SICK PLS 101 is a low-level laser scanner, thus it has lower resolution compared to the modern laser scanner, which means it generates lower point density data (refer to Table 2.1). In addition to that, some surfaces of the interior might have missing data. However, necessary actions have been taken as mentioned in Section 4.2.2 of Chapter 4 to ensure the collected data is enough to reconstruct the interior. In addition to that, the methods selected here are able to model and map the data.

But before the data can be reconstructed and modelled, it needs to be grouped into respective surfaces first, to avoid erroneous reconstruction during modelling later on. Data representing the floor needs to be grouped accordingly, as well as other surfaces like walls and ceiling. During the early stage of conducting this research, the surfaces were clustered manually based on prior knowledge of the room's area. Information like the measurement of the room is needed to guide this process. From this information, points which lay below 0.5 metre can be set as the floor points, for example, and can also be applied towards other surfaces.

Plotting features in MATLAB also allows users to interact with the plot, meaning that users can select manually points that represent any surface and record them. However, as the above manual processes do not differentiate PreSuRe with commercial software packages (point cloud data software packages also need users input to select and group the data accordingly), therefore there is a need to produce something that may be required by the users, which is automatic surface recognition. By having an automatic surface recognition process, it removes a manual step which also speeds up the process and reduces the tendency to remove important data as with the manual process.

In reconstructing partial room data which consists of empty room and sparse room (Room 1 and Room 2), all the important surfaces have been assigned according to the definitions of room surfaces as mentioned in Oxford Dictionary of English (2011). Here, wall is being defined as *'an upright side of a building or room'* and *'placed in a vertical position'*, whereas ceiling is *'the upper interior surface of a room'* and floor *'the lower surface of a room'* or simply *'the ground'*. Therefore, based on these definitions, all points in vertical are being assigned as the wall, as well as lower points and upper points as floor and ceiling respectively. Figure 5.18 shows the result of applying this into Room 1 data, by assigning the lower point as floor, most left points as the left wall, most right points as the right wall, furthest points as the back wall and upmost points as the ceiling.

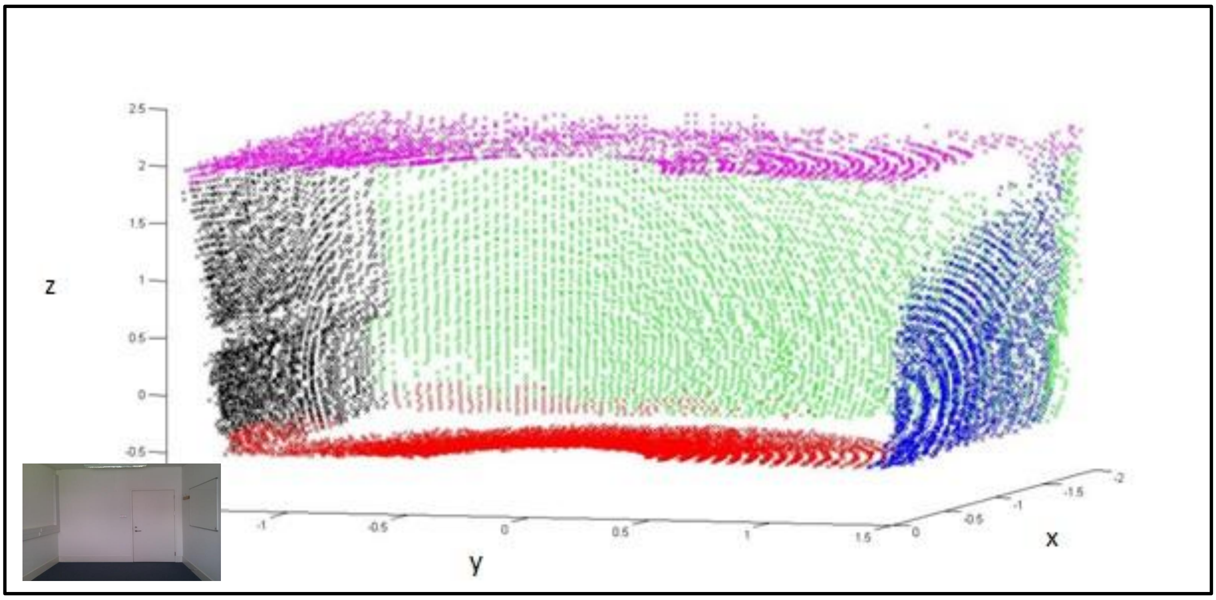



Figure 5.18: Result of assigning the surfaces according to the definition works with partial room data

However, when processing complex interior data, the above method is not suitable as they may consist of complex geometrical structures like a pillar and layered or multileveled ceiling. To recognize and group the points of these type of interiors accordingly, a histogram is being adapted as it can calculate the number of points at each surface, quite similar to Okorn, et al. (2010) work as mentioned above. As these surfaces are the main features, they usually consist of a lot more points compared to other things like clutter. Apart from that, as most clutter has been removed in data surfacing process, most of the data left represents these surfaces therefore they can be assigned accordingly. However, the floor data points have been assigned prior to the histogram process according to the above definition and thus, the lower data points have been assigned as floor, like reconstructing partial room data. It is good to assign floor points first too, as these points can be removed before applying a histogram to extract data of other surfaces as this can reduce recognition confusion. Nevertheless, this approach has its limitations, where interiors with sloped, layered or multileveled floor may not be detected, as only one surface represents the floor is assigned. But, this type of interior has not be seen throughout conducting this research, furthermore all current researchers are also using the same assumption in reconstruction building interior (i.e. all floors are even). A good example is the stairs, but it is out of scope as this research concentrates on room structure, which has been defined earlier in Chapter 1 as a closed space / area.

Figure 5.19 shows how histogram can be used to extract data points representing surfaces of the interior of Room 3.

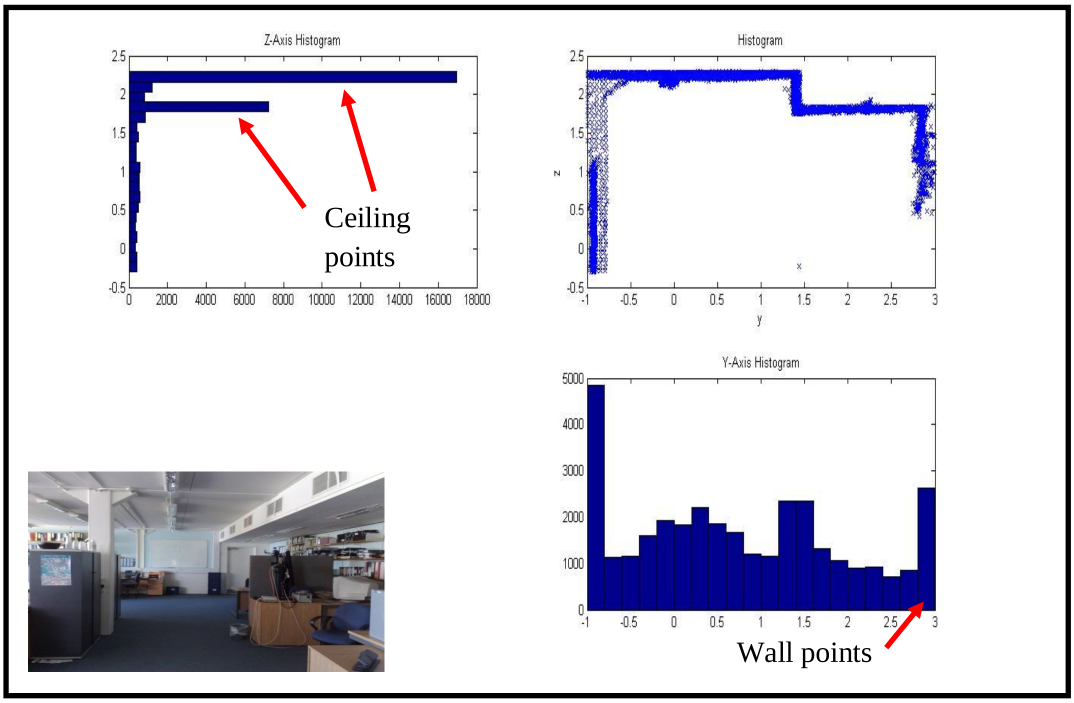


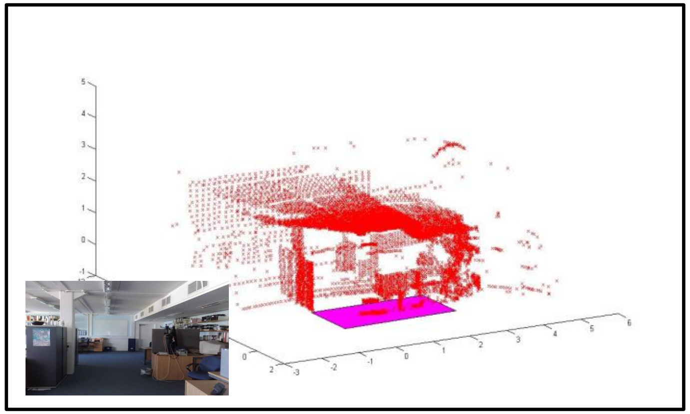

Figure 5.19: Results of applying histogram to recognize surfaces of interior

After all the respective points have been assigned, they can be reconstructed. Here, a computational geometry method called convex hull is adapted to reconstruct the surfaces. Convex hull is one of the favourable methods in reconstructing surfaces from point cloud data, as it considers all points when reconstructing it, without neglecting any points. Section 2.3.1 of Chapter 2 shows how convex hull works.

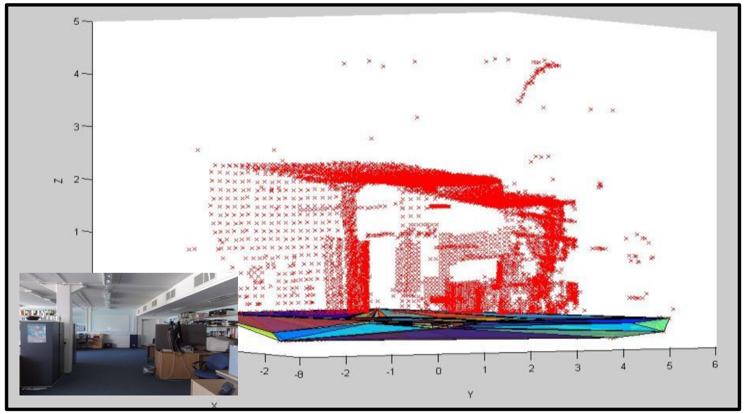
But before convex hull is adapted, several other methods that could reconstruct surfaces from point cloud data, identified from literature, were tested. However, there are several limitations that did not allow it to be further adapted. Table 5.2 summarizes these methods and the related issues that prevented them from being used as the method to reconstruct interior surfaces from point cloud data in this research. Figure 5.20 shows the end results of applying these methods towards Room 3 data in reconstructing the floor surface. All the mentioned methods are briefly discussed in Section 2.3.1 of Chapter 2.

| Method | Limitation |
|---|---|
| RANSAC (Cantzler, *et al.*, 2002) | Result did not resemble a real interior, not all points are considered |
| EM (Haehnel, *et al*., 2003) | Result did not resemble a real interior |
| PCA (Johnson and Hebert, 1999) | Result did not resemble a real interior |

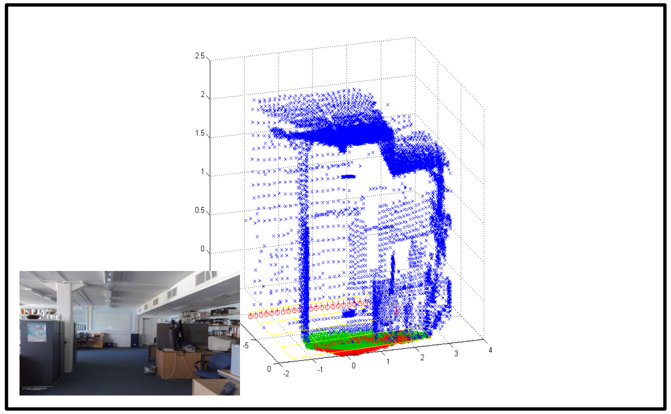
Table 5.2: Summary of data reconstruction method tested to the interior data collected in this research



(a)



(b)



(c)

Figure 5.20: Results of applying: (a) RANSAC; (b) EM; (c) PCA; to Room 3 data for surface reconstruction

Nevertheless, the reconstruction result from the above convex hull does not do enough to represent the real interior, as the supplied data is not complete due to the missing points that are caused by occlusions and clutter. Therefore, relationship modelling is adapted here to ensure respective surfaces that share similar relationships can be used to define the surfaces' borders. Similar relationship modelling has also been used by Nuechter and Hertzberg (2008) to reconstruct surfaces. Figure 5.21 summarizes on how this relationship modelling is used to obtain borders of sharing surfaces that have a relationship with each other to produce a model that represents the real interior. Figure 5.22 shows a sample of the reconstruction result before and after applying relationship modelling towards Room 1 data.

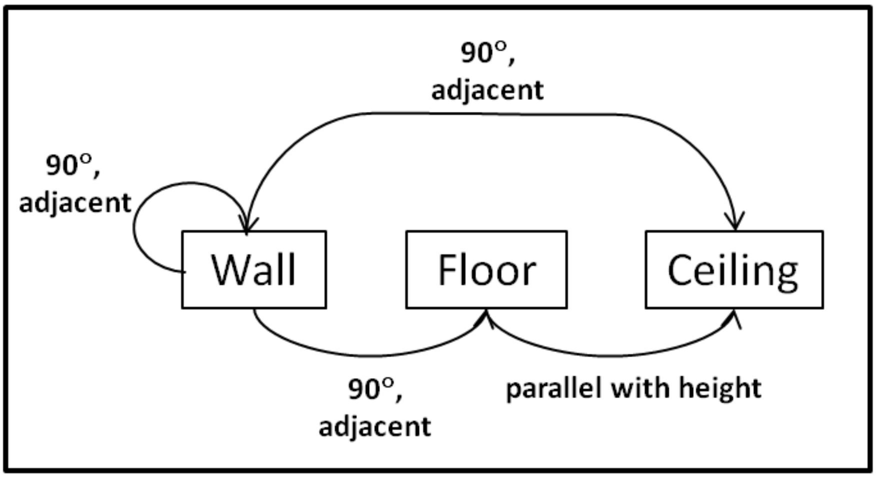
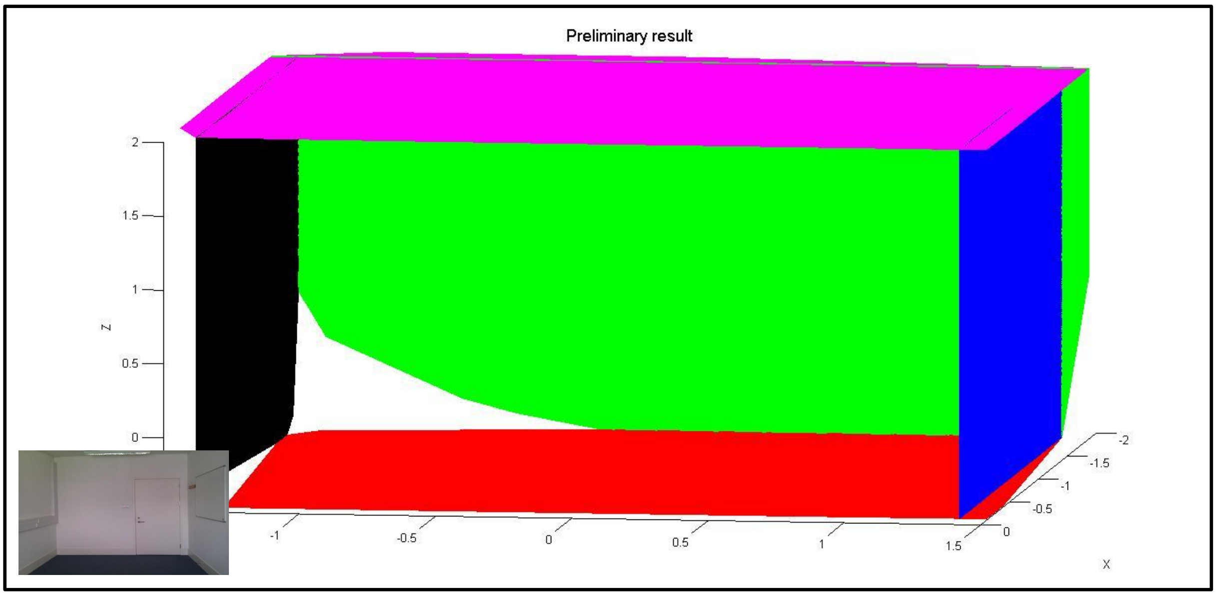
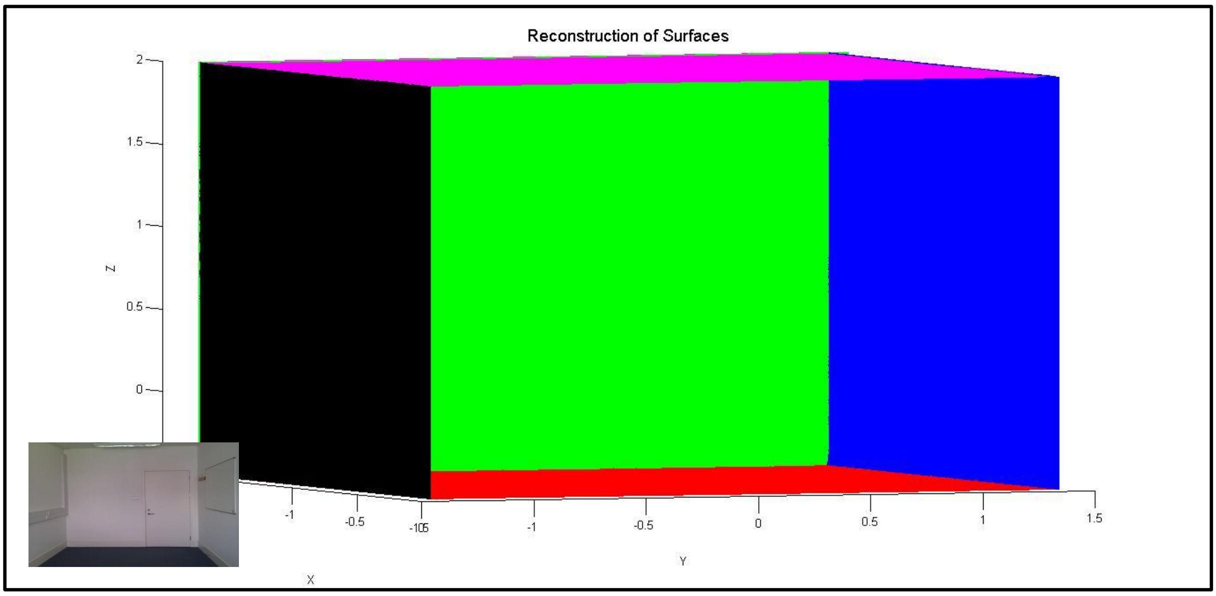



Figure 5.21: Relationship modelling used in this research to aid reconstructing the real interior (Source: Abdul Shukor, *et al.,* 2011)




(a)




(b)

Figure 5.22: Reconstruction result of Room 1 data: (a) before relationship modelling; (b) after applying relationship modelling

After all the structure has been reconstructed, the model will then be mapped and visualized. Before 3D modelling of building interiors has been used widely, some people are still confused with the 3D CAD drawings (that can be generated by the CAD software package), as according to them, the features in 3D modelling are also present in 3D CAD drawings. But, according to Smith and Tardif (2009), CAD drawings are just *'pictorial representations of buildings*' and might not be enough and brought little value for professionals and experts. What makes the model developed in this research different from a normal 3D CAD drawing are the semantic information contained within it. All surfaces are being labelled and mapped to aid visualization, plus, with the adaptation of relationship modelling as mentioned above, the model comes with semantic relationship information, where the surfaces that share relationships with others can be modified automatically when one of them is altered. This feature is essential, especially when providing a visualization aid to architects that are planning for future renovation. By having this semantic information in this model, less tedious and time consuming work is needed to implement it and support BIM in the post reconstruction stage as well. Further information on this semantic information is covered in Chapter 7.

## 5.5 Data assessment

As no previous research has come out with a quantitative assessment method to evaluate the model's measurement accuracy, this research is aimed to develop one method that can be adapted by others. The lack of such method is due to the unavailability of ground truth to compare the result's measurement with. Assessing the accuracy of 3D models of synthetic items is usually straightforward as users can access the dataset online and the real model data available can be used as the ground truth to aid accuracy comparisons. Examples of synthetic objects that are available and currently being used by plenty of researchers is the Stanford Bunny and Happy Buddha (Stanford 3D Scanning Repository, 2011). Models of building interiors are often being subjected to professional authorization due to the fact that it involves another's confidential work, thus making it difficult to be made available to the public for research evaluation.

However, as building owners and managers are often equipped with 2D as-built drawings, the measurements from the drawings can be used for comparison to evaluate a 3D model's accuracy. Therefore, this research has come out with an idea to utilize measurement from 2D as-built drawings to evaluate the resulting model from the new algorithm. More information on how as-built drawing measurements are utilized to verify the resulting model can be found in Chapter 6.

In addition to the above, the performance of the algorithm can also be measured in terms of the noise and clutter percentage. This is important as the research is using a measurement system (i.e. 3D laser scanner) that does produce noise data, and due to the presence of furniture and equipment, these can create complex interiors with clutter and sometimes with complicated geometrical structures. Therefore, a suitable method will be proposed to calculate the percentage of noise data to assist the quantitative assessment process of this modelling.

Let's recall the above noise data removal stage during the preprocessing. Here, the process is being developed to remove noise data that exists in the raw data collected by the laser scanner. Therefore, the amount of resulting clean data from the noise data removal stage can be used to determine how much noise data is present. In this research, percentage of noise data can be calculated by:

$$Percentage\ of\ noise\ data = \frac{Noise\ data}{Raw\ data} \times 100 \quad (5.3)$$

where

$$Noise\ data = Raw\ data - clean\ data \quad (5.4)$$

*Raw data = number of points recorded / collected by the laser scanner*

*Clean data = number of points remaining after the data has been 'cleaned' using the noise data removal algorithm*

Meanwhile, the data surfacing stage conducted after the preprocessing can be used to figure out the percentage of clutter that exists in the interior, as the purpose of this stage is to remove clutter from the interior before modelling and reconstruction work can be performed. Here, the percentage of clutter can be determined by:

$$Percentage\ of\ clutter\ data = \frac{Surfaces\ of\ clutter}{Clean\ data\ surface} \times 100 \quad (5.5)$$

where

$$Surfaces\ of\ clutter = Clean\ data\ surface - \ surface\ after\ data\ surfacing \quad (5.6)$$

*Clean data surface = surfaces of clean data*

*Surface after data surfacing = resulting surfaces from data surfacing (refer to Figure 5.23)*

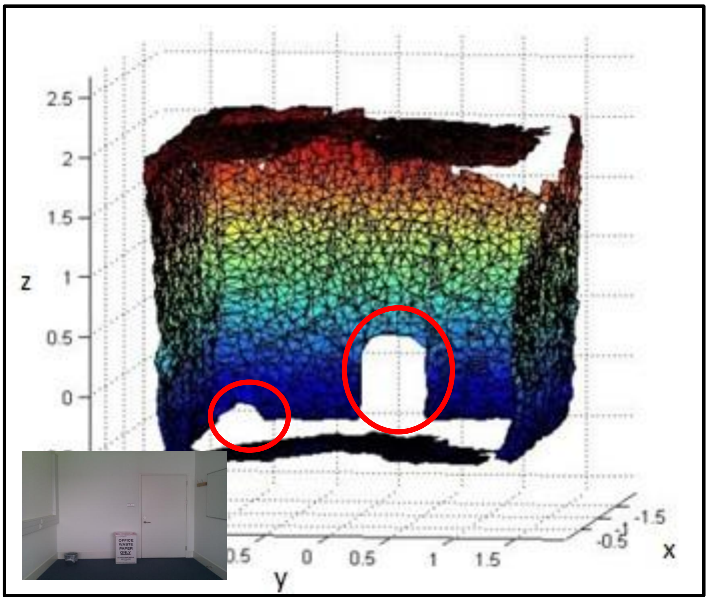
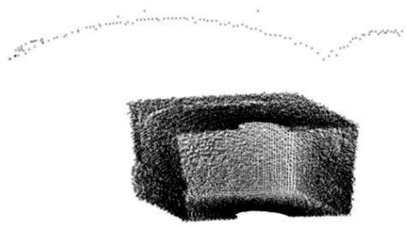
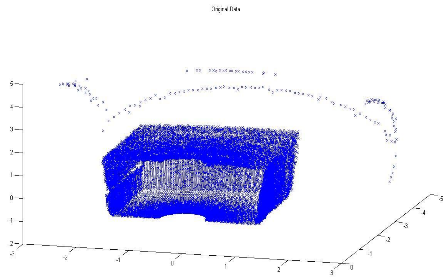
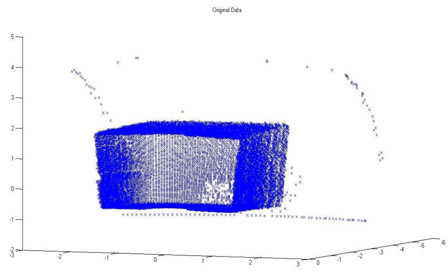
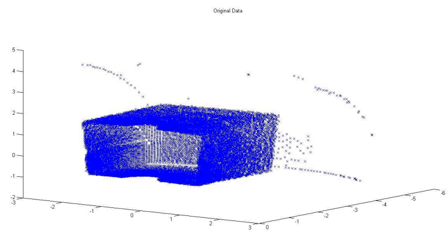
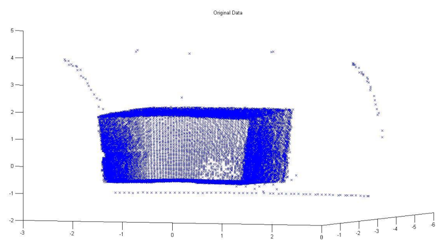


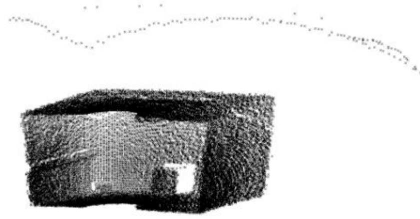
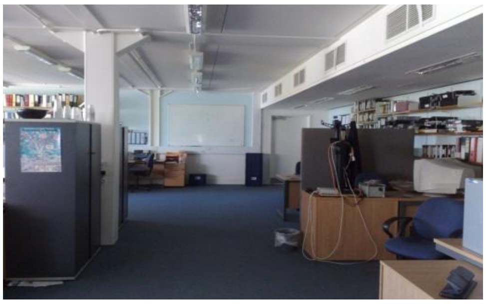
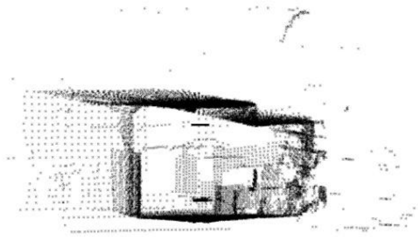
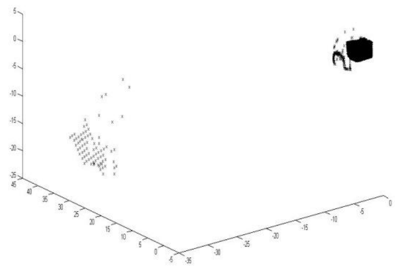
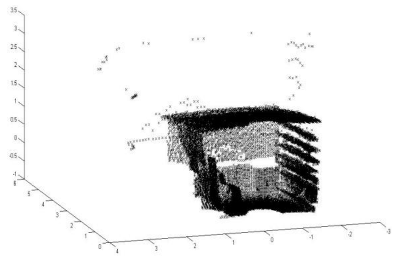
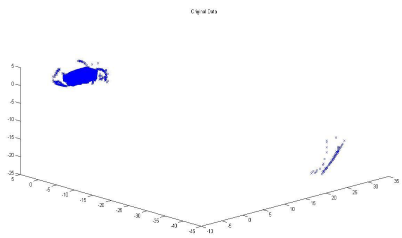

Figure 5.23: Resulting surfaces from data surfacing method. Surfaces representing clutter (as in red circles) has been removed by the algorithm

All the above equations, plus the additional measurements taken from 2D as-built drawings, were used to evaluate the performance and accuracy of the modelling developed in this research.

## 5.6 Results and discussions

Before results of applying all the above process in PreSuRe algorithm can be shown and discussed, it is good to define all the dataset collected by the SICK laser scanner to train and test the algorithm first. Table 5.3 shows all the dataset used in this research to verify the algorithm. The dataset, taken from 5 different sets of interior, were divided into training and testing dataset.

| Room type | Figure of the room | Raw data collected by laser scanner |
|---|---|---|
| Room 1: Empty (5 datasets collected for training and testing) |  |  Dataset 1 - 25,470 points |
| | |  Dataset 6 - 25,438 points |
| | |  Dataset 7 - 25,430 points |
| | |  Dataset 8 - 25,432 points |
| | |  Dataset 9 - 25,430 points |

| | | |
|---|---|---|
| Room 2: Sparse (1 dataset collected) |  |  Dataset 2 - 25,470 points |
| Room 3: Complex interior (1 dataset collected) |  |  Dataset 3 - 21,719 points |
| Room 4: Complex interior (2 datasets collected for training and testing) |  |   Dataset 4 - 50,777 points |
| | |  Dataset 10 - 50,829 points |

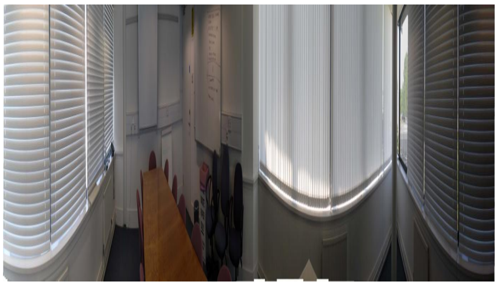
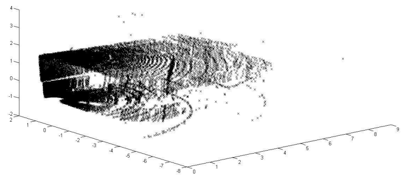
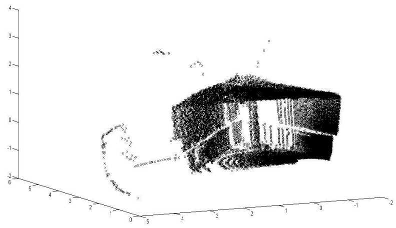
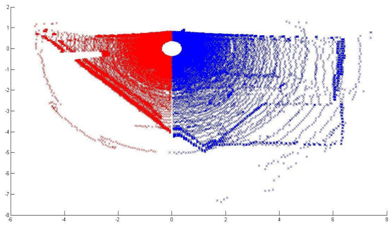
| | | |
|---|---|---|
| Room 5: Complex interior (2 datasets collected for training and testing) |  |   Dataset 5 - 50,364 points |
| | |  Dataset 11 - 50,388 points |

Table 5.3: The training and testing datasets collected in this research to verify the algorithm

All of the above dataset have been used to train and test PreSuRe algorithm. In this chapter, results and discussions of Room 2 training dataset (Dataset 2) are shown, while the results of the others shall be discussed in Chapter 6. Dataset 2 is chosen as it undergoes all processes in the algorithm, compared to Dataset 1 which omits data surfacing as it represents an empty room that does not have any clutter to be removed prior modelling. Figure 5.24 to 5.26 show the results obtained from data preprocessing, data surfacing as well as data modelling and interpretation processes towards Dataset 2.

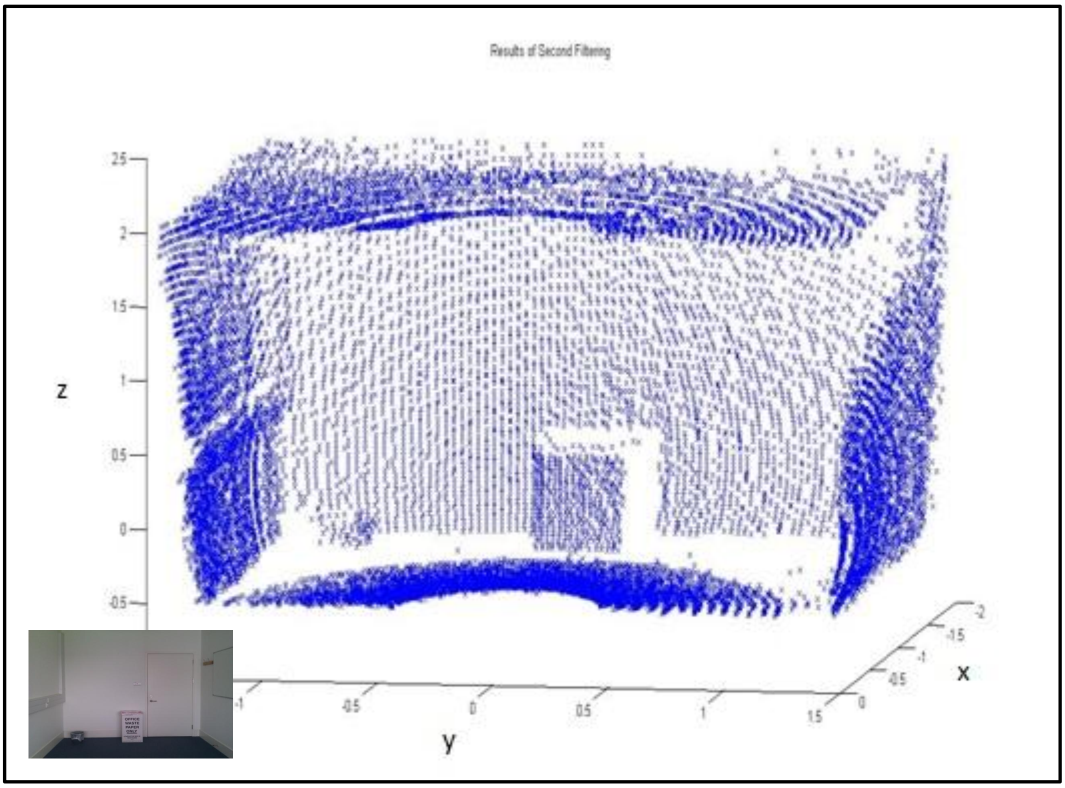



Figure 5.24: Data preprocessing result of Dataset 2

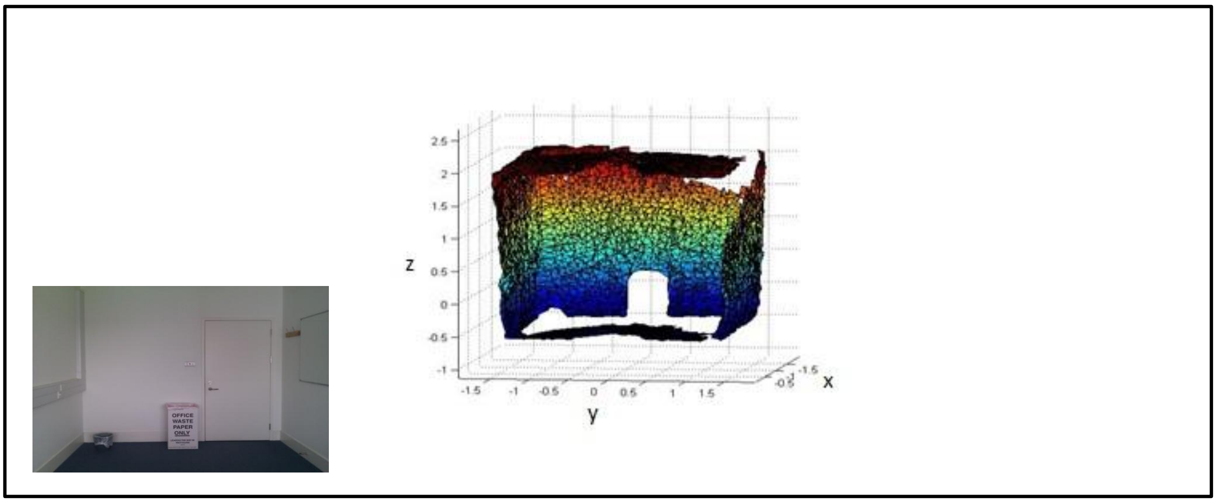



Figure 5.25: Data surfacing result of Dataset 2

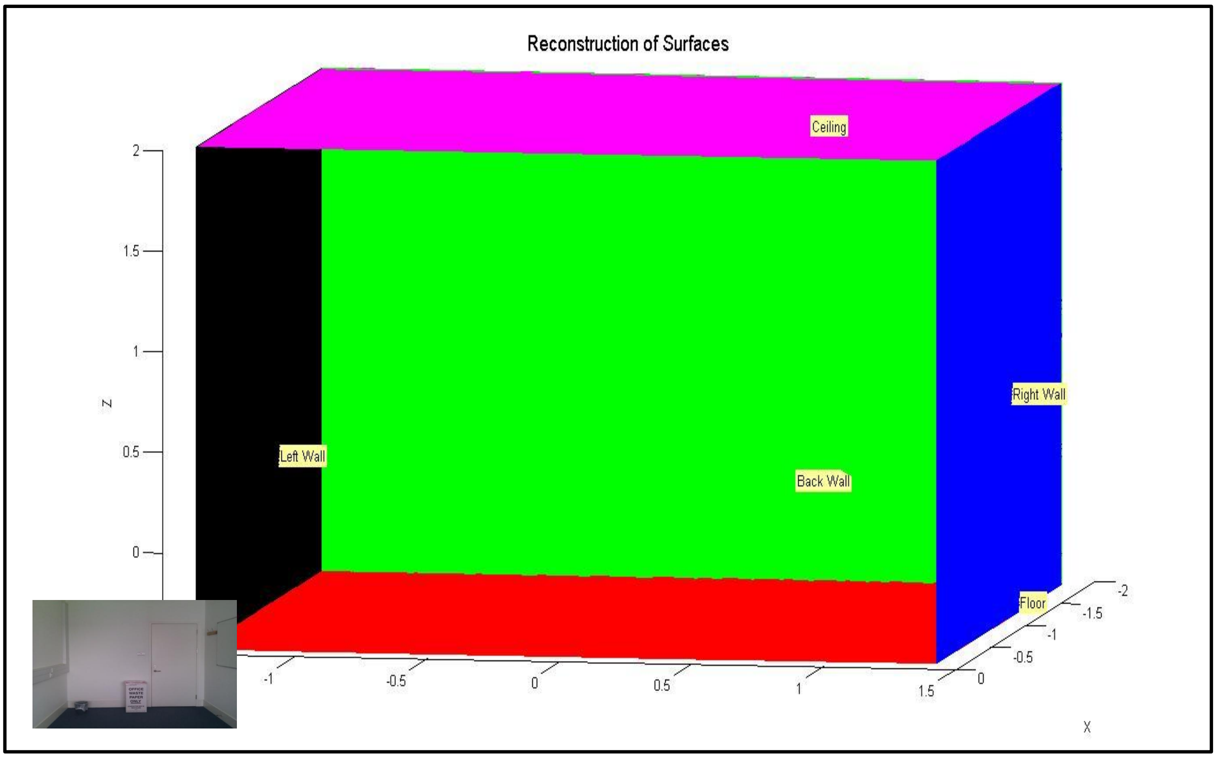



Figure 5.26: 3D modelling and interpretation of Dataset 2

As shown in Figure 5.26, PreSuRe algorithm has successfully model and interpret Dataset 2. The resulted model is a 3D representation of the structure of the interior, where in this research, structure represents all the important surfaces that exist in the interior. The model has a low level of visualization detail, where straightforward taxonomy of defining the surfaces applies. For example, non-structural interior features like cable skirting is being defined as part of the wall, therefore the data representing it that might be present is being assigned into the wall surface. As these non-structural interior features are usually within tolerances as defined by the US General Services Administration (GSA) of ± 50mm (Tang, *et al.*, 2010), therefore it is good to say that this taxonomy can be applied.

## 5.7 Contributions

There are significant contributions developed in this chapter alone. A new algorithm pipeline has been introduced here that can be applied towards producing 3D modelling of building interiors. Most of the building interiors, especially those which are still in use are usually full of clutter. Therefore, this clutter needs to be removed first (virtually rather than physically) prior to modelling, hence the data surfacing process is being included in the pipeline. As no previous research has come out with this data surfacing step before reconstructing the interior, with the advantage this brings, it is good to have an extra process of data surfacing before reconstructing interior data.

The platform developed in this research is also a new one, consisting of new and adapted methods in modelling building interior data. New methods of data registration as well as data assessment have been developed to fulfil the requirement in this research area. As most available data registration methods are not suitable to register data obtained by SICK PLS 101 laser scanner as used in this research, a novel method to register them together has been created and included in the platform. To measure out the accuracy of the model, a new method to assess it has been introduced here by measurements from the 2D as-built drawings were utilized and compared with the model, together with the percentage of noise and clutter data. More details about data assessment can be found in the next chapter (Chapter 6), which concentrates on the validation and verification of the resulting model.

As there is a need to have an automatic solution to model 3D interior data, this research has developed an automatic platform, based on the prior knowledge of the interior. Meaning that, users need to have prior knowledge of the data that needs to be processed, for example a partial sparse room, before an appropriate solution can be applied to produce the 3D model automatically. It also generates the model within an acceptable time, even with the manual process to set-up the laser for data collection, thus making it a suitable method to be applied in producing 3D model structure of building interiors.

# Chapter 6

# PreSuRe Algorithm: Verification and Validation

*"Trust, but verify"*

**-** Ronald Reagan*

The aim of the resulting 3D model generated using the developed algorithm is to assist professionals in related applications. The model can be used as a record to assist and plan further maintenance and renovation of that particular interior. As professionals always deal with accuracy, therefore it is important to verify and validate the outcome to achieve this aim.

To date, there is no method designed to validate the end model - most of the results are accepted based on the vision (i.e. if it's looking good then the model is good and can be accepted). Thus, this research has come out with a method to measure the accuracy of the model by utilizing the measurement obtained from 2D as-built drawing of the same interior. Measurements from the end model will be compared with the measurements from as-built drawings to show the accuracy. Furthermore, other important entities apart from the measurements such as the percentage of noise due to the laser scanner, plus the percentage of

*BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 1November 2012].

clutter that exists in the interior, as well as the time taken for the algorithm to produce the end results are also being assess.

This chapter is designed to show verifications and validations of the developed algorithm on the remaining training dataset. Previous chapter (Chapter 5) which highlighted on the development of algorithm has shown the results of one dataset (Dataset 2 of Room 2), therefore the rest of the results will be discussed and verified in this chapter.

## 6.1 Data preprocessing

Figures 6.1 to 6.4 show the results of applying data preprocessing towards Dataset 1 and Dataset 3 to 5. As seen on these figures, all noise data has been removed by the algorithm. Percentage of noise data on these datasets are as in Table 6.1. The percentages were calculated based on equations 5.3 and 5.4 as defined in Chapter 5.

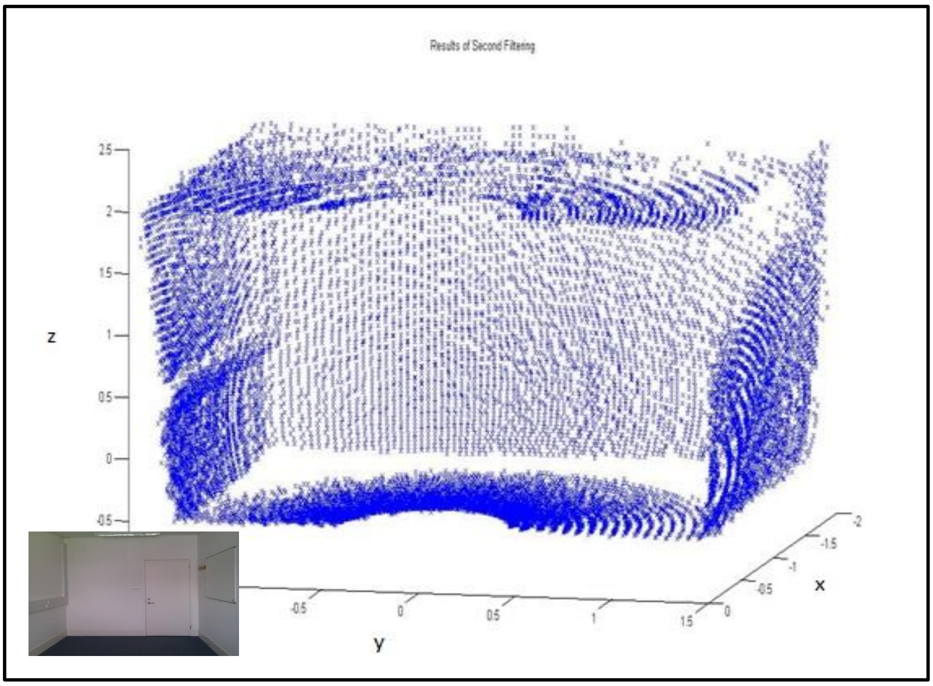



Figure 6.1: Resulting clean data of Dataset 1

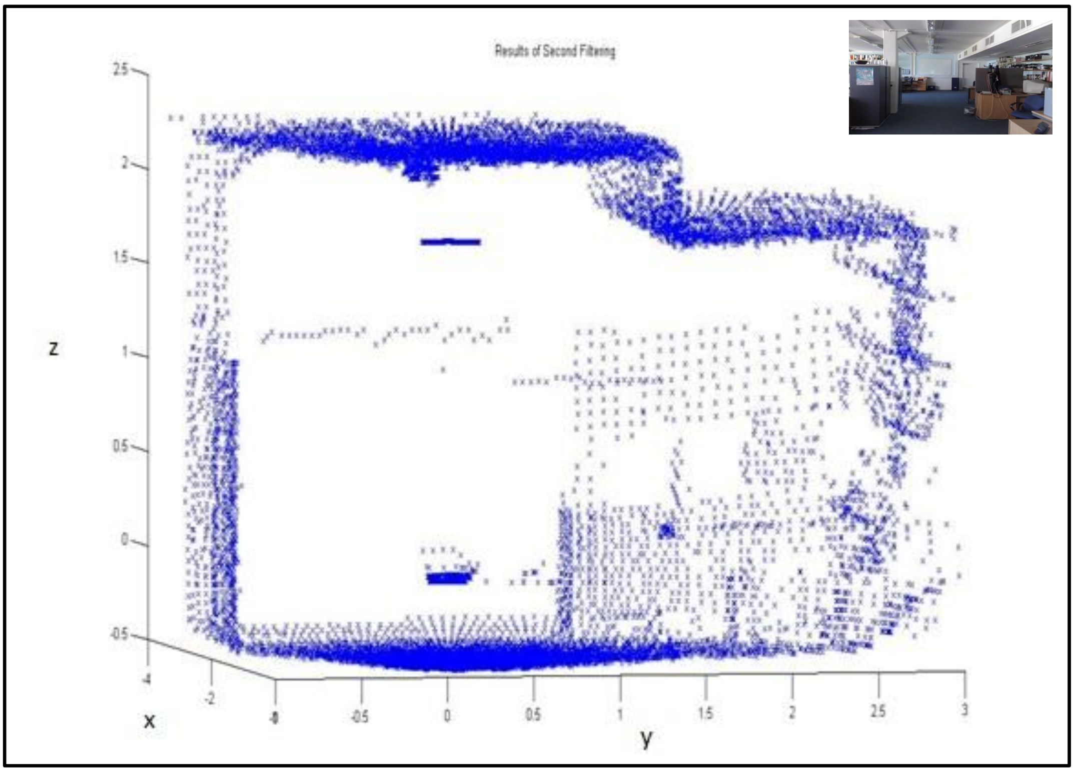



Figure 6.2: Resulting clean data of Dataset 3

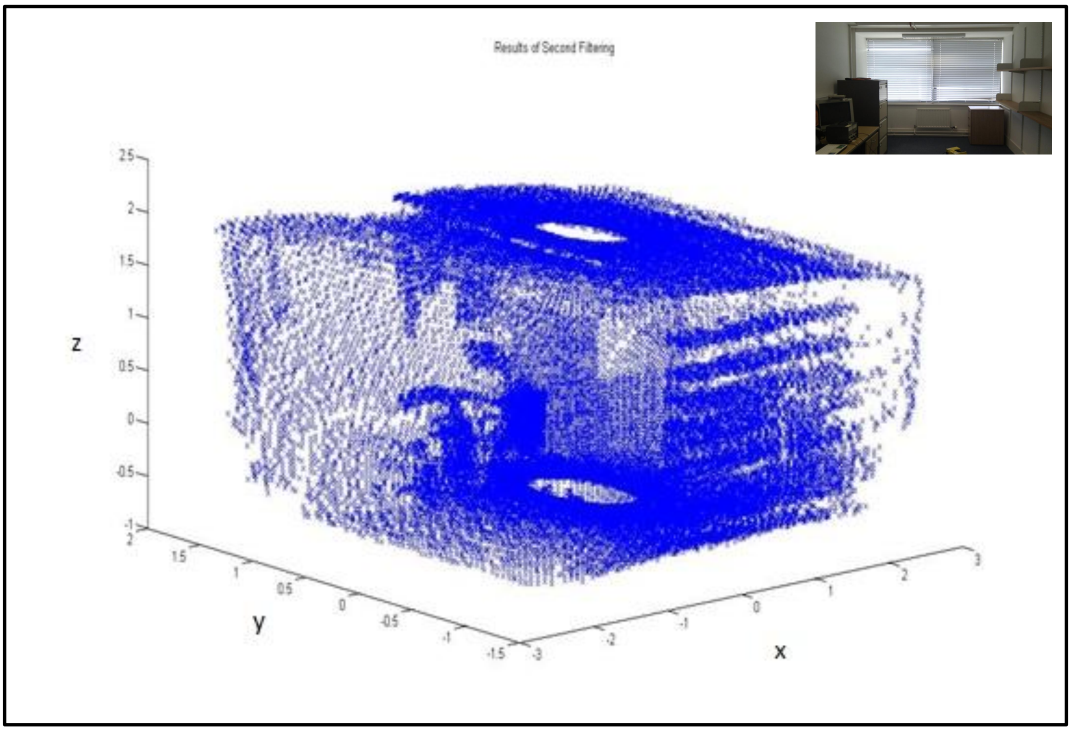



Figure 6.3: Resulting clean data of Dataset 4

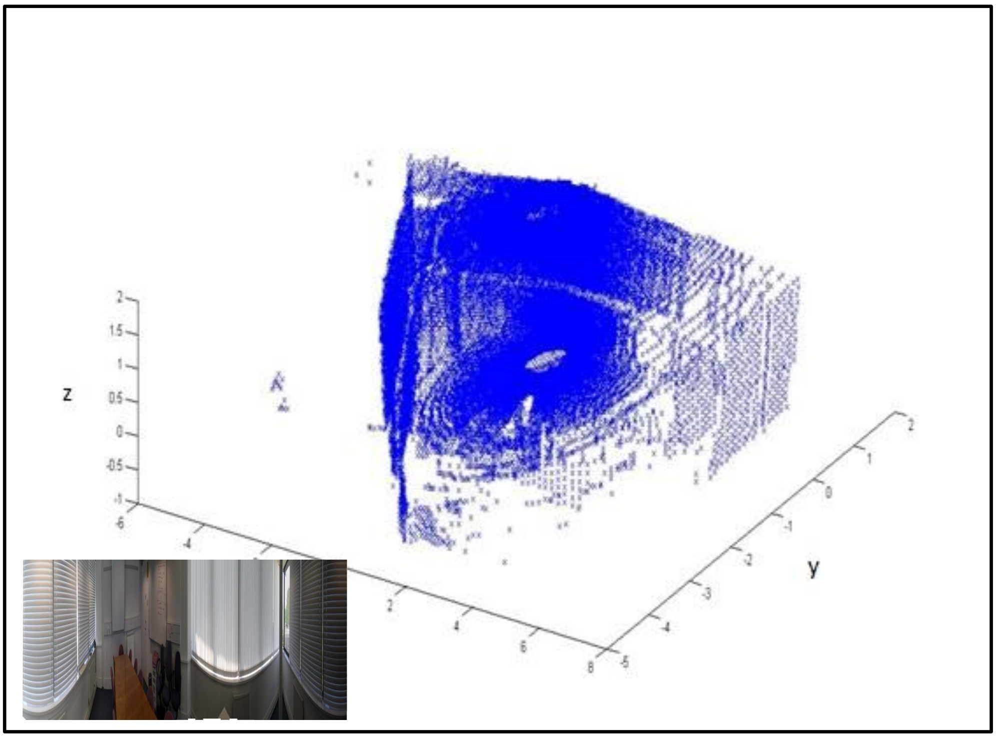



Figure 6.4: Resulting clean data of Dataset 5

| Dataset | No. of points | | Percentage of Noise |
|---|---|---|---|
| | Raw | Clean | |
| 1 (Room 1) | 25,470 | 24,721 | 2.94 % |
| 2 (Room 2) | 25,470 | 24,437 | 4.06 % |
| 3 (Room 3) | 21,719 | 20,906 | 3.74 % |
| 4 (Room 4) | 50,777 | 50,121 | 1.29 % |
| 5 (Room 5) | 50,364 | 50,223 | 8.31 % |

Table 6.1: Percentage of noise data removed by PreSuRe algorithm

## 6.2 Data surfacing

Figures 6.5 to 6.7 show the results of applying data surfacing method towards Dataset 3 to 5. As Dataset 1 represents an empty interior, thus data surfacing (i.e. process of removing clutter data) is unnecessary. As seen on these figures, clutter data has been removed by the algorithm and the remaining surfaces represents the important structure of each interior. Percentage of clutter on these datasets are described in Table 6.2 using equations 5.5 and 5.6 in Chapter 5.

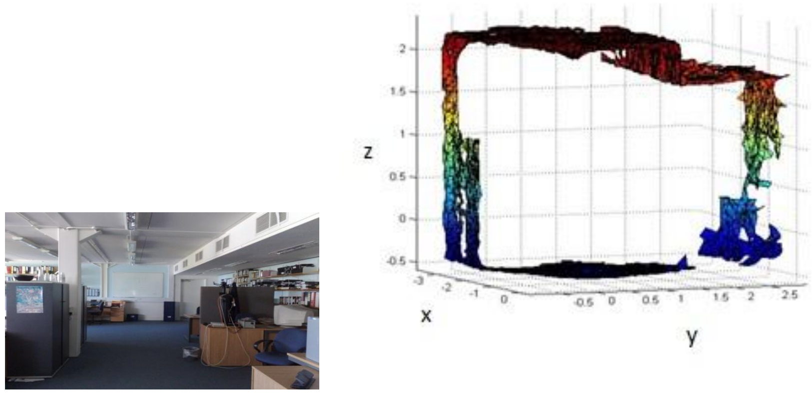



Figure 6.5: Data surfacing result of Dataset 3

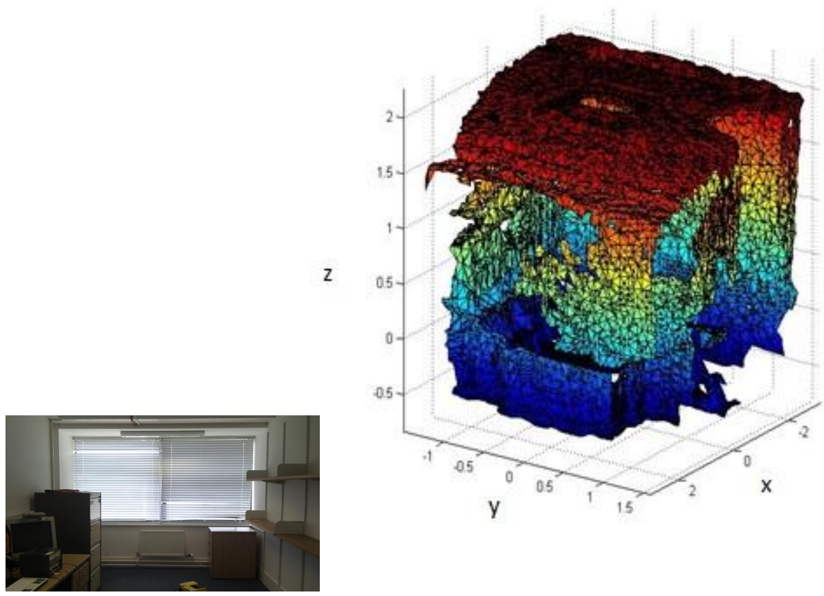



Figure 6.6: Data surfacing result of Dataset 4

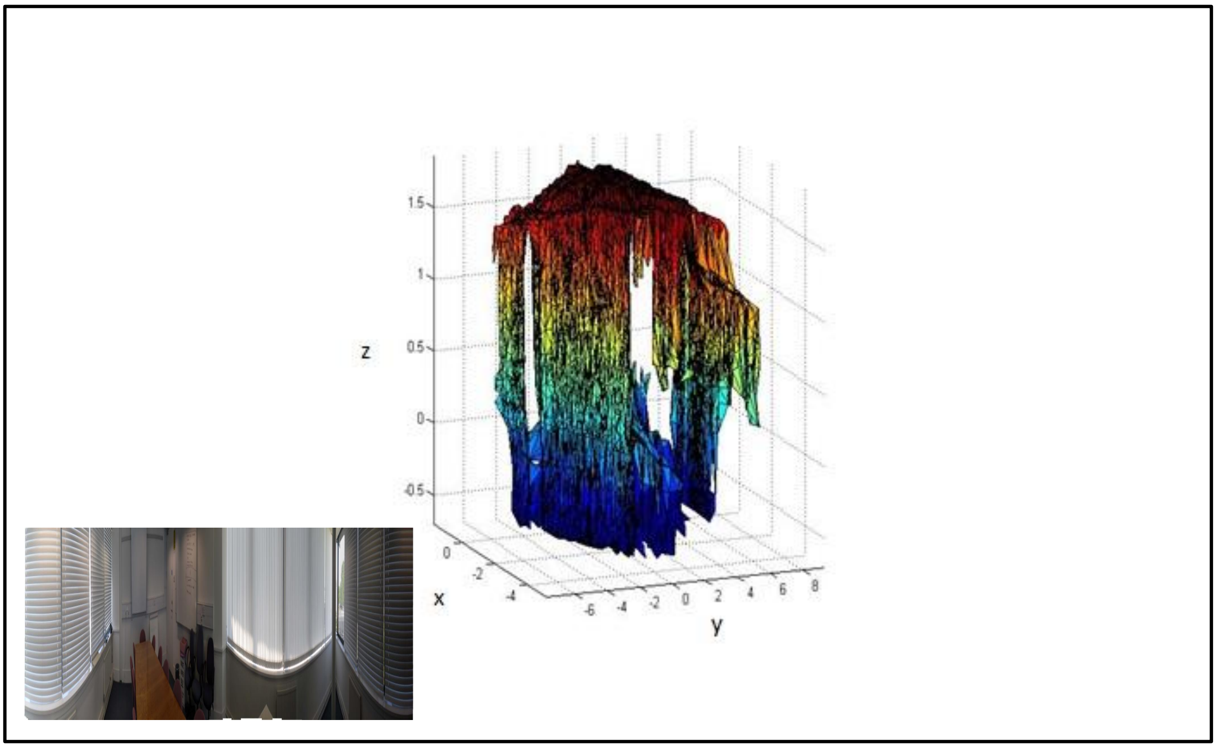



Figure 6.7: Data surfacing result of Dataset 5

| Dataset | No. of polygon meshes | | Percentage of Clutter |
|---|---|---|---|
| | Before surfacing | After surfacing | |
| 1 (Room 1) | - | - | Nil |
| 2 (Room 2) | 114,940 | 70,642 | 38.54 % |
| 3 (Room 3) | 107,075 | 49,648 | 53.63 % |
| 4 (Room 4) | 307,698 | 163,740 | 46.79 % |
| 5 (Room 5) | 314,440 | 155,993 | 50.39 % |

Table 6.2: Percentage of clutter data removed by PreSuRe algorithm

## 6.3 Data modelling

Figures 6.8 to 6.11 show the modelling results of data reconstruction and interpretation methods towards Dataset 1 and Dataset 3 to 5. All the important structures have been successfully reconstructed and interpreted by PreSuRe algorithm.

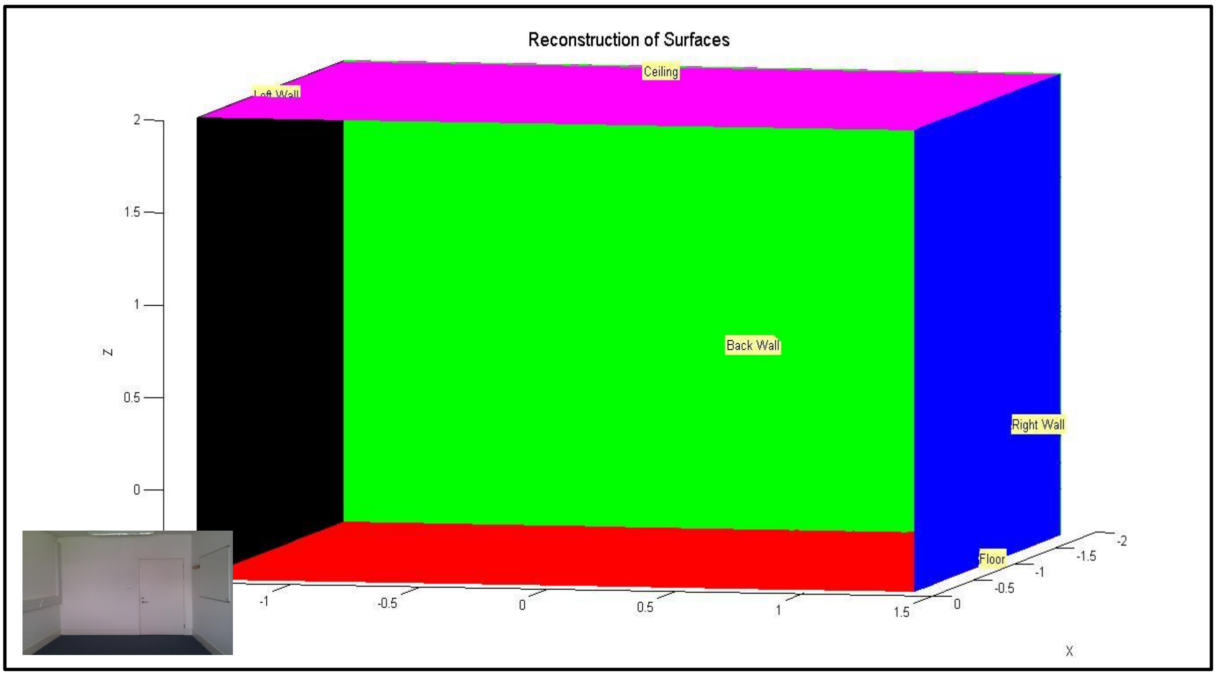



Figure 6.8: 3D modelling of Dataset 1

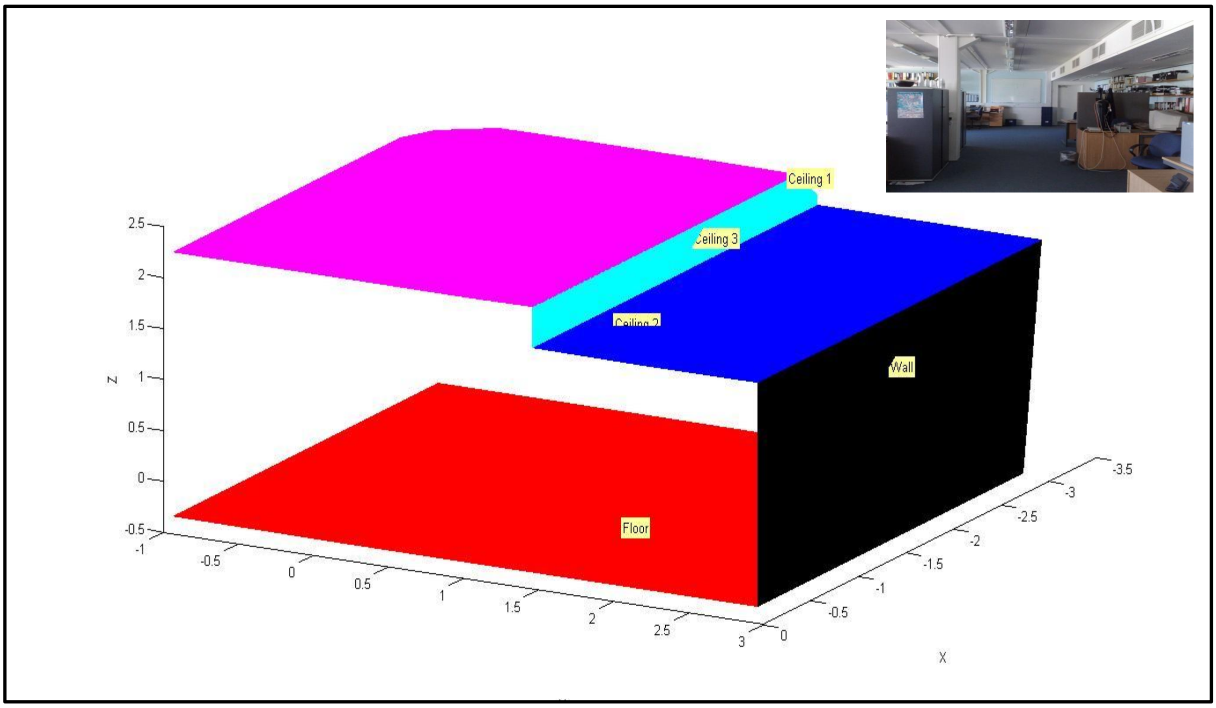



Figure 6.9: 3D modelling of Dataset 3

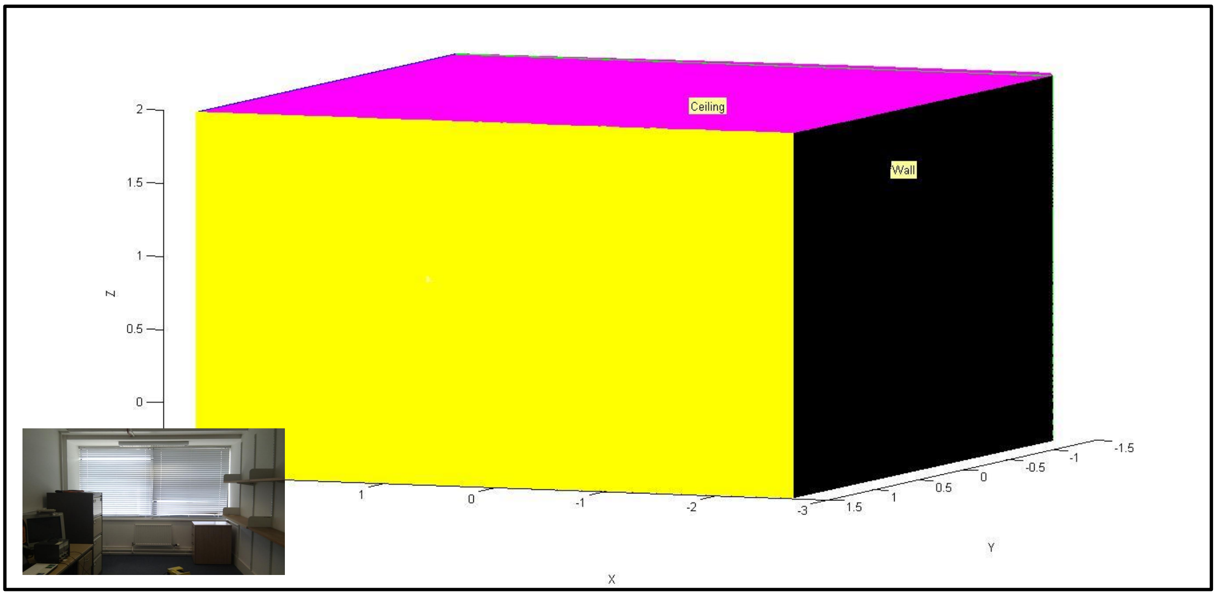



Figure 6.10: 3D modelling of Dataset 4

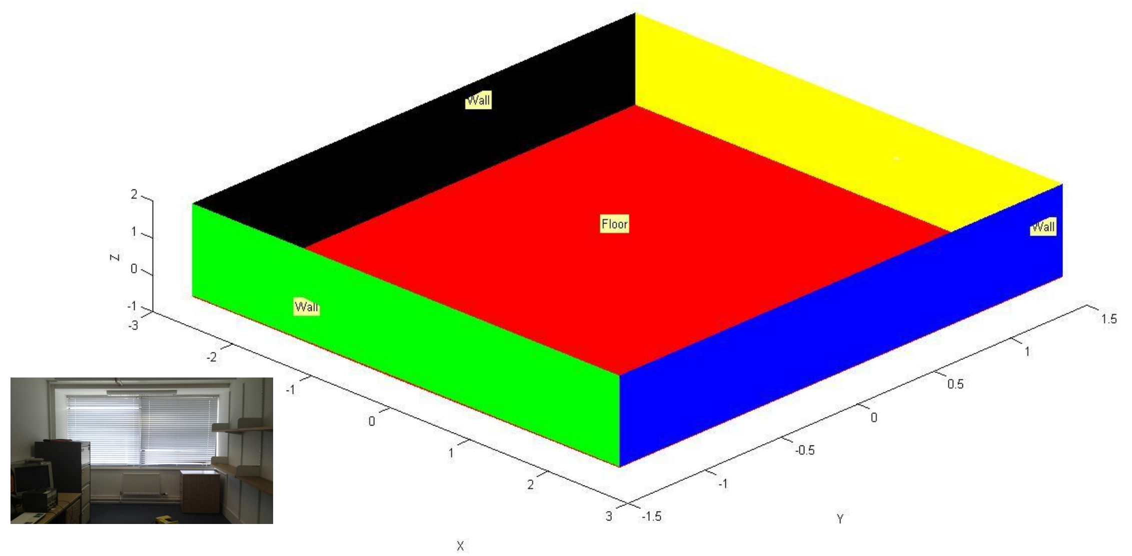



Figure 6.11: 3D modelling of Dataset 4 where ceiling is removed to show the interior model

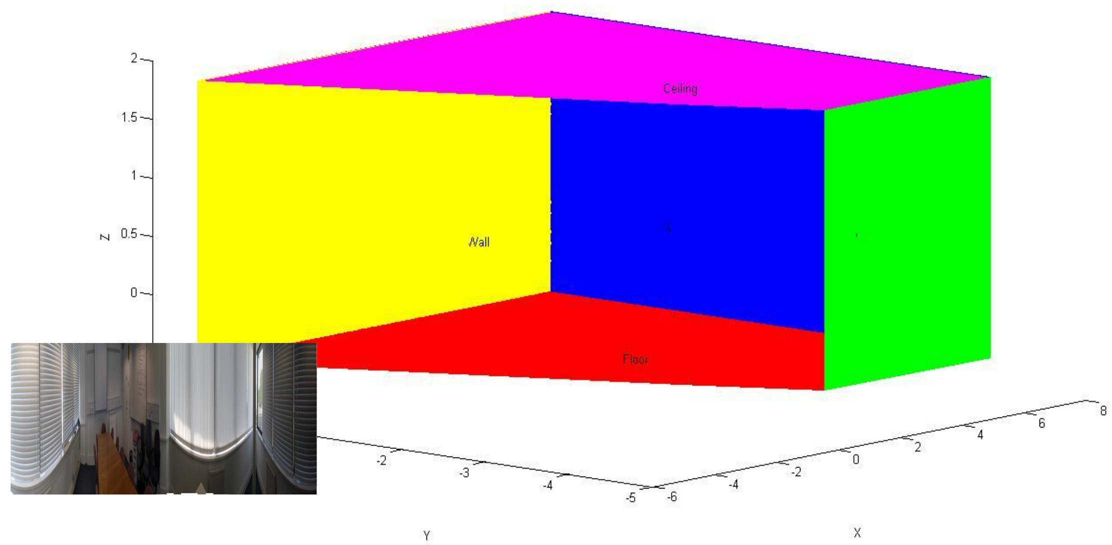
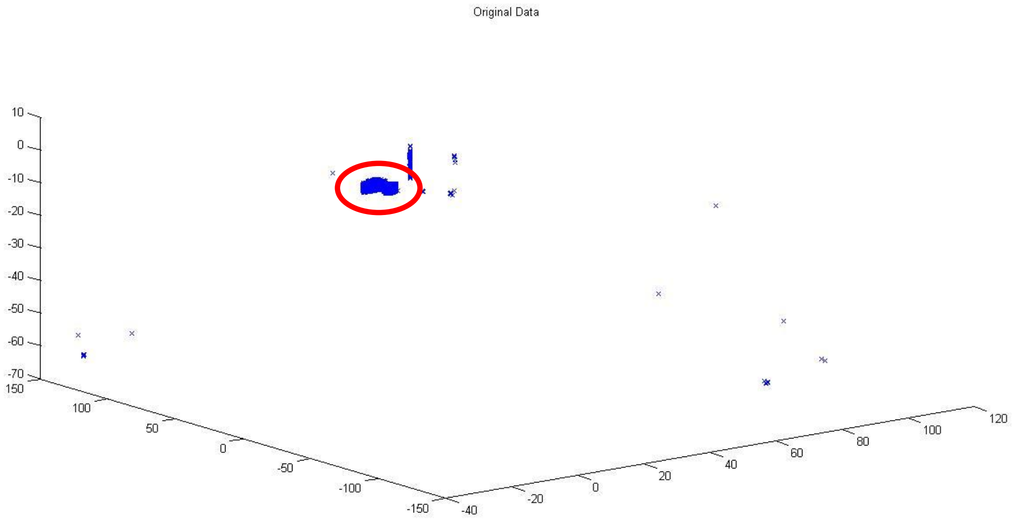



Figure 6.12: 3D modelling of Dataset 5

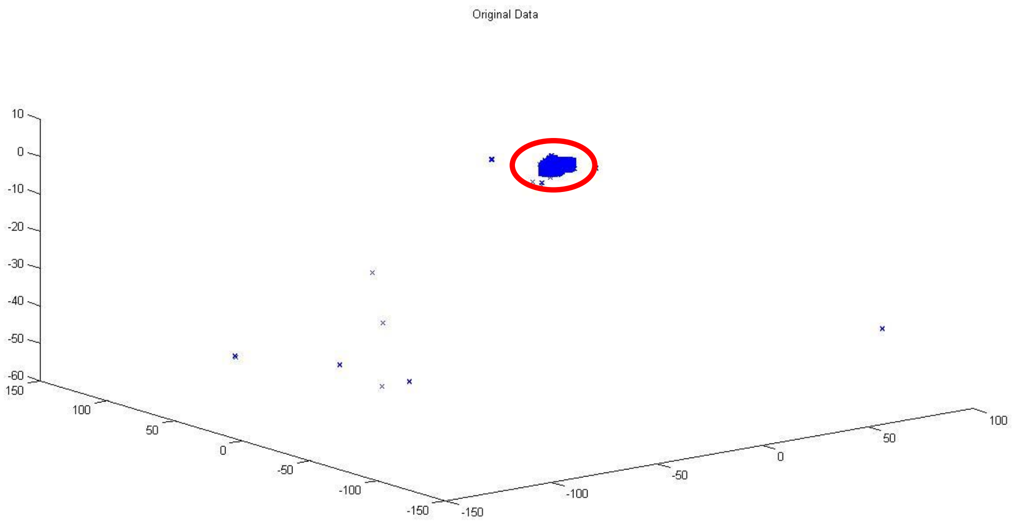
## 6.4 Discussions

The scope of this research is to produce a 3D model of a closed interior interpreting important structures and surfaces as defined in Chapter 1. Final models shown in this chapter, as well as the one in Chapter 5, have revealed that PreSuRe algorithm developed in this research is able to generate these models. All processes in PreSuRe (preprocessing, surfacing and modelling) are important and needed to produce the model. In fact, the algorithm can also be extended to process data obtained from state-of-the-art laser scanners.

As mentioned in Section 2.2.1 in Chapter 2 regarding existing methods in noise data removal, some researchers (Okorn, *et al.*, 2010) (Stamos, *et al.*, 2006) (Budroni & Boehm, 2009). assumed clean, ready-to-be-processed data as they were collected using a state-of-the-art laser scanner. However, raw data collected by a modern laser scanner (FARO Focus$^{3D}$) as shown in Figure 6.12 is full of noise data, therefore it needs to be preprocessed prior to modelling. Figure 6.13 shows the results of applying preprocessing method in PreSuRe towards this data. As this raw data is big in size (more than 2GB), they were preprocessed in 2 halves, separated by the laser scanner software. Using the data assessment equations 5.3 and 5.4, 0.36% of noise is present in the raw data. This proved that the assumption of clean, ready-to-be-processed data supplied by the modern laser scanner is not applicable, and thus, necessary data preprocessing should always be conducted prior to reconstruction.

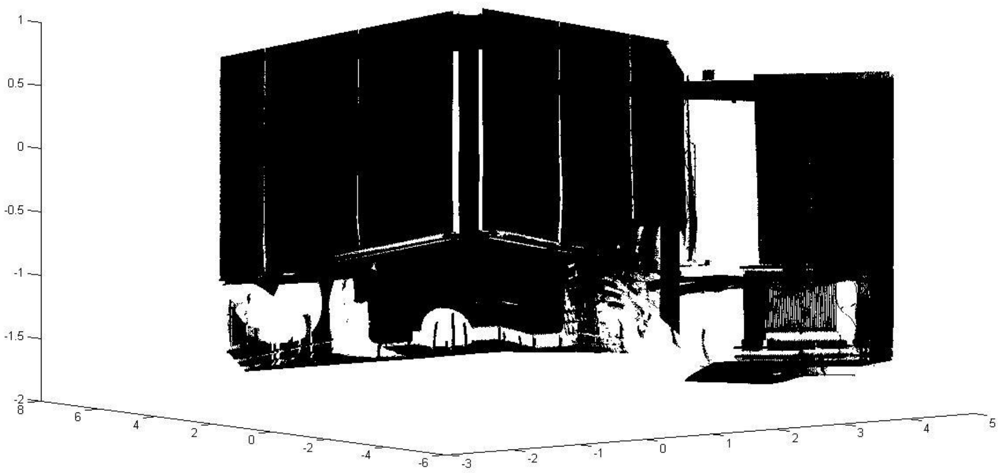



(a)

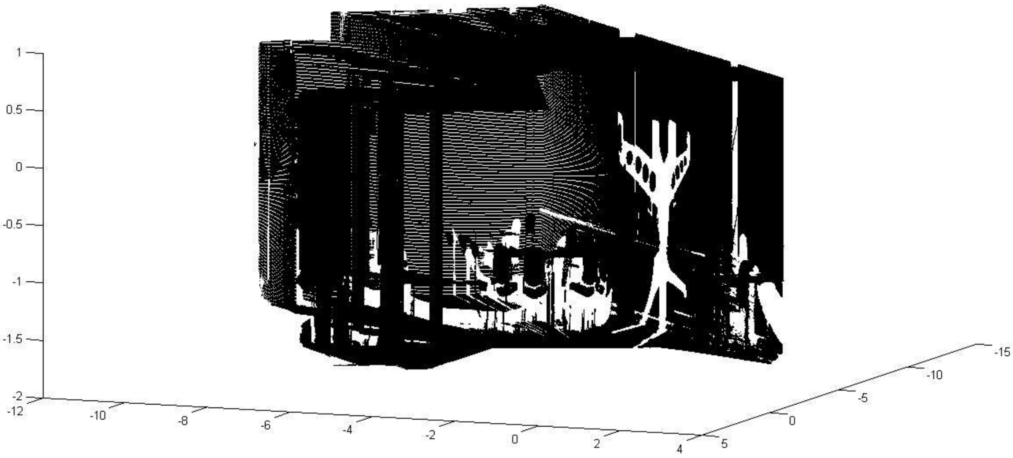



(b)

Figure 6.13: (a) and (b) Data obtained from FARO Focus$^{3D}$ laser scanner representing a room interior. Notice that the data representing the interior (as in the red circles) are surrounded by noise data



(a)



(b)

Figure 6.14: The clean data of: (a) the first half; (b) the second half of the previous data, preprocessed using PreSuRe algorithm

The resulting model as shown in Section 6.3 can be used in several applications that will be covered later in Chapter 7. As these applications usually involve professionals, accuracy of the model needs to be measured appropriately. Table 6.3 shows the accuracy of the model compared to the measurement obtained from 2D as-built drawings. All the measurements achieved more than 95% accuracy, with 100% accuracy for sparse interior. However, it did not reach 100% accuracy when modelling Dataset 4 and 5. This is expected as parts of the blinds that cover the windows in both rooms were broken during the data collection process, thus allowing points that are beyond the room to be collected too (refer to Table 5.3).

| Dataset | Percentage | | Accuracy of modelling compared to 2D as-built drawing |
|---|---|---|---|
| | Noise | Clutter | |
| Dataset 1 | 2.94 % | Nil | 100 % |
| Dataset 2 | 4.06 % | 38.54 % | 100 % |
| Dataset 3 | 3.74 % | 53.63 % | N/A* |
| Dataset 4 | 1.29 % | 46.79 % | 96.45 % |
| Dataset 5 | 8.31 % | 50.39 % | 98.45 % |

* Measurements not available due to the length and width of room which is outside laser scanner's range

Table 6.3: Data assessment results of all modelling

Table 6.4 summarizes the time taken to process the data. Notice that most processes were being conducted nearly in real-time, while others are still within acceptable time, compared to other methods that might take hours to model (El-Hakim, *et al.,* 1997) (Mian, *et al*., 2006) (Whitaker, *et al.*, 2006). The overall algorithm was grouped into its respective processes, as not all data requires the same set of processes, for example Room 1 did not require any data surfacing due to being empty, and partial data did not need to be registered before reconstruction. Note that the noise data percentage does not depend on the percentage of clutter present, as most of the noise present in the raw data are outliers and thus, exist outside the interior and were separated with the required data. It has been shown earlier that the data obtained from a state-of-the-art laser scanner (FARO Focus$^{3D}$) could also produce noise data, therefore it is better to preprocess interior data prior to reconstruction.

| Process / Dataset | Partial | | | Full | |
|---|---|---|---|---|---|
| | Dataset 1 | Dataset 2 | Dataset 3 | Dataset 4 | Dataset 5 |
| Data preprocessing | 1 s | 1 s | 0.8 s | 1 s | 2 s |
| Data surfacing | N/A | 2 s | 2 s | 5 s | 6 s |
| Data modelling | 1 s | 1 s | 0.8 s | 1.2 s | 0.9 s |

Table 6.4: Time taken (in seconds) to perform different processes for each room type

There are a few limitations, though. The histogram method chosen to remove noise data works perfectly to remove noise in a sparse type room, but still noise exists after the process for complex interior like Room 5. However, applying data surfacing afterwards will ensure the noise is still being removed, therefore this is not a major issue. Meanwhile, the data registration method developed in this research requires a straight wall to be assigned as the reference wall, but since the majority of the interiors will have at least one straight wall, it should not be a problem to be tested on the vast majority of interiors. In data surfacing, the appropriate radius of "fretting" ball in the ball fretting algorithm needs to be defined carefully, as it also depends on the size and clutter of the room. As in the data modelling and mapping processes, a histogram is also being adapted to assign points into each surface respectively, and this is quite complicated when dealing with interiors with complex geometrical structures like Room 5, where it has a non-sparse structure. However, the relationship modelling process has assisted all the surfaces to be reconstructed, producing an ideal model as shown in Figure 6.11.

In modelling a complex interior, as in Room 5 (Dataset 5), notice that the pillar in the room is not being reconstructed by the algorithm. This is a substantial limitation of the current implementation. Although the pillar is an important structure within the room, the PreSuRe algorithm is only able to generate a low Level of Detail (LoD) of the outer structures of an environment. Future work will need to address this limitation. Further explanation on the LoD of the resultant model can be found in Chapter 8.

## 6.5 Summary

This chapter has verified and validated the resulting model developed using datasets obtained by the low-cost, low-specification laser scanner as described in Chapter 4. All important structures and surfaces have been reconstructed and interpreted as shown. As no previous researchers have come out with a method to assess the accuracy of the end model, utilizing measurements from 2D as-built data proved to be significant in validating the resultant 3D model. Resulting 3D models of the test datasets, together with details of their noise and clutter percentages as well as their accuracy can be found in Appendix B. As these models are aimed at assisting professionals in related applications, more information on how they can be utilized shall be discussed further in Chapter 7.

# Chapter 7

# Interior Scene Understanding: Applications

*"The noblest pleasure is the joy of understanding"*

**-** Leonardo da Vinci*

The 3D modelling or the graphical representation obtained from this research, as demonstrated in Chapter 5 and 6, can be used for several related applications. As the model is a general visualization signifying the structure of an interior, not only can a specific application benefit from it, but a number of applications can utilize it as well. Based on the survey results in Chapter 3, there is a need for the resulting model from this research in various applications as more and more professionals and practitioners in AEC are moving towards applying 3D modelling to represent interiors, as people can really sense the real environment and feel the same experience when being exposed to a 3D visualization.

A building interior drawing is being used as a platform in recording the real condition of an interior. Architects and engineers who deal with structural, mechanical and electrical issues could use this model in developing 3D as-built drawings, which can be useful in recording

*BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 19May 2011].

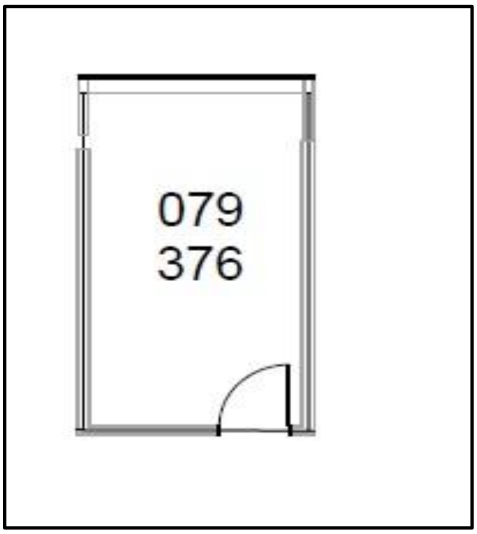
the current condition of an interior. This record can also be used for reverse engineering and accessed during maintenance, renovation and forensic use (Yunus, 2011) (Ratay, 2000). Owners and managers of a particular building could further exploit the 3D as-built drawings in managing facilities and monitoring maintenance processes of utilities under their responsibility. Archaeologists use 3D visualization to preserve historical sites and utilise them for conservation and education (Cignoni & Scopigno, 2008). In robotics, 3D modeling and mapping can assist a domestic mobile robot in understanding the indoor environment surrounding it, for example a robotic vacuum cleaner or a mobile security monitoring robot.

This chapter will demonstrate how the resulting model from this research can benefit the above applications. It will show that not only existing applications can benefit from using the resulting model, but it will also highlight the potential implications that may utilize the model based on its novel features and unique visualization capabilities.

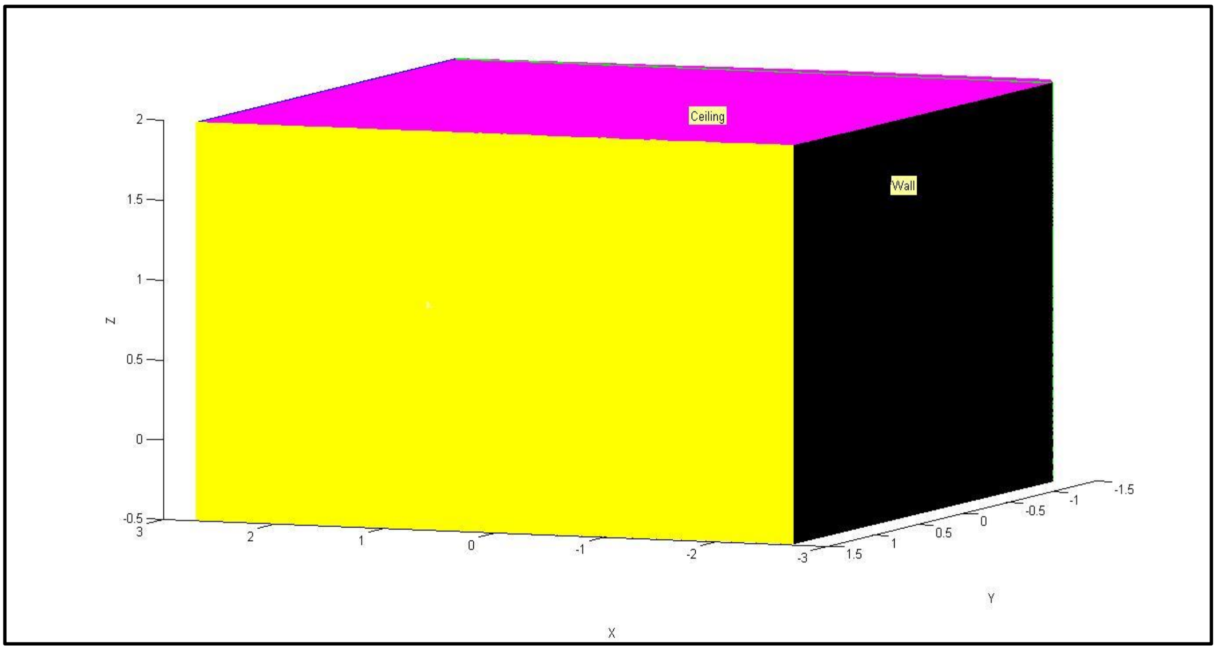
## 7.1 3D as-built drawings

As-built drawings are layouts that represent the building interior and structure as it is used – also being referred to 'as-is' drawings. They have been used extensively by architects and engineers to record the existing interior conditions of a particular indoor environment of a building, which may be different from the planned and designed conditions. These drawings serve as a record for the building owners, managers, insurers, as well as local council and fire and disaster committees to study the forensic structural information later on. Traditionally, as-built drawings are developed in 2D but recent needs of 3D as-built from the rapid rise of Building Information Modeling (BIM) have urged the usage of 3D as-built. 3D as-built can later be used for building and property management to optimize the modelling.

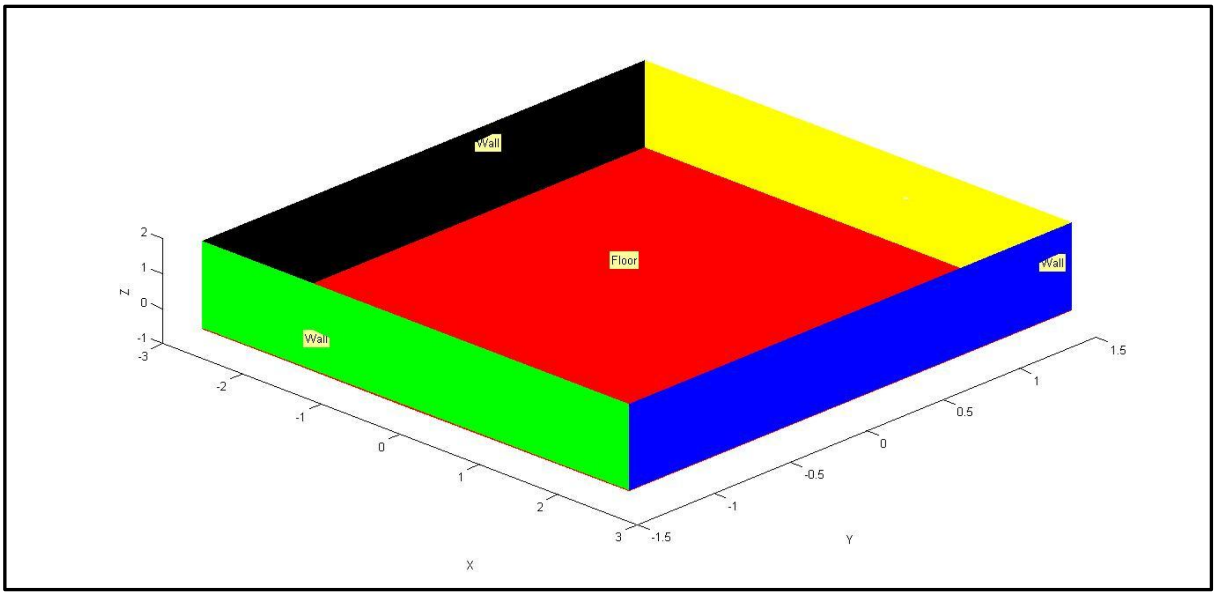
The 2D as-built representations are lacking some important information, for example the room's height and ceiling structure. This kind of representation can cause confusion especially from the public as unlike the professionals in AEC, most of them cannot understand the features of an interior just from a 2D drawing. To highlight the difference and benefit of having a 3D representation, Figure 7.1 shows the 2D as-built drawing and its 3D model developed from this research of the same interior (Room 4).




(a)




(b)




(c)

Figure 7.1: Room 4: (a) 2D as-built drawing; (b) 3D model developed in this research; (c) ceiling can be removed to provide more visualization

There are a lot of applications of this model for as-built drawings, apart from simply a recording of a building's size and layout. It can be used to assist maintenance, act as a guideline to future renovation, and during emergency situations to ascertain the total loss due to a fire or earthquake and provide invaluable information for rescuing or evacuation from the building. Plus, as-built can be used as evidence for forensic structural engineering cases, when any structural failure happens. There are two types of as-built drawings, Mechanical and Electrical (M&E) as-built (related to equipment or furniture inside the interior, electrical systems, piping, ducting, etc.) and civil or architecture and structural drawings (representing the structure of the interior). As the scope of research is developing 3D models representing structure of an interior, the M&E drawings are then out of the scope of this research.

One of the important features that is lacking in all the commercial software like Revit and Pointools is the semantic features. The automatic semantic information provided by PreSuRe algorithm developed in this research is not only mapping and labelling the important surfaces, but also the features that are important in providing professionals with some visualization information when planning renovation work. When any of the measurement of the important structure is being modified for renovation, the model will automatically shows what will happen to the overall interior. This semantic features is as shown in Figure 7.2. To show how it works, let say an architect would like to do renovation work and want to extend one corner of the floor by 0.1 meter. The same algorithm can be used to visualize what will happen to other effected surfaces (left and back wall). The first model in Figure 7.2 shows this example when the right corner (as shown by the arrow) of the floor is being extended 0.1 metres from 1.9 to 2 metres. As seen from this figure, the back wall (in green) is also expanded automatically when the corner of the floor is extended by 0.1 metres.

Other similar descriptions offered by commercial software are also provided by PreSuRe algorithm. Figure 7.3 and 7.4 show these features, for example the measurement of the width of the wall and removal of ceiling to see top view model respectively.

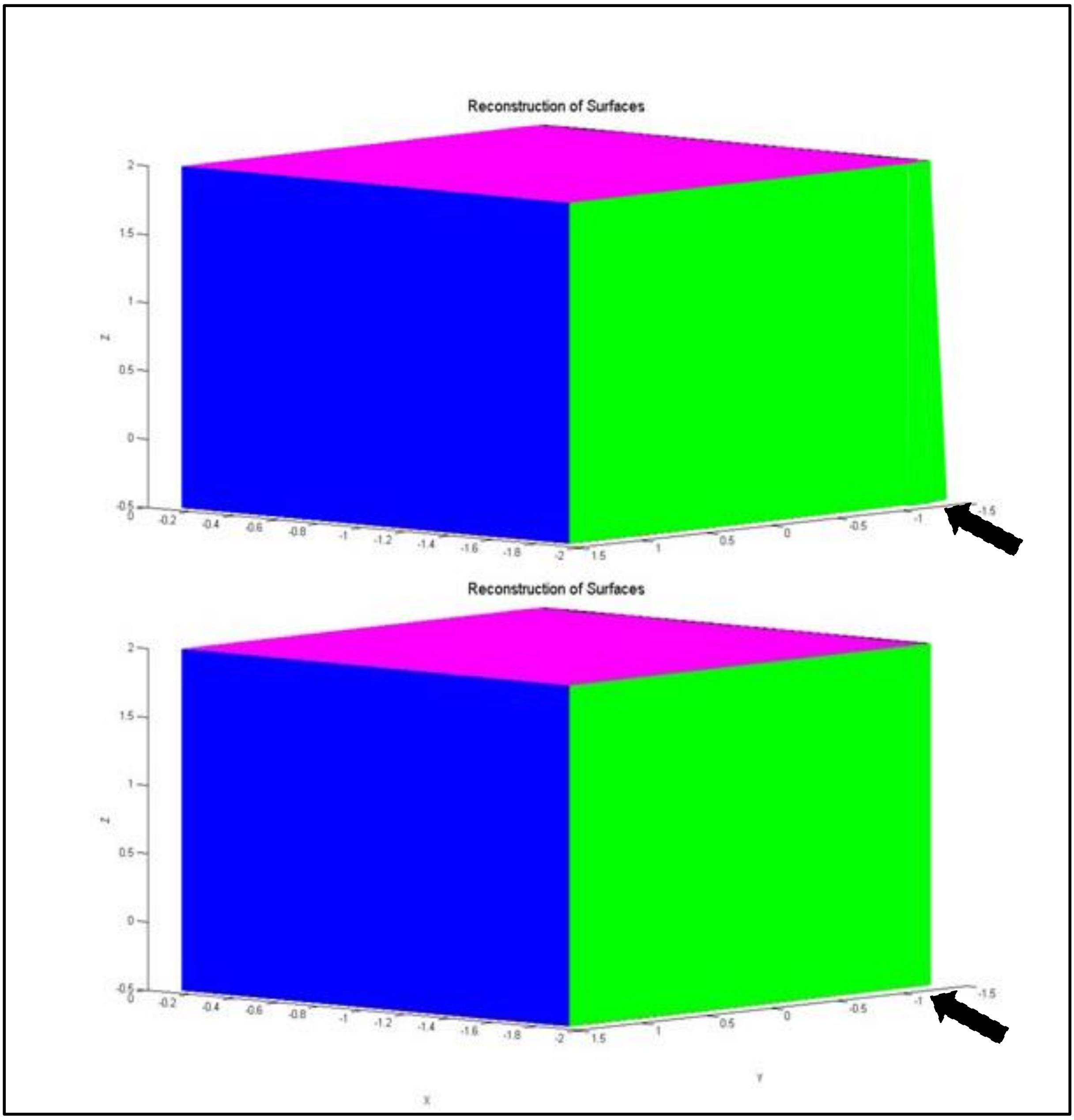



Figure 7.2: Semantic information offered by PreSuRe algorithm, where the model is being modified automatically once the floor measurement is being changed. This semantic features can assist professionals in planning future renovations

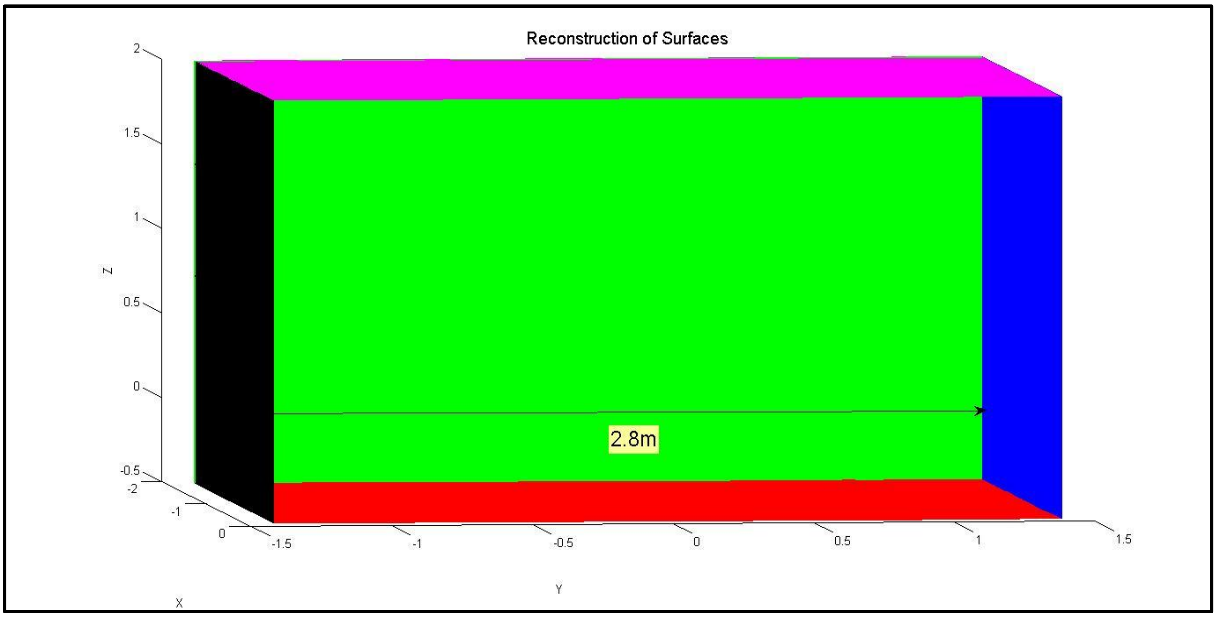



Figure 7.3: The model developed in this research could also be used to show important measurement

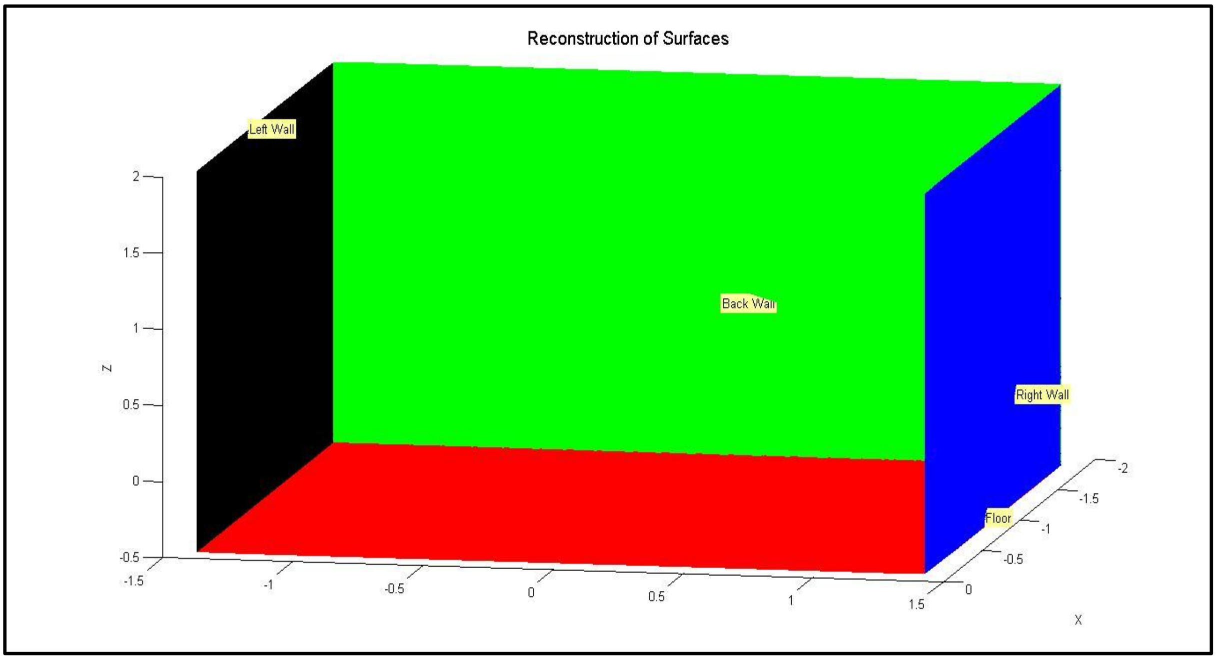



Figure 7.4: Ceiling can also be removed to show top view model of the room

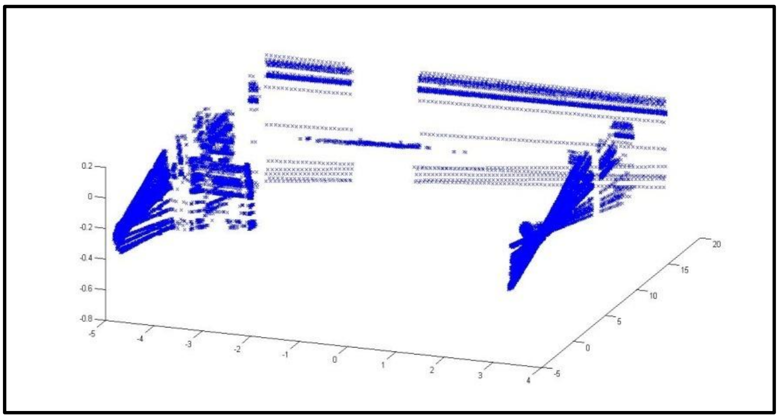
## 7.2 Autonomous vehicle navigation

The 3D model developed from this research can also be used to assist an autonomous vehicle in navigating around an interior. Autonomous vehicle mapping has become important since the birth of Simultaneous Localization and Mapping (SLAM) issues which has surrounded the mobile robotics community from the last two decades. It is important for an autonomous vehicle to have the ability to map its indoor surroundings which can help it to understand the environment before some actions can be taken. Earlier methods saw that most of the maps are in 2D. But knowing the importance of understanding in autonomous vehicle mapping, 3D maps have now become a trend. These visualization elements in 3D are important especially for human-assistance service robots, which already seen some advances like the capability of recognizing cups in the kitchen area (Rusu, *et al.*, 2008) and opening a closed door (Petrovskaya & Ng, 2007).

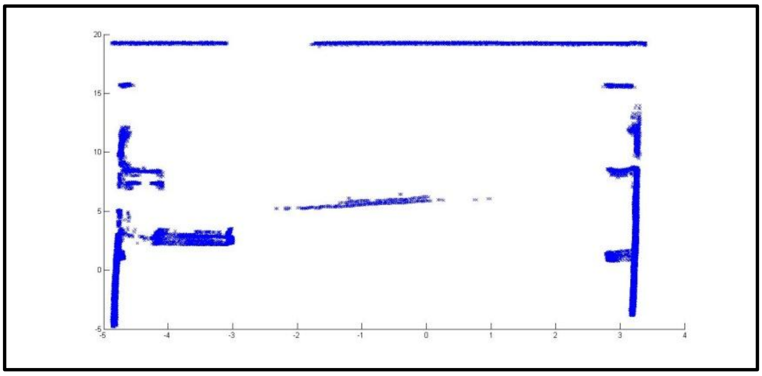
Interior mapping, from the autonomous vehicle point of view, does not require accuracy of details. It is enough for the robot to recognize any obstacles in front of it or within its range, for example walls and doors that may obstruct it from making the necessary moves forward. Some mapping did not even consider the ceiling as it will not make any impact on its journey. However, due to the rise of rescue robot usage in critical situations like natural disasters and after-effect investigation, the need to have accurate and real-time mapping may be needed to allow a smooth operation without any delay.

As the resulted 3D model from this research is specifically designed to assist various applications, the PreSuRe algorithm can also be used to process 3D point cloud data acquired from an autonomous vehicle. Figure 7.5 below shows the raw data obtained from an

Unmanned Aerial Vehicle (UAV), while Figure 7.6 shows the resulted model by applying this method. Note that due to the working nature of the UAV (to navigate around the premises), horizontal surfaces like ceilings and floors are not recorded. The developed model can be utilized by the UAV to navigate and explore an interior, especially when dealing with a dangerous site like a radioactive contaminated environment.



(a)



(b)

Figure 7.5: The raw data collected by the UAV, (a) in 3D, (b) in 2D

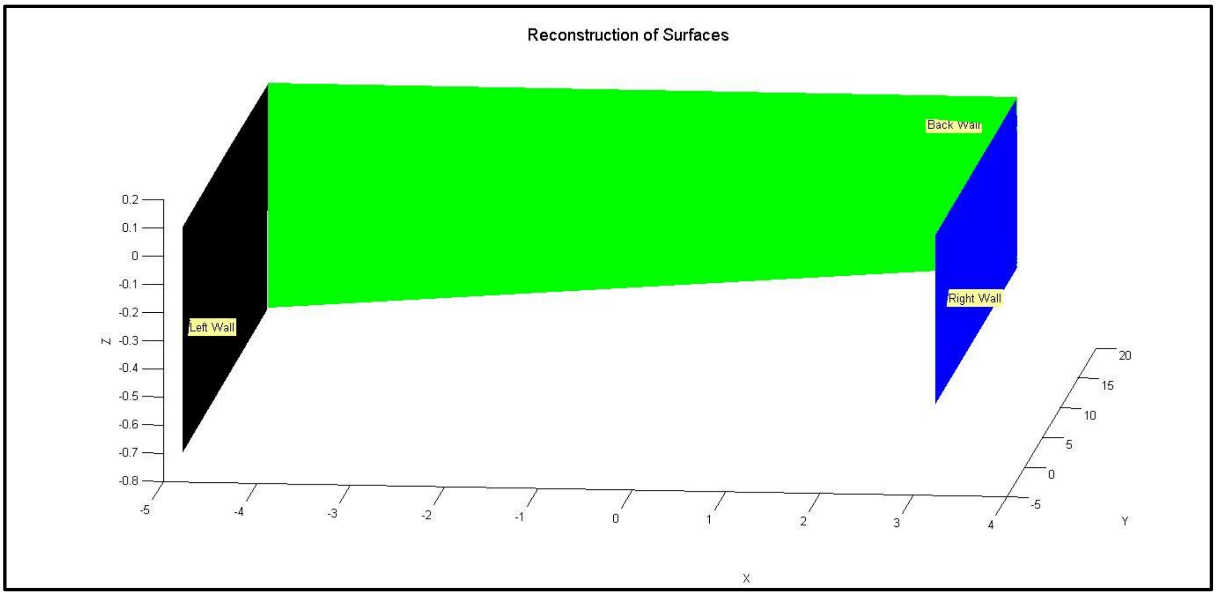



Figure 7.6: 3D model of the above raw data reconstructed using the same method developed in this research

Based on the above figure, there are a number of important features present in this model that can be exploited by any autonomous vehicle:

- **Visualization / semantic information**

  Labelling the structure has proven to be beneficial towards an autonomous vehicle as this feature can be used to recognise things around them in the interior, as well as for navigation purposes as they can avoid hitting them. Apart from that, the model can be further extend in assisting a service robot to accomplish things or interpret a command such as "move 5 metres towards the right wall" for example.

- **Structural information**

  Autonomous vehicles can be used to get interior conditions during emergency situations like during a fire or in post earthquake rescue, especially when dealing with a dangerous site (e.g. nuclear facilities) or other circumstance (e.g. structurally unstable or collapsed building). As the model developed here consists of structural information like height of the wall and length of the room, this information can be utilized by the robot to compare the current situation and assist related people in rescuing and evacuation tasks. For these scenarios, although the existence of clutter like furniture are useful in the model, they could be moved, therefore such a model may not be accurate to assist the tasks. Representation of location of walls are more useful in this situation.

## 7.3 Historical building conservation

Although most of the historical site conservationists are working with preserving exterior conditions or recording the high level of detail in the interiors, a structural model as developed in this research can also be used to serve the purpose of conserving a historical building. Referring to a conversation with a manager who works with a historic environment adviser, there is a plan to develop a visual model representing Buckingham Palace (in London, UK) for educational purposes, where only the structural information is used without considering all the details, for example the plaster sculptures on the walls and ceilings (Baldock, 2011). Thus, the model developed in this research can be used in providing information for educational purposes in historical building conservation as well.

Figure 7.7 shows how the model would look like for this purpose. This model can be used for:

- **Giving information for educational purposes**

  Not all people can understand how previous people from other eras lived. By representing the structural information of historical interiors, the younger generation could benefit from this information and understand more about the living conditions back then. Visual 3D representation plus positioning system as featured by this model (refer to Figure 7.7) can be fully utilized together with the additional aspect of "walkthrough" interactive programme to provide information for these purposes.

- **Preserving historic buildings or monuments**

  Old, damaged buildings could benefit from a model showing the structural condition before and after the damage. Apart from that, as the historical buildings are more prone to damage due to weather, visitors, pollution and possibly natural disasters like earthquakes, flooding or landslide, the developed model can be used as a permanent record of every detail and assist future renovation and maintenance work.

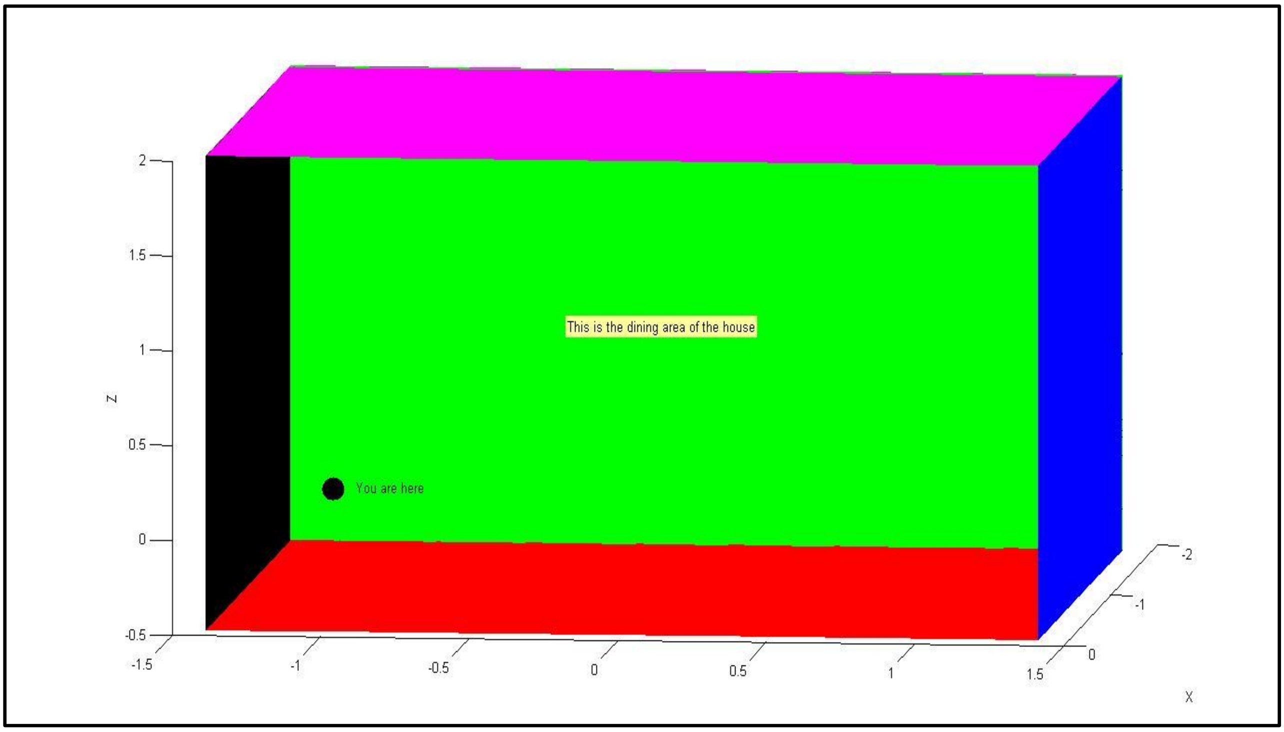



Figure 7.7: Author's impression on how to utilize the model developed in this research to provide education and visualization of historical building interior, plus preserving it at the same time

## 7.4 Facility management

One of the potential applications that will get the most benefit from the resultant model developed in this research is space management. Space management is the prime aspect in property-based computer-aided FM where it is used to supervise how much space usage of an interior and its suitability for use. Space management is also being used to record the spaces within big buildings, both commercial and non-commercial ones, like a university or hospital, as they usually have lots of rooms that need to be controlled and supervised. For example, in a university's case, there is one unit which assists various academic departments that share the same facilities like classrooms, lecture halls, auditoriums, etc. through a common platform to avoid inefficient planning. Some departments may require more classes due to an increase in student demand, therefore by having a space management unit to monitor space usage, other departments that have extra room capacity may allocate them to those who need them instead of constructing new facilities to accommodate them. Current practice shows that these are recorded in an object-oriented database that links to the CAD drawing to ease the management process (Bishop, 2011) (Robert & Lees, 2011).

This normal practice in space management of using databases linked to the CAD drawings often contributes towards related problems, such as:

- **Accessibility issue**

  Current practice requires two different software platforms to manage the space usage of an interior. One will have all the information about the space in tabular form, while another one holds the CAD drawing of that particular interior for visualization purposes. Using separate software packages will lead into accessibility issues like the need to have separate licenses to have access to both pieces of software, and sometimes information needed cannot be obtained due to technical reasons like linking problems (missing of data due to the inability of FM software to extract all the details needed from the CAD software). Therefore, having one platform that holds both sets of information together would be very much appreciated by professionals and will solve this issue.

- **Lack of features or standardization issues**

  Often the software used to hold information about the space of interest presents the information in a tabular format, i.e. all the data is stored in a table and this feature lacks visualization which is needed to demonstrate the usage of space in the interior. Apart from that, it is normal practice for the CAD drawing to be maintained by another department or organisation typically architects or building management engineers, which may lead to standardization issues as mentioned in Chapter 3. By integrating a 3D model that is able to hold all information needed to manage an interior's space will overcome these issues as individuals can access and use the same model to assist them in their work.

Due to the above limitations by the current approach, therefore the model developed here has the following advantages:

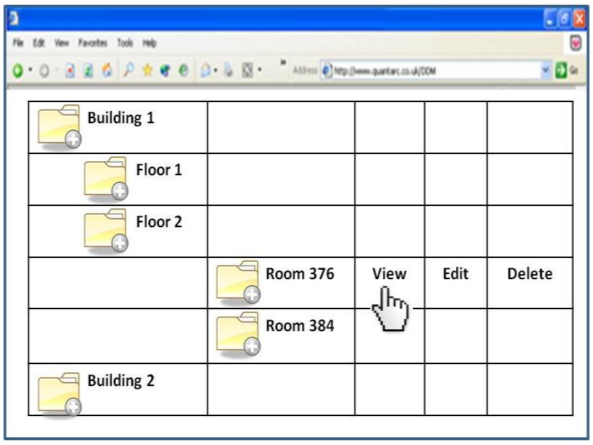
- **Visual representation in 3D**

  The drawings of the interiors are done in 3D in this research, therefore a lot of visual information can be presented, extracted and exploited by just using the same model. Confusion can also be minimized as 3D representations are easy to most individuals to interpret and can add a lot of visibility features to them.

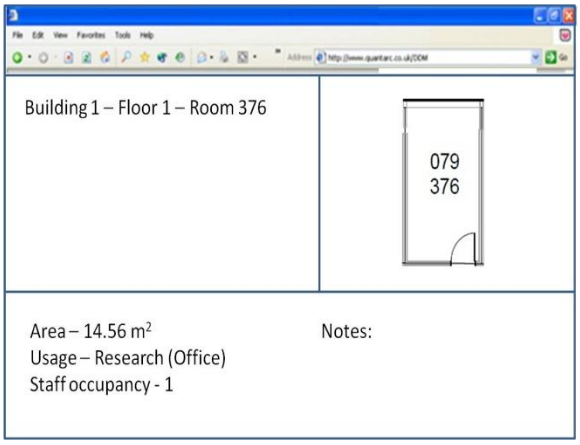
- **Integration of data and visual information**

  The model developed in this research integrates the 3D representation of an interior with related information of that interior. Therefore, all these features can be accessed within one easy to use platform and should reduced accessibility issues.

Figure 7.8 shows the current approach of how space management is carried out, and Figure 7.9 highlights the features developed in this research that can counter the current approach's limitations.




(a)




(b)

Figure 7.8: (a) Typical representation of space management's software features (based on estate management software called QuEMIS used by Space Management and Timetabling Unit, University of Warwick), people need to click the view to get access to the as-built drawing and more descriptions on that particular space, which leads to another platform or software package needed to be opened, as shown in (b)

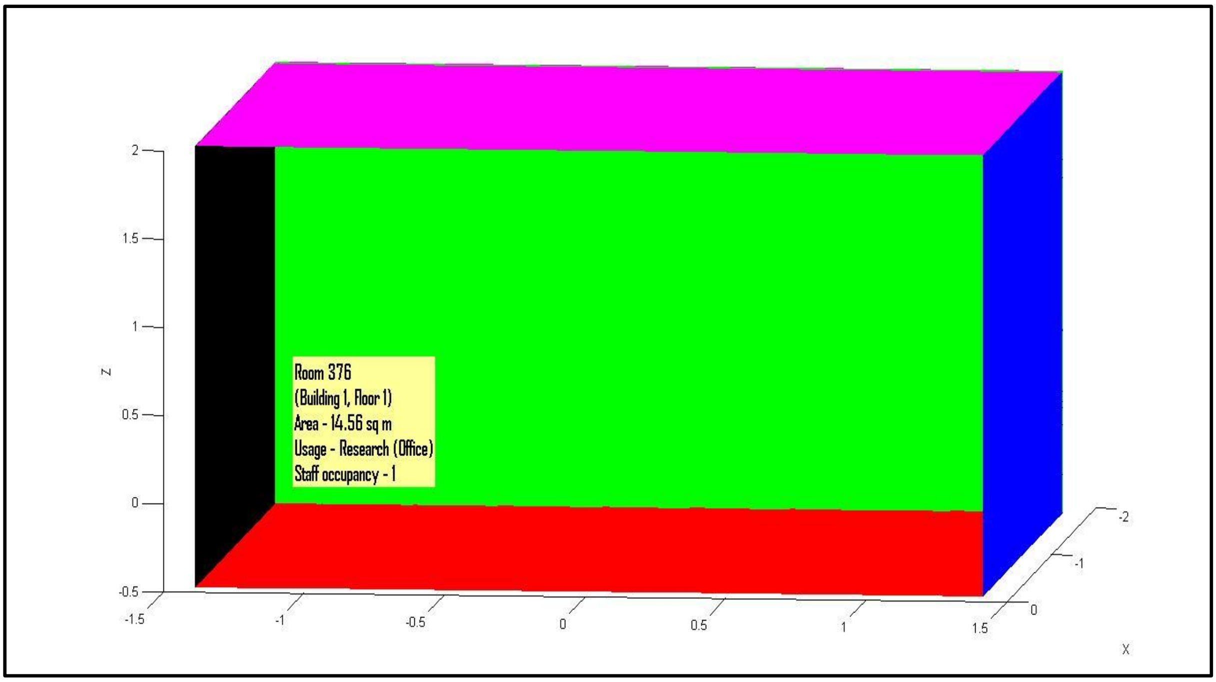



Figure 7.9: By using the resultant model, space management users can get full information with its 3D visual without having to access to another platform or software

## 7.5 Contributions

This chapter has shown how professionals and experts could exploit the 3D model developed in this research towards various applications as previously described. While other applications like 3D as-built drawings, historical building preservation and autonomous vehicle navigation have or can benefit from having a 3D model to aid their purpose, applications like space management, which are still using conventional methods of tabular representation linked with 2D drawings, can also benefit from using the 3D model. This new potential application of space management is among the contributions of what the resulting 3D model from this research could assist organisations that are responsible for controlling and supervising buildings. The outcome of the 3D model produced from this research, which concentrated on visualizing the structure of an interior, makes it an ideal solution, in author's opinion, for space management applications.

Based on the figures in this chapter, another contribution that the developed 3D model makes is that it is a universal solution that can be used by various applications. As the resulting model is a general structure reconstruction of an interior in 3D, this model can be utilized by professionals in many different areas, without being generated with a specific application in mind. Therefore, the same model can be used by anyone who wants to work with the same interior without having accessibility or feature issues.

Another important contribution is the semantic features offered by the model generated from this research, as shown in Figure 7.2. None of the existing methods that are able to produce a 3D model of the building interior from laser scanner data has this feature yet, but it is so important as it can assist professionals by providing a visual impression in preparing for future renovation work. Experts and professionals can see what will happen and plan what to do next by just inserting the respective renovation and by applying the same method, the resulting 3D model will give some idea of what to expect. The advantage of having semantic information in this method could also differentiate the 3D model developed in this research with a normal 3D CAD drawing.

# Chapter 8

# Conclusions

*"A conclusion is the place where you get tired of thinking"*

**-** Arthur Bloch*

This research has proposed a method to develop 3D modelling of building interiors. The method was developed as a result of the current limitations and gaps in methods and software packages exposed from carrying out surveys and literature reviews. As this is only currently emerging, not much literature is available to recognize the gaps, therefore, by conducting a survey among the practitioners was essential and the existing constraints could be identified and hence, motivate the direction of this research.

This chapter will summarize the whole concept of both hardware and software - the adapted SICK PLS 101 laser scanner used in this research and PreSuRe algorithm - beginning from why it is developed to how it works, its features, its limitations and recommendations to improve on it in the future. PreSuRe, which stands for **Pre**processing, **Su**rfacing, **Re**construction, plus "sure" from as**sur**anc**e** of measurement, is an algorithm developed to

*BrainyQuote [internet]. Available at: http://www.brainyquote.com/ [Accessed 15 March 2012].

produce 3D modelling of a building interior from laser scanner data. This model can be used to represent interiors for various applications - from AEC (3D as-built drawings), FM (space management), autonomous vehicle navigation, to preserving historical buildings, as shown in Chapter 7. Although the implementation has not been done yet, but based on the interest shown during a number of informal discussions with several related professionals and experts, the resulting result is practicable to be used in these applications.

## 8.1 Adapted SICK PLS 101 laser scanner

In this research, a SICK PLS 101 laser scanner is adapted to provide a low-cost solution compared to the state-of-the-art laser scanners (refer to Table 2.1 for price details). This laser scanner is mounted on a mobile platform with a fixed height attached with a servo motor to allow a hemispherical scan area. The idea of using a laser scanner is due to its many advantageous qualities compared to other sensors in collecting 3D data to represent building interiors, as discussed in Chapter 4. Traditional means of collecting interior measurements by using a measuring tape is a laborious process and the data captured is limited and prone to errors depending on the experience or skill of the individual. Thus, a 3D laser scanner is used in this research to gather interior data in 3D and it can provide a rapid and accurate solution. Although the cost of state-of-the-art 3D laser scanners is high and prohibitive to some, a low-cost laser scanner is used to provide 3D data in this research, making it a reasonable alternative that can be considered by professionals or organisations.

Being a low-cost, low-level laser scanner, its range and measurement accuracy is lower compared to the more expensive laser scanners. However, since the scope of the research is to produce 3D structure modelling of building interiors, which has a low level of detail

(LoD), the SICK PLS 101 laser scanner adapted here is sufficient enough to be used. Necessary actions have to be taken as listed in Chapter 4, like placing the scanner appropriately during data collection to ensure correct registration and maximum viewability. Although the adapted laser scanner has some limitations like producing a lot of noise data, plus missing or incomplete data due to clutter and occlusions, the PreSuRe algorithm which is developed in this research is capable of handling this as it was designed to work in an optimised fashion with the adapted laser scanner.

## 8.2 PreSuRe algorithm

The algorithm developed in this research has successfully produced 3D modelling of building interiors from 3D point cloud data obtained from a low-cost, low-level laser scanner. The raw data obtained from the laser scanner is preprocessed first, to remove noise data as well as registering the data using a new method if required. It has been shown in Chapter 5 that even the raw data collected by the state-of-the-art laser scanner contains noise data, therefore it needs to be preprocessed first to avoid reconstruction confusion later on. After that, data representing clutter is then removed in the process called data surfacing, before the data can be reconstructed. Semantic information like mapping and labelling the surfaces is then carried out in order to assist visualization afterwards. To ensure correct modelling, comparison of measurements were made from both the resulting model and the original 2D as-built of the same room.

Currently, the as-built drawings representing current conditions of interiors are being documented in 2D, which are inadequate in terms of visualization and features compared to 3D models. Therefore, the PreSuRe algorithm is developed to process the collected 3D data to produce a 3D as-built drawing that can be used by building owners, professionals and experts, in other words anyone. As the generated 3D models have a universal structure for the visualization of interiors, the same model can be used in various applications and thus, this can overcome accessibility and standardization issues.

The PreSuRe algorithm could also be extended to model new environments, as current methods are only restricted to model one interior. Most of the existing methods in producing 3D model of building interior have only tested their algorithm towards one indoor environment. With prior knowledge of the interiors, users can use PreSuRe algorithm to model the data. People with partial empty room data could skip the data surfacing process to achieve optimal processing time, whereas users with complex interior data can select appropriate data surfacing to remove clutter data. PreSuRe has been tested to model complex, real interiors, with non-ideal geometrical structures as well as clutter and occlusions. Since no quantitative measurement method is available to assure correct 3D modelling of interiors, PreSuRe algorithm is also equipped with an assurance method by comparing the model's measurement with existing as-built dimensions. Automation is another gap in this research area, and PreSuRe offers an automatic solution which can overcome all current commercial software limitations which wholly depend on a user's input. Another limitation of available software, which is the ability to handle interiors with clutter and occlusions, has also being solved by this method.

## 8.3 Contributions

This research makes significant contributions, which includes a literature review as well as several contributions made by the hardware and the PreSuRe algorithm itself. The review developed here consists of existing techniques in producing 3D models of building interiors using laser scanner data as well as applications that could benefit from this research's model, with additional information on the current advantages and limitations from the surveyed experts. As this research area has only started in the last 20 years, therefore not so many reviews are available to discuss it. By including surveys from the experts in the review, others could capitalise on the current limitations and gaps in this research area which this survey uncovered.

In the hardware point of view, having the adapted SICK PLS 101 laser scanner to collect 3D data representing building interiors will provide a low-cost alternative in 3D modelling. A low-level scanner would generate the interior data in ASCII file format, which is a standard file format that can be used by all software packages. This type of format is also preferred by English Heritage to store their historical site data. The file generated by the adapted scanner is within the acceptable size (around 2MB) compared to the ASCII data file produced by the modern laser scanner of 2GB in average. This will allow data sharing over the internet without having to worry about data transfer timing due to a massive data set. Furthermore, the algorithm developed here is designed to process data generated by this laser scanner, providing a full solution for generating 3D models of building interiors.

The PreSuRe algorithm developed in this research has overcome several gaps, including the ability to model realistic environments with clutter and occlusions in ideal (or sparse) as well as non-ideal geometrical structures, without the limitations applied to a single sample interior only. PreSuRe proposed a new algorithm pipeline to generate a 3D model representing structure of building interiors, by including a data surfacing process in order to remove and determine the percentage of clutter that exists in the interiors. By combining a new method in registering 3D interior point cloud data, as well as adapting existing methods, PreSuRe can be used to model new environments, as demonstrated and shown in Chapter 5 and 6. The newly generated registration method has been developed as most of the existing data registration approaches require a high percentage of overlapping points to register two data sets together. The ability to perform this automatically makes PreSuRe different from the features offered by commercial software packages, which are typically entirely dependent on the user's input in order to get them to work.

The 3D model generated from this research can be used towards various applications in AEC, FM, archaeology visualization as well as autonomous vehicle navigation. Its added feature of semantic information makes the model notably different from ordinary 3D drawings produced using CAD software, which can assist individuals, particularly "CAD-illiterates" when planning renovation work.

## 8.4 Limitations

Although this research has proposed several advantages, there are few limitations that need to be considered:

- **Feature or reference wall in data registration method**

  As mentioned earlier in this chapter, PreSuRe uses a new method to register data representing the whole interior collected by the SICK laser scanner. The laser scanner must be placed beside a reference wall where it can be used to calculate the angle of difference between the same wall generated by the two data sets when registering them together. As the method requires the angle of difference between them, the reference wall must be a straight wall. Therefore, it cannot be used if the reference wall is not a straight one, as it will generate a false angle of difference which makes it unable to register the data correctly. However, it is very rare to have an interior without containing at least one straight wall, therefore this limitation is very isolated.

- **Source of raw data**

  This research has designed the algorithm to work with the data obtained by the SICK PLS 101 laser scanner, as it provides sufficient data to reconstruct the structure of an interior. Thus, when processing data using a state-of-the-art laser scanner, a higher processing time is required, as the data is very dense and has a large file size. Therefore, the source of raw data needs to be of appropriate size (e.g. within 2 megabyte / MB) in order to achieve optimum processing time.

- **Level of Detail (LoD) of resultant model**

  The scope of this research is to produce a structural model of building interiors in 3D, where only important surfaces are reconstructed, with the taxonomy of all non-structural entities within the surfaces (e.g. cable skirting within walls, windows and doors within walls) are considered as part of the respective surfaces. This yields a 3D model with low LoD, which is appropriate enough for the applications as mentioned in Chapter 7.

- **Floor assumption**

  It is assumed that in this research, all floor surfaces are in one plane, therefore it is not suitable to be used in reconstructing interiors with layered or multileveled floor. However, there is no such interior found throughout performing this research, thus a 3D model representing this type of interior has not been investigated.

- **Automatic solution**

  Although the method developed in this research produced an automatic solution, but it is only limited to several types of interiors that have been tested - partial sparse interior, partial complex interior (layered ceilings, layered walls, pillar), full data of a boxed-type room with clutter and occlusions, and a complex trapezium-shaped interior with pillar.

## 8.5 Further work

There are a number of suggestions that can be used to enhance this research in the future:

- **Volumetric modelling**

  It is important, especially for as-built drawings, to have volumetric modelling. This type of model generates 3D representations of surfaces within a volume, not only in a plane. Volumetric modelling is also one of the existing gaps identified by Tang, *et al.* (2010) in this research area. Having volumetric modelling will produce a more realistic visualization representing the interior, plus users could also get more information about the surfaces. Existing related features in CAD-based software like the thickness of walls can be included to enhance the volumetric modelling in this research.

- **Modelling unusual geometrical structures**

  Newly built buildings are having more "non-ideal" (not sparse) geometrical structures, in fact unusual geometrical structures are getting more and more popular. It is good to have a platform that could also produce 3D models representing unusual geometrical structures in the future, making it more robust.

- **Features improvement**

  The developed model in this research is a general one and being generated to assist professionals in various applications. However, if the model is to be specifically designed for an exact application in the future, features developed in this research need to be improved. For example, if the resultant model needed to be designed exclusively for 3D as-built drawing purposes, features like modelling of the door and window could be an added advantage, plus other things like the pillar. In addition to this, to have a 3D model that can be accessed digitally without depending on a particular software platform would be much appreciated. There are some examples of 3D volumetric models developed using MATLAB that can be viewed in 3D using Adobe Acrobat, therefore this feature could assists 3D accessibility without depending on specialist software packages.

- **Automation and processing time**

  The developed method in this research is being designed to work in an optimised fashion with the laser scanner data obtained from the SICK PLS 101 laser scanner. Therefore, the processing time may be higher to process data from a state-of-the-art laser scanner. But, as computer processing capability is increasing, this may not be a problem in the future. Furthermore, a more robust method could also be implemented to increase the automation of the overall system.

# References

Abdul Shukor, S.A. & Young, K. (2011a). A fast knowledge-based plane reconstruction method from noisy 3D point cloud data. In: Hamza, M.H. & Zhang, J.J., eds. IASTED (International Association of Science and Technology for Development), *12th International Conference on Computer Graphics and Imaging*. Innsbruck, Austria 16-18 February 2011. IASTED, pp. 24-31.

Abdul Shukor, S.A., Young, K. & Rushforth, E.J. (2011b). 3D modeling of indoor surfaces with occlusion and clutter. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Mechatronics*. Istanbul, Turkey 13-15 April 2011. IEEE, pp. 282-287.

Adán, A. & Huber, D. (2010). *Reconstruction of wall surfaces under occlusion and clutter in 3D indoor environments.* [internet] Pittsburgh, Pennsylvania: Carnegie Mellon University. Available at: http://www.ri.cmu.edu/pub_files/2010/4/Report_A.Adan_D.Huber_A30_2010.pdf [Accessed 14 January 2011].

Albertz, J. & Wiedemann, A. (1995). Acquisition of CAD data from existing buildings by photogrammetry. In: P.J. Pahl & H. Werner (eds.) 1995. *Computing in Civil and Building Engineering Journal*. Rotterdam & Brookfield, pp.859-866.

Albertz, J. (2001). Albrecht Meydenbauer: Pioneer of photogrammetric documentation of the cultural heritage. In: *18th International CIPA Symposium 2001*. Postdam, Germany 18-21 September 2001.

Ali, H., Ahmed, B. & Parr, G. (2008). Robust window detection from 3D laser scanner data. In: IEEE (Institute of Electrical and Electronics Engineers), *Congress on Image and Signal Processing*. Hainan, China 27-30 May 2008. IEEE.

Allen, P., et al. (2001). AVENUE: Automated site modeling in urban environments. In: IEEE (Institute of Electrical and Electronics Engineers), *3rd International Conference on 3D Digital Imaging and Modeling (3DIM 2001)*. Quebec City, Canada 28 May-1 June 2001. IEEE Computer Society.

Andrews, D., et al. (2009). Control. In: J. Bedford, & H. Papworth, eds. (2009). *Measured and drawn: techniques and practice for the metric survey of historic buildings.* Swindon: English Heritage. Ch.2.

Arayici, Y. (2007). An approach for real world data modelling with the 3D terrestrial laser scanner for built environment. *Automation in Construction*, 16, pp.816-829.

Autodesk, Inc. (2011). *Autodesk Labs Project Photofly Now 123D Catch Beta*. [internet] Available at: http://labs.autodesk.com/utilities/photo_scene_editor/ [Accessed 6 March 2012].

Baldock, T. (2011). Discussion on historical site preservation. [conversation] (Personal communication, 7 March 2011).

Bajaj, C.L., Bernardini, F. & Xu, G. (1995). Automatic reconstruction of surfaces and scalar fields from 3D scans. In: ACM (Association for Computing Machinery) *Proceedings 22nd Annual Conference on Computer Graphics* (SIGGRAPH 1995). Los Angeles, California 6-11 August 1995. ACM.

Beraldin, J.A., Blais, F. & Lohr, U. (2010) Laser scanning technology. In: G. Vosselman & H.G. Maas, eds. (2010). *Airborne and terrestrial laser scanning*. Scotland: Whittles Publishing. Ch.1.

Bergstroem, P. (2006). *Iterative Closest Point Method.* [internet] (Updated 26 Nov 2007) Available at: http://www.mathworks.com/matlabcentral/fileexchange/ [Accessed 25 April 2012].

Bernardini, F., Mittleman, J., Rushmeier, H., Silva, C. & Taubin, G. (1999). The ball-pivoting algorithm for surface reconstruction. *IEEE Transactions on Visualization and Computer Graphics*, 5 (4), pp.349-359.

Besl, P.J. & McKay, N. (1992). A method for registration of 3-D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14 (2), pp.239-256.

Bishop, A. (2011). Discussion on laser scanner usage in facilities management. [conversation] (Personal communication, 27 April 2011).

Blake, B. (2007). Metric survey techniques for historic buildings. In: M. Forsyth, ed. (2007). *Structures and construction in historic building conservation*. Wiley-Blackwell. Ch.4.

Bluesky International Limited (2012). *A brief history of LiDAR*. [internet] Available at: http://www.lidar-uk.com [Accessed 9 February 2012].

Bosche, F. (2010). Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction. *Advanced Engineering Informatics*, 24, pp.107-118.

Breckon, T.P. & Fisher, R.B. (2008). Three-dimensional surface relief completion via nonparametric techniques. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 30 (12), pp.2249-2255.

Brilakis, I. et al. (2010). Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics*, 24, pp.456-465.

Bryan, P. (2011). Discussion on laser scanner usage in historical site preservation. [conversation] (Personal communication, 7 March 2011).

Budroni, A. & Boehm, J. (2009). Toward automatic reconstruction of interiors from laser data. In: ISPRS (International Society of Photogrammetry and Remote Sensing), *3rd International Workshop 3D-ARCH*, Trento, Italy 25-28 February 2009. ISPRS.

Cantzler, H., Fisher, R.B. & Devy, M. (2002). Quality enhancement of reconstructed 3D models using coplanarity and constraints. In: L. Van Gool (ed.) 2002. *Lecture Notes in Computer Science*. Berlin Heidelberg: Springer-Verlag, pp.34-41.

Castellani, U., Livatino, S. & Fisher, R.B. (2002). Improving environment modelling by edge occlusion surface completion. In: IEEE (Institute of Electrical and Electronics Engineers), *International Symposium on 3D Data Processing, Visualization and Transmission (3DPVT 2002)*. Padova, Italy 19-21 June 2002. IEEE.

Cignoni, P. & Scopigno, R. (2008). Sampled 3D models for CH applications: A viable and enabling new medium or just a technological exercise? *ACM Journal on Computing and Cultural Heritage*, 1, 1, Article 2, pp.1-23.

Computational Geometry Algorithms Library (2012). *2D Alpha Shapes*. [internet] Available at: http://www.cgal.org [Accessed 5 May 2012].

David 3D Solutions GbR (2011). *DAVID Laserscanner*. [internet] Available at: http://www.david-laserscanner.com/ [Accessed 13 December 2011].

de Berg, M., Cheong, O., van Kreveld, M. & Overmars, M. (2008). *Computational geometry: Algorithms and applications*. 3rd ed. Berlin: Springer-Verlag.

Dell'Acqua, F. & Fisher, R. (2002). Reconstruction of planar surfaces behind occlusions in range images. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24 (4), pp.569-575.

Eich, M., Dabrowska, M. & Kirchner, F. (2010). Semantic labeling: Classification of 3D entities based on spatial feature descriptors. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Robotics and Automation (ICRA 2010)*. Anchorage, Alaska 3-8 May 2010. IEEE.

El-Hakim, S.F., Boulanger, P., Blais, F. & Beraldin, J.A. (1997). A system for indoor 3-D mapping and virtual environments. *Videometrics V*. (3174), pp.21-35.

El-Hakim, S.F. (2001). 3D modeling of complex environment. In: SPIE (The International Society for Optics and Photonics), *Electronic Imaging 2001*. San Jose, California 21-26 January 2001. SPIE.

Elmqvist, N. & Tsigas, P. (2008). A taxonomy of 3D occlusion management for visualization. *IEEE Transactions on Visualization and Computer Graphics*, 14 (5), pp.1095-1109.

FARO Technologies Inc. (2012). *FARO laser scanner software*. [internet] Available at: http://www.faro.com/focus/us/software [Accessed 30 November 2012].

Fitzgibbon, A. (2001). Robust registration of 2D and 3D point sets. In: BMVA (British Machine Vision Association), *Proceedings of the British Machine Vision Conference (BMVC 2001)*. Manchester, UK 10-13 September 2001. BMVA Press.

Furukawa, Y., Curless, B., Seitz, S.M. & Szeliski, R. (2009). Reconstructing building interiors from images. In: *International Conference on Computer Vision (ICCV 2009)*. Kyoto, Japan 29 September - 2 October 2009.

Gamble, A. (2011). Discussion on laser scanner usage in as-built. [conversation] (Personal communication, 3 May 2011).

Giaccari, L. (2009). *Ball fretting*. [internet] Available at: http://www.advancedmcode.org/ [Accessed 19 August 2010].

Gillham, B. (2008). *Developing a questionnaire*. 2nd ed. London: Continuum International Publishing Group.

Gueorguiev, A., Allen, P., Gold, E. & Blaer, P. (2000). Design, architecture and control of a mobile site-modelling robot. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Robotics and Automation (ICRA 2000)*. San Francisco, CA April 2000. IEEE.

Gupta, A., Satkin, S., Efros, A.A. & Hebert, M. (2011). From 3D scene geometry to human workspace. In: IEEE (Institute of Electrical and Electronics Engineers), *Computer Vision and Pattern Recognition (CVPR 2011)*. Colorado Springs, Colorado 21-23 June 2011. IEEE.

Haehnel, D., Triebel, R., Burgard, W. & Thrun, S. (2003). Map building with mobile robots in dynamic environments. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Robotics and Automation (ICRA 2003)*. Taipei, Taiwan 14-19 September 2003. IEEE.

Han, F., Tu, Z. & Zhu, S.C. (2002). A stochastic algorithm for 3D scene segmentation and reconstruction. In: A. Heyden et al. (eds.) 2002. *Lecture Notes in Computer Science*. Berlin Heidelberg: Springer-Verlag, pp.502-516.

Hebert, M. (2000). Active and passive range sensing for robotics. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Robotics and Automation (ICRA 2000)*. San Francisco, California 24-28 April 2000. IEEE.

Horn, B.K.P. (1987). Closed-form solution of absolute orientation using unit quarternions. *Journal of the Optical Society of America A*, 4(4), pp.629-642.

Huber, D., *et al.* (2010). Using laser scanners for modeling and analysis in architecture, engineering, and construction. In: *44th Annual Conference on Information Sciences and Systems (CISS 2010)*. Princeton, New Jersey 17-19 March 2010. IEEE.

Johnson, A.E. & Hebert, M. (1999). Using spin images for efficient object recognition in cluttered 3D scenes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 21 (5), pp.433-449.

Jones, D.M., ed. (2007). *3D laser scanning for heritage: advice and guidance to users on laser scanning in archaeology and architecture*. UK: English Heritage.

Krishnan, A.K. & Krishna, K.M. (2010). *A visual exploration algorithm using semantic cues that constructs image based hybrid maps.* [internet] Bonn, Germany: University of Bonn. Available at: http://www.ais.uni-bonn.de/~holz/iros10wssm/proceedings/06_krishnan_final.pdf [Accessed 8 November 2010].

Kroon, D.J. (2009). *Finite Iterative Closest Point.* [internet] Available at: http://www.mathworks.com/matlabcentral/fileexchange/ [Accessed 8 May 2012].

Kymmell, W. (2008). *Building information modeling: planning and managing construction projects with 4D CAD and simulations*. USA: McGraw-Hill.

Lambert (1998) [internet]. Available at: http://www.cse.unsw.edu.au/~lambert/java/3d/hull.html [Accessed 8 December 2010].

Lemmens, M. (2011). *Geo-information: technologies, applications and the environment*. Springer.

Marchland, P. & Holland, O.T. (2003). *Graphics and GUIs with MATLAB*. Florida: Chapman & Hall / CRC.

Meadati, P. (2009). BIM extension into later stages of project life cycle. In: T. Sulbaran & C. Sterling (eds.) 2009. *Proceedings of the 45th Annual Conference*. Gainesville, Florida 1-4 April 2009. Associated Schools of Construction.

Mian, A.S., Bennamoun, M. & Owens, R. (2006). Three-dimensional model-based object recognition and segmentation in cluttered scenes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 28 (10), pp.1584-1601.

Murray, D. & Little, J.J. (2000). Using real-time stereo vision for mobile robot navigation. *Autonomous Robots*, 8, pp.161-171.

Nitzan, D., Brain, A.E. & Duda, R.O. (1977). The measurement and use of registered reflectance and range data in scene analysis. In: *Proc. of the IEEE,* 65 (2), pp.206-220.

Nuechter, A. & Hertzberg, J. (2008). Towards semantic maps for mobile robots. *Robotics and Autonomous Systems*, 56, pp.915-926.

Nyland, L. & Lastra, A. (2001). Visualizing the real world. *IEEE Computer Graphics and Applications*, 21 (5), pp.6-10.

Olufs, S. & Vincze, M. (2011). *Robust room-structure estimation in Manhattan-like environments from dense $2^{1/2}$D range data*. [internet] Bonn, Germany: University of Bonn. Available at: http://www.ais.uni-bonn.de/~holz/iros10wssm/proceedings/04_olufs_vincze_final.pdf [Accessed 8 November 2010].

Okorn, B., Xiong, X., Akinci, B. & Huber, D. (2010). Toward automated modeling of floor plans. In: *5th International Symposium on 3D Data Processing, Visualization and Transmission (3DPVT 2010)*. Paris, France 17-20 May 2010. IEEE.

Oxford Reference Online (2010). Oxford dictionary of English. [internet] Oxford University Press. Available at: http://0-www.oxfordreference.com.pugwash.lib.warwick.ac.uk/ [Accessed 5 July 2011].

Papadimitriou, G. (2010). *Spin images.* [internet] University of Edinburgh, UK. Available at: http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/AV0910/SpinImages.pdf [Accessed 9 May 2012].

Park, A. (1998). *Facilities management: an explanation*. 2nd ed. London: Macmillan Press Ltd.

Pathak, K., Vaskevicius, N. & Birk, A. (2010). Uncertainty analysis for optimum plane extraction from noisy 3D range-sensor point-clouds. *Intelligent Service Robotics*, 3, pp.37-48.

Petrovskaya, A. & Ng, A.Y. (2007). Probabilistic mobile manipulation in dynamic environments, with application to opening doors. In: *International Joint Conference on Artificial Intelligence,* Hyderabad, India 6-12 January 2007.

Quantapoint, Inc. (2011). *A history of innovation and success*. [internet] Available at: http://www.quantapoint.com/ [Accessed 21 July 2011].

Point Grey Research, Inc. (2012). *The stereo catalog.* [internet] Available at: http://www.ptgrey.com/products/Point_Grey_stereo_catalog.pdf [Accessed 11 February 2012].

Pu, S. & Vosselman, G. (2007). Extracting windows from terrestrial laser scanning. In: ISPRS (International Society of Photogrammetry and Remote Sensing), *Workshop on Laser Scanning and SilviLaser*, Espoo, Finland 12-14 September 2007. ISPRS.

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

Purslow, T. (2012). Discussion on Z+F laser scanner. [conversation] (Personal communication, 27 January 2012).

Rabbani, T., Dijkman, S., Heuvel, F. & Vosselman, G. (2007). An integrated approach for modelling and global registration of point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, 61, pp.355-370.

Ratay, R.T., ed. (2000). *Forensic structural engineering handbook*. New York: McGraw-Hill.

Roberts, M. & Lees, R. (2011). Discussion on space management at the University of Warwick. [email] (Personal communication, 2 June 2011).

Rusu, R.B., *et al*. (2008). Towards 3D point cloud based object maps for household environments. *Robotics and Autonomous Systems*, 56, pp.927-941.

Sappa, A.D. (2002). Improving segmentation results by studying surface continuity. In: IEEE (Institute of Electrical and Electronics Engineers), *16th International Conference on Pattern Recognition (ICPR 2002)*. Quebec City, Canada 11-15 August 2002. IEEE Computer Society.

Scott, A., Parker, L.E. & Touzet, C. (2000). Quantitative and qualitative comparison of three laser-range mapping algorithms using two types of laser scanner data. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Systems, Man and Cybernetics*. Nashville, Tennessee 8-11 October 2000. IEEE.

Sequeira, V., Goncalves, J.G.M. & Ribeiro, M.I. (1995). 3D environment modelling using laser range sensing. *Robotics and Autonomous Systems*, 16, pp.81-91.

Smith, D.K. & Tardif, M. (2009). *Building information modeling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers*. New Jersey: John Wiley & Sons, Inc.

Smith, I. (2002). *A tutorial on Principal Components Analysis*. [internet] Cornell University, USA. Available at: http://www.cs.otago.ac.nz/cosc453/student_tutorials/principal_components.pdf [Accessed 26 May 2011].

Stamos, I., Yu, G., Wolberg, G. & Zokai, S. (2006). 3D modeling using planar segments and mesh elements. In: IEEE (Institute of Electrical and Electronics Engineers), *International*

*Symposium on 3D Data Processing, Visualization and Transmission (3DPVT 2006)*. Chapel Hill, USA 14-16 June 2006. IEEE.

Stanford University Computer Graphics Laboratory (2011). *The Stanford 3D scanning repository*. [internet] Stanford University, USA. Available at: http://graphics.stanford.edu/data/3Dscanrep/ [Accessed 25 April 2012].

Stulp, F., Dell'Acqua, F. & Fisher, R. (2001). Reconstruction of surfaces behind occlusions in range images. In: IEEE (Institute of Electrical and Electronics Engineers), *3rd International Conference on 3D Digital Imaging and Modeling (3DIM 2001)*. Quebec City, Canada 28 May-1 June 2001. IEEE Computer Society.

Sule, D.R. (2009). *Manufacturing facilities: location, planning and design*. 3rd ed. USA: CRC Press.

Sun, X., Rosin, P.L., Martin, R.R. & Langbein, F.C. (2009). Noise analysis and synthesis for 3D laser depth scanners. *Graphical Models*, 71, pp.34-38.

Tang, P., *et al*. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in Construction*, doi: 10.1016/j.autcon.2010.06.0007 [Accessed 13 July 2010].

Tarsha-Kurdi, F., Landes, T. & Grussenmeyer, P. (2007). Hough-transform and extended RANSAC algorithms for automatic detection of 3D building roof planes from LIDAR data. In: ISPRS (International Society of Photogrammetry and Remote Sensing), *Workshop on Laser Scanning and SilviLaser*, Espoo, Finland 12-14 September 2007. ISPRS.

Thrun, S. (2002). *Robotic mapping: A survey*. [internet] Pittsburgh, Pennsylvania: Carnegie Mellon University. Available at: http://robots.stanford.edu/papers/thrun.mapping-tr.pdf [Accessed 11 May 2011].

Thrun, S., Burgard, W. & Fox, D. (2000). A real-time algorithm for mobile robot mapping with applications to multi-robot and 3D mapping. In: IEEE (Institute of Electrical and Electronics Engineers), *International Conference on Robotics and Automation (ICRA 2000)*. San Francisco, California 24-28 April 2000. IEEE.

Verma, V., Kumar, R. & Hsu, S. (2006). 3D building detection and modeling from aerial LIDAR data. In: IEEE (Institute of Electrical and Electronics Engineers), *Computer Vision and Pattern Recognition (CVPR 2006)*. New York, New York 17-22 June 2006. IEEE.

Wang, J. & Oliveira, M.M. (2002). Improved scene reconstruction from range images. In: G. Drettakis & H.P. Seidel (eds.) 2002. *EUROGRAPHICS*. Oxford: Blackwell Publishers, pp.521-530.

Wang, J. & Oliveira, M.M. (2003). A hole-filling strategy for reconstruction of smooth surfaces in range images. In: IEEE (Institute of Electrical and Electronics Engineers), *XVI*

*Brazilian Symposium on Computer Graphics and Image Processing* (SIBGRAPI 2003). Sao Paolo, Brazil 12-15 October 2003. IEEE Computer Society.

Warner, L. (2004). *Introduction to clustering techniques*. [internet] Institut Universitari De Linguistica Aplicada (IULA), Spain. Available at: http://www.iula.upf.edu/materials/040701wanner.pdf [Accessed 26 May 2011].

Wengert, C. & Bianchi, G. (2008). *Absolute Orientation.* [internet] (Updated 9 Jun 2010) Available at: http://www.mathworks.com/matlabcentral/fileexchange/ [Accessed 24 December 2011].

Whitaker, R.J., Gregor, J. & Chen, P.F. (1999). Indoor scene reconstruction from sets of noisy range images. In IEEE (Institute of Electrical and Electronics Engineers), *2nd International Conference on 3D Digital Imaging and Modeling (3DIM 1999)*. Ottawa, Canada 4-8 October 1999. IEEE Computer Society.

Wustemann, L. & Booty, F. (2009). Space design and management. In: F. Booty, ed. 2009. *Facilities management handbook*. Massachusetts: Butterworth-Heinemann. Ch.11.

Xiong, X. & Huber, D. (2010). Using context to create semantic 3D models of indoor environments. In: F. Labrosse et al. (eds.) *Proceedings of the British Machine Vision Conference (BMVC 2010)*. Aberystwyth, Wales 31 August-3 September 2010. BMVA Press.

Yapo, T.C., Stewart, C.V. & Radke, R.J. (2008). A probabilistic representation of LiDAR range data for efficient 3D object detection. In: IEEE (Institute of Electrical and Electronics Engineers), *Search in 3D Workshops at Computer Vision and Pattern Recognition*. Anchorage, Alaska 27 June 2008. IEEE.

Young, N.W., Jones, S.A., Bernstein, H.M. & Gudgel, J.E. (2009). *The business value of BIM: Getting Building Information Modeling to the bottom line.* [internet] TPM Inc., USA. Available at: http://www.tpm.com [Accessed 29 June 2011].

Yunus, M.A. (2011). Discussion on laser scanner usage in as-built. [email] (Personal communication, 26 January 2011).

Zoller + Froehlich GmbH (2012). *Z+F LaserControl.* [internet] Available at: http://www.zf-laser.com/Z-F-LaserControl [Accessed 30 November 2012].

# Appendix A

# Questionnaire for Survey Methodology

**Usage of LIDAR in as-built development – Questionnaire**

**Name: ________________________________** **Position: ______________________________________**

**Company: ________________________________________________________________________________**

LIDAR (LIght Detection And Ranging) is a 3D scanning device that able to obtain information of a distant target from its transmitted light. In this research, LIDAR is used to get data of an indoor area (office, room, hall, etc) which is currently in used to develop a 3D modelling of the related space. This questionnaire is to gather as much information of current usage of LIDAR in indoor modelling, which is commonly being named as as-built drawing.

1) How long have you been involved in as-built drawing development?
   ___________________________________________________________________________________

2) Have you ever use LIDAR to develop an as-built before?
   Yes (please proceed to (a)) No (please proceed to (b))

   (a) In what as-built application / area do you use it?
      - Pipeline / heating / ventilating layout
      - Building (planar surfaces / room dimension)
      - Landscape / interior design
      - Facilities management
      - Others, please state:______________________________________________________________

   (b) If you had a device that able to extract geometric and spatial relationship of an indoor area, would you use it?
      Yes (Why: _______________________________________________________________________)
      No (Why: _______________________________________________________________________)

3) What software do you use currently for as-built drawing?
   ___________________________________________________________________________________

4) Any limitation/s of the above software in indoor mapping?
   - Obstacle / occlusion handling: ____________________________________________________
   - Data handling: _______________________________________________________________
   - Noise / error removal handling: ___________________________________________________
   - Modelling accuracy: ____________________________________________________________
   - User interface: _______________________________________________________________
   - Rapidness in producing useful result: _______________________________________________
   - Others, please state:____________________________________________________________

5) In the future, what information would you like to have from indoor mapping using LIDAR:
   ___________________________________________________________________________________

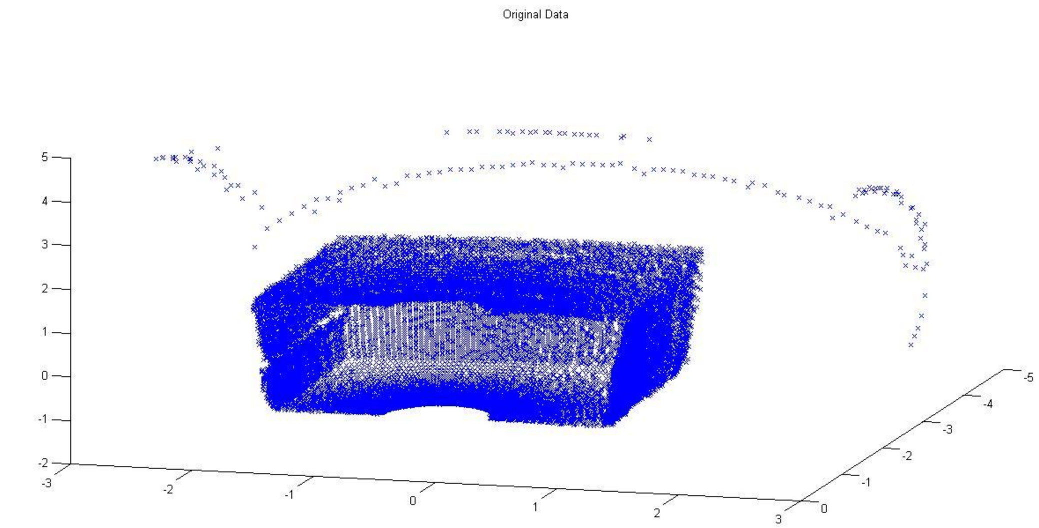
Thank you for your time. I would like to ensure that all these responses will be treated confidentially and anonymously for academic purpose. This research is an independent work and does not involve with any commercial company. I value your input and it is hope that the outcome will be useful to help you in the future.

# Appendix B

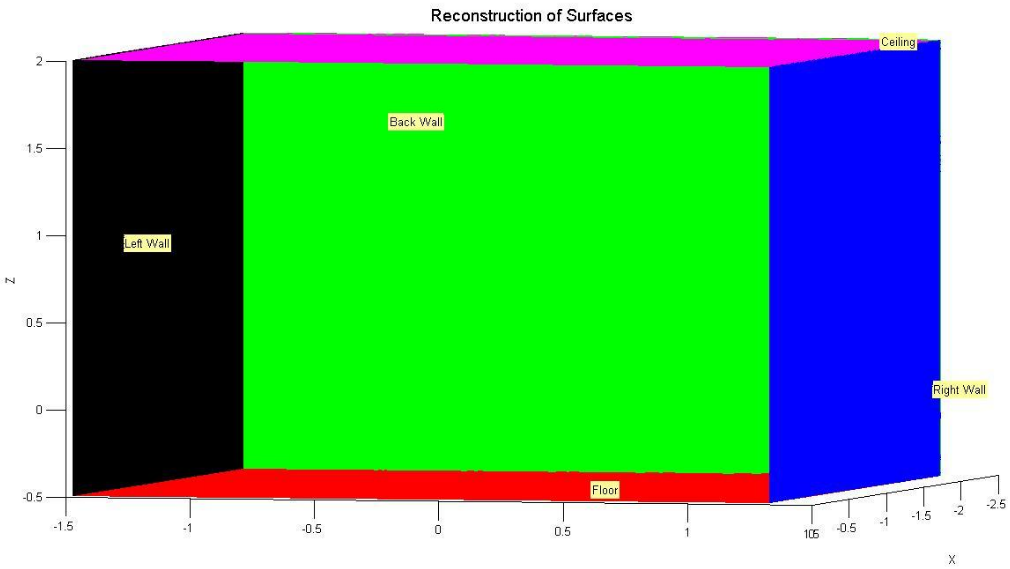
# 3D Modelling Results of Testing Data

## B.1 Room 1

### B.1.1 Dataset 6



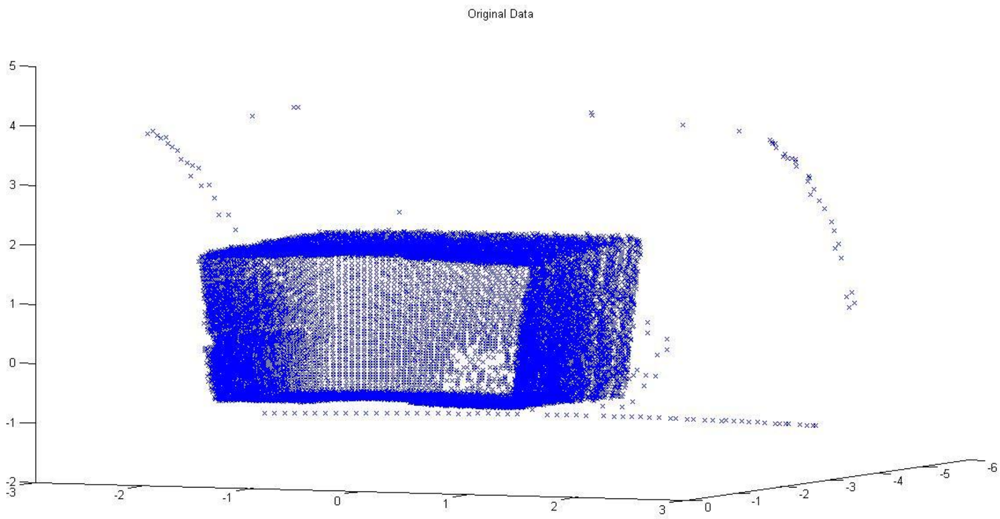

Original data (25,438 points)



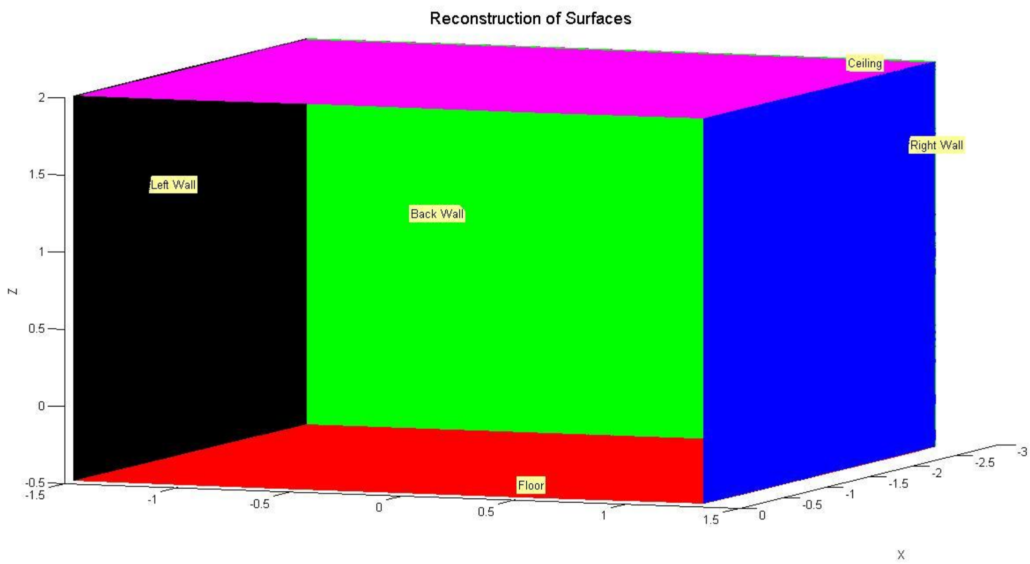

3D modelling

Noise: 2.25%, Accuracy: 100%

B.1.2 Dataset 7



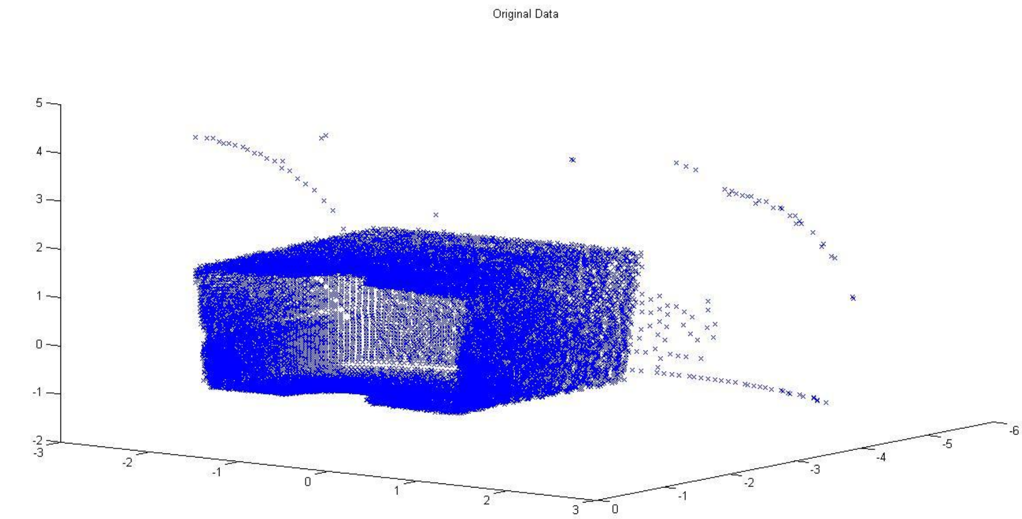

Original data (25430 points)



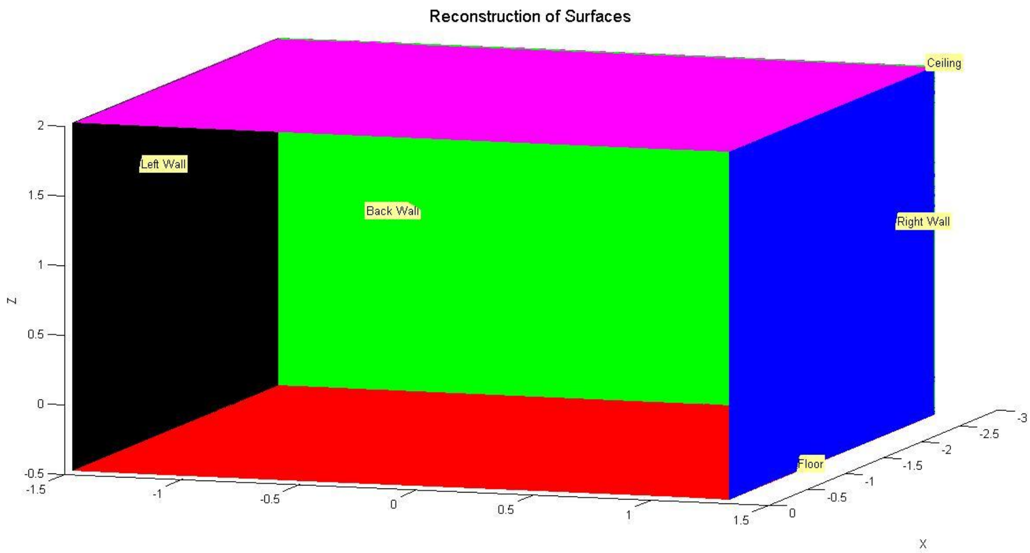

3D modelling

Noise: 2.34%, Accuracy: 100%

### B.1.3 Dataset 8



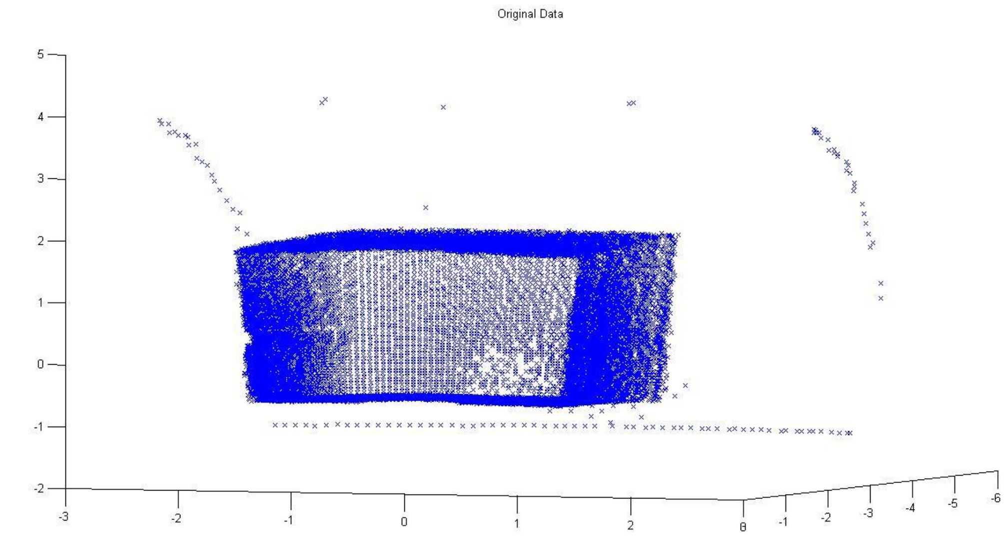

Original data (25432 points)



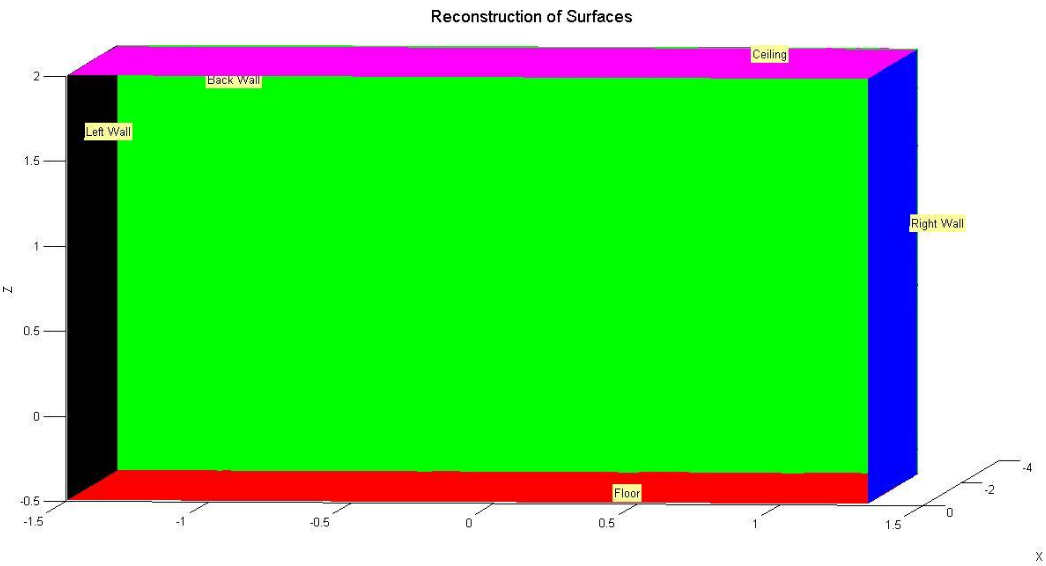

3D modelling

Noise: 2.34%, Accuracy: 100%

B.1.4 Dataset 9




Original data (25430 points)

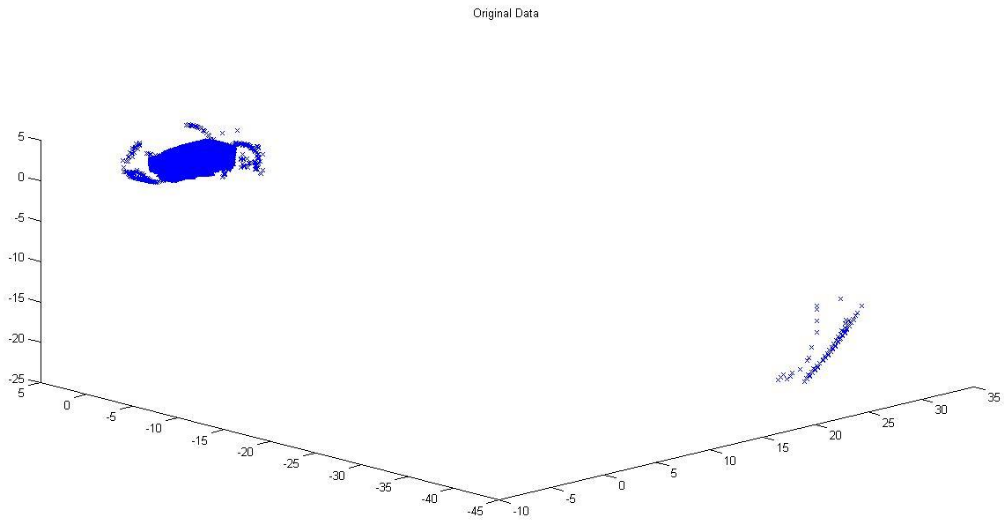



3D modelling

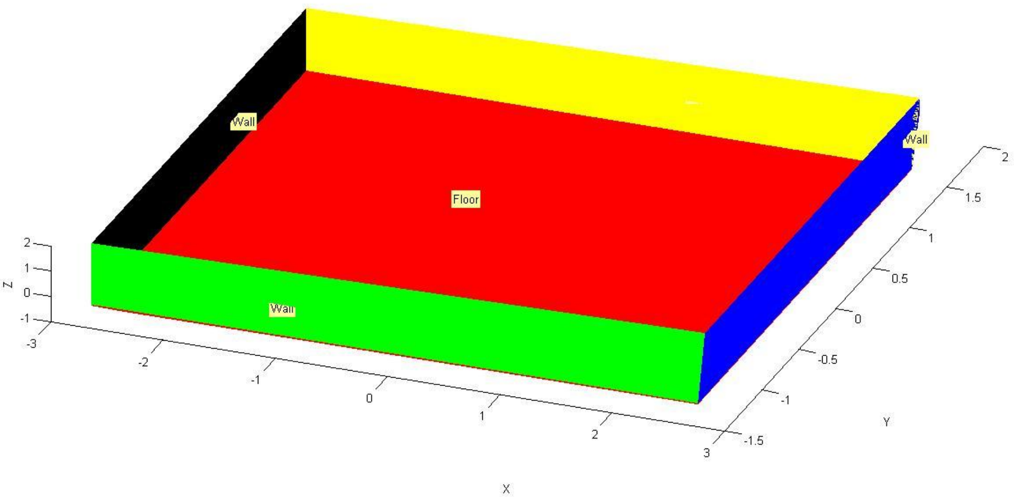
Noise: 2.32%, Accuracy: 100%

## B.2 Room 4

### B.2.1 Dataset 10




Original data (50,829 points)

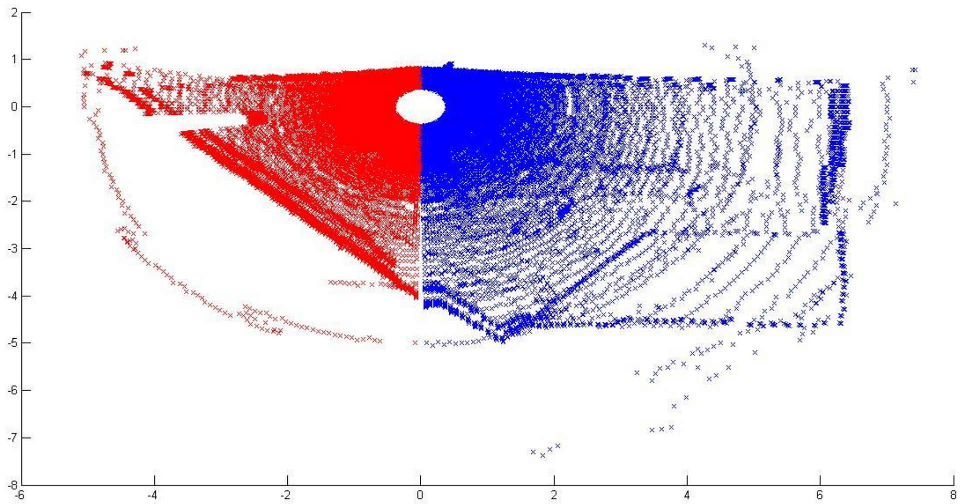



3D modelling

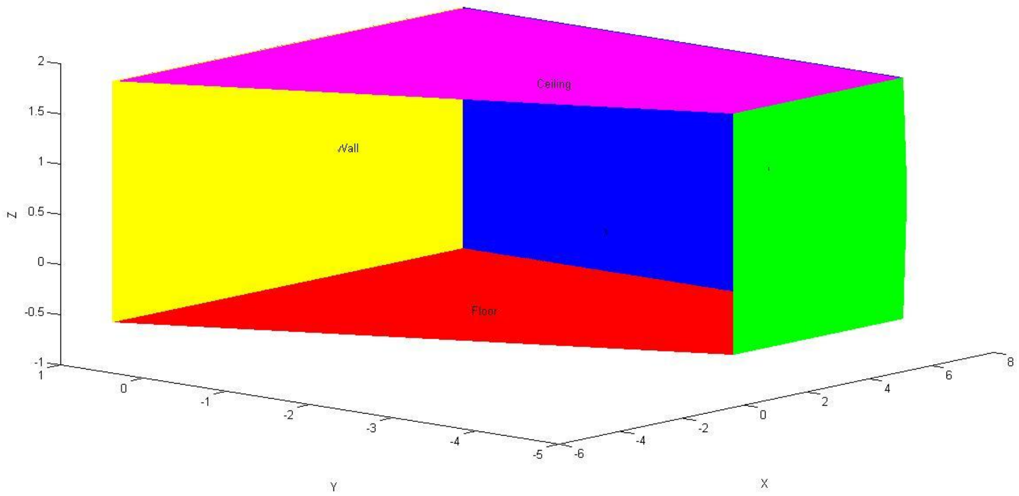
Noise: 5.64%, Clutter: 47.53%, Accuracy: 96.45%

## B.3 Room 5

### B.3.1 Dataset 11



Original data (50,388 points)




3D modelling

Noise: 2.72%, Clutter: 67.76%, Accuracy: 98.55%

# Appendix C

## Glossary*

**3D modelling** Digital representation in 3D, which in this research, illustrates building interior

**Clutter** Data that represents other things apart from the one defining the closed-surfaces of the room (wall, ceiling, floor), such as the furniture and other equipment like computers, bins, top book rack etc

**Complex indoor environment / interior** An interior with complex geometry construction / composition of the building (for example, incline or layered ceiling, existence of pillar) as well as non-structural interior (such as cable skirting), together with the presence of furniture and equipment that create occlusions and clutter issues

**Complex geometrical structure** Interior with non-sparse construction / composition

**Mapping** A 3D model which incorporates labelling of important surfaces of the interior

**Noise data** Point cloud obtained from the laser scanner that does not resemblance the overall image of the space, for example outliers that are outside of the room

**Occlusion** Holes and shadows within the data signifying the surfaces due to clutter, which create incomplete and missing data

**Sensor fusion** A system where two or more sensor used and the data from all the sensors need to be fused (processed) together to solve the issue

**Sparse room / space** A cubic structure of a room (box-type) with little objects that would create slight clutter and occlusion problems

**Station markers** An object placed usually on the ground as a symbol to mark the correct latitude and longitude of that particular marker

**Synthetic items data** Data representing man-made objects, for example toys, blocks, historical statuettes and carvings, that have been collected in a controlled environment, where the surroundings (lighting, percentage of clutter and occlusions, etc) is changeable according to the needs

**Targets** Multiple items of consistent shape, size and drawing placed around any object of interest when collecting data (in terms of images / point cloud / etc) to ease data registration process later on

* This glossary provides definition of terms used and are within the scope of this research, therefore it should not be used as a referring tools to other works