Assessment of Mobile Laser Scanning Data in 3D Cadastre

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

The growing population and the consumption of land have caused an increasing pressure of land use especially in the commercial and residential districts of the urban area. The limited land resources drive the government and people to exploit the space that above and below the earth surface, and have caused the 3D property situation such as the overlapping building complex, interlocking constructions and the underground facilities. This tendency dramatically changes the relation between human and land, leading to a growing importance of land ownership. Moreover, it extends the cadastre task from the 2D land parcel to the 3D space.

To be able to register and represent the overlapping objects existing on the 2D parcel, the 3D cadastre which aims to "register and give insight into the right and restriction on 3D property units"(Stoter and Oosterom, 2006) becomes to be a necessity. From the cadastre registration perspective, the term 3D property refers to the bounded amount of legal space which is required by physical objects. Therefore, for each property unit, how reconstruct the physical object and then to represent the "legal space unit" correctly is the premise of a precise 3D registration.

Along with the rapid development of the 3D data acquisition and reconstruction techniques, now it is possible to model the building objects with detailed geometric information into a 3D form. In this research, the Mobile Laser Scanning (MLS) data and the processed building facade maps are implemented for the building objects reconstruction. The suitability of applying the MLS products in 3D cadastre for physical building and apartment units modelling is assessed. Besides exploring the 3D objet acquisition and modelling, this research also discusses the concept of "legal space registration & physical structure representation". An external PhysicalBuilding package which aims to integrate the physical building data and model into 3D cadastre data set for legal space registration has been developed in this study. This package has been designed to be used as an extension of the LADM. Within this PhysicalBuilding package, the classes which describe the building unit by using different forms of geometric primitives are designed.

Secondary data of a study area in Istanbul were collected including: scientific articles, project reports; MLS data, facade maps, building construction plans, cadastral maps and the DEM data. Within the procedure of the physical building modelling by using the MLS data, the building units that cadastre interests including the whole building objects, the storeys and the apartment units were reconstructed. The experimental results show that the applicability of introducing the MLS data for 3D a physical building model in the extended LADM cadastre dataset. Currently, the data collection and maintenance of a physical model is not always the cadastre task, these data are organized in the other datasets in relevant organizations. In this research, the physical building models and the generated geometric information are maintained in the proposed PhyscialBuilding Package separately; they can be further accessed, processed or integrated in cadastral data set.

Keywords: 3D Cadastre; Mobile Laser Scanning (MLS) data; facade map; LADM; legal space; physical structure.

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1. GENERAL INTRODUCTION

1.1. Introduction

Traditionally, the cadastre is 2D based. In Cadastre 2014 (Kaufmann and Steudler, 2001), it is defined as "Cadastre is a methodically arranged public inventory of data concerning all legal land objects in a certain country or district, based on a survey of their boundaries. The outlines of the property, the identifier together with descriptive data, may show for each separate land object the nature, size, value and legal rights or restrictions associated with the land object". Along with the growing population in the world, the consumption of land is also increasing. This tendency dramatically changes the relation between human and land, and leads to a growing importance of land ownership. Moreover, the growing pressure on land particularly in the commercial district of and residential district the urban area has caused the overlapping properties such as high-rise residential complexes and constructions. From the perspective of cadastre, how to register these overlapping objects in 2D parcel, and how to display them in 2D cadastral map become a challenge. Therefore, the 3D cadastre, which extended the cadastral registration to the third dimension, becomes to be a necessity.

The definition of 3D modelling, could be found in Remondino (2006): "The three-dimensional modelling of an object can be seen as the complete process that starts from data acquisition and ends with a 3D virtual model visually interactive on a computer. Three-dimensional modelling of objects is an intensive and long-lasting research problem in the graphic, vision and photogrammetric communities." Traditionally, the photogrammetry is the main tool used for acquiring data in 3D modelling. The technology of image based modelling (IBM), could recover or represent 3D object information accurately by using a set of 2D image measurements (Remondino and El-Hakim, 2006). In recent years, a lot of effort was used to develop new approaches that could be used for acquiring, processing and visualization of 3D models. Today, airborne laser scanning which is based on costly active sensors has capability to produce dense point clouds for three-dimensional measurements, become a mature approach for obtaining surface models (Brenner, 2005). At the same time, ground-based Lidar, which has the advantage of providing details of building facades as required for the production of realistic 3D city modelling, is also developed and widely applied for field survey (Shan and Toth, 2008).

The "Historical Peninsula project" of 3D city modelling of Istanbul Historic Peninsula was initiated by Istanbul Greater Municipality's Directory in the 2006, in Turkey. The 3D data collection was implemented by Mobile Laser Scanning (MLS) for the building exterior structure on the street level. The main idea behind the project was to "document the cultural heritage, protect the historical environment and to model the city in 3D" (Buhur et al., 2008). In addition, the suitability of applying these data and product in cadastre domain is worth considering. This research work collects and uses data and relevant reports from this project.

1.2. Research problem, objective and questions

1.2.1. Problem definition

The importance of 3D cadastre issue has been stated for years and some countries address it in their legal definition (Erdogan, 1998, Stoter and Ploeger, 2003, Steudler et al., 2004). Although the complex property right can be defined from the existing legal item, how to clearly register the situation and the amount of space of 3D property in current cadastre systems is still a challenge. Previous researches have mainly addressed the development of conceptual models implement the cadastral registration of 3D property, such as the Core Cadastre Domain Model and its later version Land Administration Domain Model (LADM) (Kaufmann and Steudler, 2001, Van Oosterom et al., 2006, Groothedde et al., 2008, Ingvarsson, 2005, Stoter and van Oosterom, 2005), but have not given insight into what kind of 3D geometric information should be recorded for the 3D legal object registration or what kind of technique could be used to acquire 3D data for cadastral purposes .

In a 3D cadastral system, it is possible to acquire multiple properties at the same 2D location (e.g. building or apartment complex) with the relevant cadastral registration records (e.g. area and ownership). Therefore, the boundary of properties along the vertical dimension is required (e.g. each floor of the building). In addition, for a 3D cadastre to fulfil the requirement of "Registering and giving insight into the right and restriction on 3D property unit" (Stoter and Ploeger, 2003), for each floor of the building, every individual property unit should also be defined. Therefore, the building construction plans should be introduced and integrated with floor information in order to generate inner boundary for each property unit (see Figure 1.2.1.1).

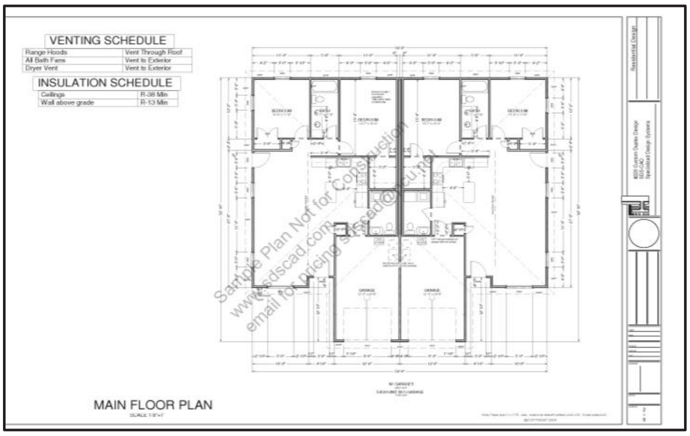


Figure 1.2.1.1 Building construction plans

Moreover, 3D cadastre records the space of each owner by means of a right (Stoter and Oosterom, 2006). For each property unit, how to model this "space" correctly is the premise of a precise 3D registration. For example, the façade structure, such as an overhanging balcony and eaves are spaces that cannot be recorded in a simple solid 3D building model. However, their consideration affects the amount of bounded space that belongs to one property unit. For this purpose, the geometric structures of the wall, which not only indicates the limit or extent of one property unit, but also affords sufficient information for building reconstruction in 3D cadastre domain, should also be recorded.

According to the above mentioned requirements, accurate physical building models are indispensable to register 3D property. Therefore, the collection and extraction of 3D geometric information is essential for establishing a 3D cadastral system. In general, the measurement and footprint produced from cadastral surveys are an effective and accurate source of information for 3D building construction (Lemmens, 2003). They could be used as input data to generate a block-shaped building with efficient planimetric accuracy. This representation of a 3D building, where roofs have no structure and are formed by horizontal planes, is referred to as Level of Detail 1 (LOD1) in CityGML (Kolbe et al., 2005, Ledoux and H Meijers, 2009). However, the block-shaped model fails to represent the wall structures, only one property could be defined from each block. Nowadays, the use of aerial image and aerial laser scanning (ALS) are major approaches for the 3D data acquisition and object reconstruction (Zheng et al., 2009, Remondino and El-Hakim, 2006, Brenner, 2005, Vosselman. and Dijkman., 2001), but the major weaknesses of airborne system is the incomplete representation of the walls and the footprint of the building (Rutzinger et al., 2009, Oude Elberink, 2008).

In order to accurately register the property unit in three dimensions, the vertical position and height of each floor should be extracted from façade, and added to the 3D building model as floor surface. Moreover, the volume of overhanging part of the façade, such as the balcony, should also be included. However, the common drawback of the above mentioned data acquisition approaches is the insufficient representation of building outline and façade structures. To tackle this problem, the Mobile Laser Scanning (MLS) system, which could use to extract detailed building geometry for 3D façade reconstruction, is a promising option. Although the MLS has already been implemented in the 3D city modelling and urban planning during the last few years (Buhur et al., 2008, Brenner, 2009, Becker, 2009), whether this data and reconstructed model could fulfil the requirement of 3D cadastre is still being assessed.

1.2.2. Research objective

The aim of this research is to reconstruct 3D physical objects and generate 3D geometric information by using MLS data, and to assess the accuracy and applicability of this approach in the 3D cadastral registration.

The research objective could be defined from two perspectives:

- Cadastral requirements: to assess an appropriate physical building model to implement the cadastral registration of 3D property.
- Applicability assessment: to assess the applicability of reconstructing 3D physical objects by using MLS data for 3D cadastre.

1.2.3. Research question

According to the research objectives mentioned above, the related research questions are formulated in the Table 1-1.

Table 1-1 Research objectives with the relevant research questions

`	Research objectives	Related research questions
Cadastral requirement	To assess an appropriate physical building model to implement the cadastral registration of 3D property.	(1) What are the benefits of registering a property unit in 3D? (2) What kinds of data should be introduced for representing building units in 3D cadastre model? (3) What is the advantage of integrating the physical building model and spatial data into LADM for building units registration?
Applicability assessment	To assess the applicability of reconstructing 3D physical objects by using MLS data for 3D cadastre purpose.	(4) What type of building information could be reconstructed from MLS data for cadastral purpose? (5) What is the geometric accuracy of the 3D information acquired from the reconstructed building model? (6) What is the restriction of MLS data for 3D physical objects reconstruction? (7) How the application of MLS data improves 3D physical objects acquisition for cadastre purpose?

1.3. Related work

A new approach to cadastral registration was proposed by the guidelines of Cadastre 2014 (Kaufmann and Steudler, 2001). The statements of this report lead the cadastre into a 3D view. The 3D cadastre is referred as to "registering and giving insight into right and restrictions not only on 2D parcels, but also on 3D property units" (Stoter and Oosterom, 2006). With respect to research in 3D cadastre, the studies already defined and developed the cadastral conceptual model LADM to implement the cadastral registration of 3D property (Kaufmann and Steudler, 2001, Van Oosterom et al., 2006, Ingvarsson, 2005, Lemmon et al., 2004, Groothedde et al., 2008), however, few researches and works gave detailed descriptions about what kind of approaches could be used to acquire 3D data for cadastral purpose or what kind of 3D data should be extracted to solve the dispute existed in 2D cadastral maps. Stoter (2006) claimed that the main drawback of the current 3D cadastral registration is that "The cadastre itself is lack of a fundamental approach by taking the legal as well as technical framework into consideration". Only the legal aspect is placed as number one priority.

When it comes to the technique, the method of collecting data and extracting 3D information is the essential part for establishing a 3D cadastral system. Traditionally, the photogrammetry is the mainly performed approach for 3D data acquisition. The overlapping aerial images are taken along the strips and then the 3D object can be reconstructed by using stereo image pairs. However, it still has difficulties for modelling the 3D building objects by taking the stereo image pairs as the single data source (Süveg and Vosselman, 2004). In the review of Remondino and El-Hakim (2006), several approaches for acquiring, processing and visualizing the 3D information from terrestrial images and point clouds data have been examined and compared. Süveg (2004) and Brenner (2005) mentioned the multiple data fusion (combination of the different data sources) such as panchromatic images, terrain models, laser scan data or cadastre map could enhance the reliability of data extraction processes. In the work of building reconstruction from airborne system, the methods using existing 2D information in conjunction with airborne data are proposed by Vosselman (2001) and Süveg (2004).

Various studies conducted on the extraction of building exterior walls have revealed that there are problems as far as integrating ALS data into the cadastral map is concerned: the extracted walls and the building footprints on the cadastral map have different representations (Oude Elberink, 2008, Rutzinger et al., 2009, Vosselman and Maas, 2010b). The mobile or terrestrial lidar, which shows the advantage of providing details of building facades as required for the production of realistic 3D city modelling, is also developed and widely applied in the use of field survey (Shan and Toth, 2008, Becker, 2009, Oude Elberink, 2010, Rutzinger et al., 2009, Pu and Vosselman, 2010). The work on MLS mapping and accuracy assessment could be found in (Barber et al., 2008, Brenner, 2009), 15cm and 10cm positional accuracy were reached respectively for the residential area mapping.

1.4. Research conceptual framework

Figure 1.2.3.1 illustrates the main elements that involved in this research.

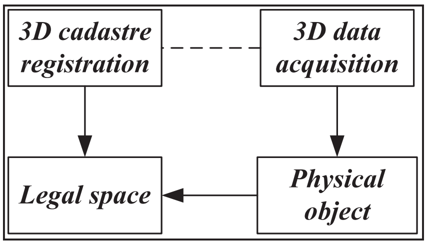


Figure 1.2.3.1 Research conceptual framework

- **Cadastral registration:** Before assessing the suitability of one data acquisition method for 3D cadastre registration, we have to realize that 3D cadastre is a complex definition which has to take the legal rights and restriction on the 3D property into account. In addition, the implementing measures of 3D cadastral registration are different due to the differences in the legal systems of countries (Stoter and Oosterom, 2006). Therefore, the analysis of what type of legal object exists in the legal framework is an essential step in the research of the 3D cadastre.

To register the legal objects defined in legislation, the analysis about the demand and suitability of registering the legal objects in the third dimension will be carried out. Here, questions about what type of 3D object could be reconstructed or modelled in a 3D cadastre spatial model, and how to register their 3D situation in cadastre should be examined.

- **Legal space and the physical object:** The physical model and legal space are two forms of expression that are related to 3D objects. To represent the registered property in 3D cadastre model, the differences between the physical representation of the real object, and the registration of legal space which is required by the physical objects have to be understood (Doner et al., 2010). Currently, the 3D model and the spatial information for physical objects in more and more countries are available and maintained in the geo-datasets (Doner et al., 2008). These data cover the spatial description of the buildings and the utilities and can be referenced as the cadastre registration.

- **3D data acquisition:** In relation to the 3D property registration, the approaches of capturing 3D object should make it possible to reconstruct physical objects and represent them in 3D cadastre spatial model. In this stage, the suitability of the proposed 3D data acquisition approach for 3D cadastre registration should be examined and assessed. Issues about whether this data acquisition approach could fulfill the requirement of 3D cadastre, what approach can be applied to reconstruct 3D object for cadastre use and what data source are needed to support cadastre registration in 3D situation, will be evaluated.

1.5. Research approach and methodology

1.5.1. Research approach

The next figure presents the main phases involved in the research:

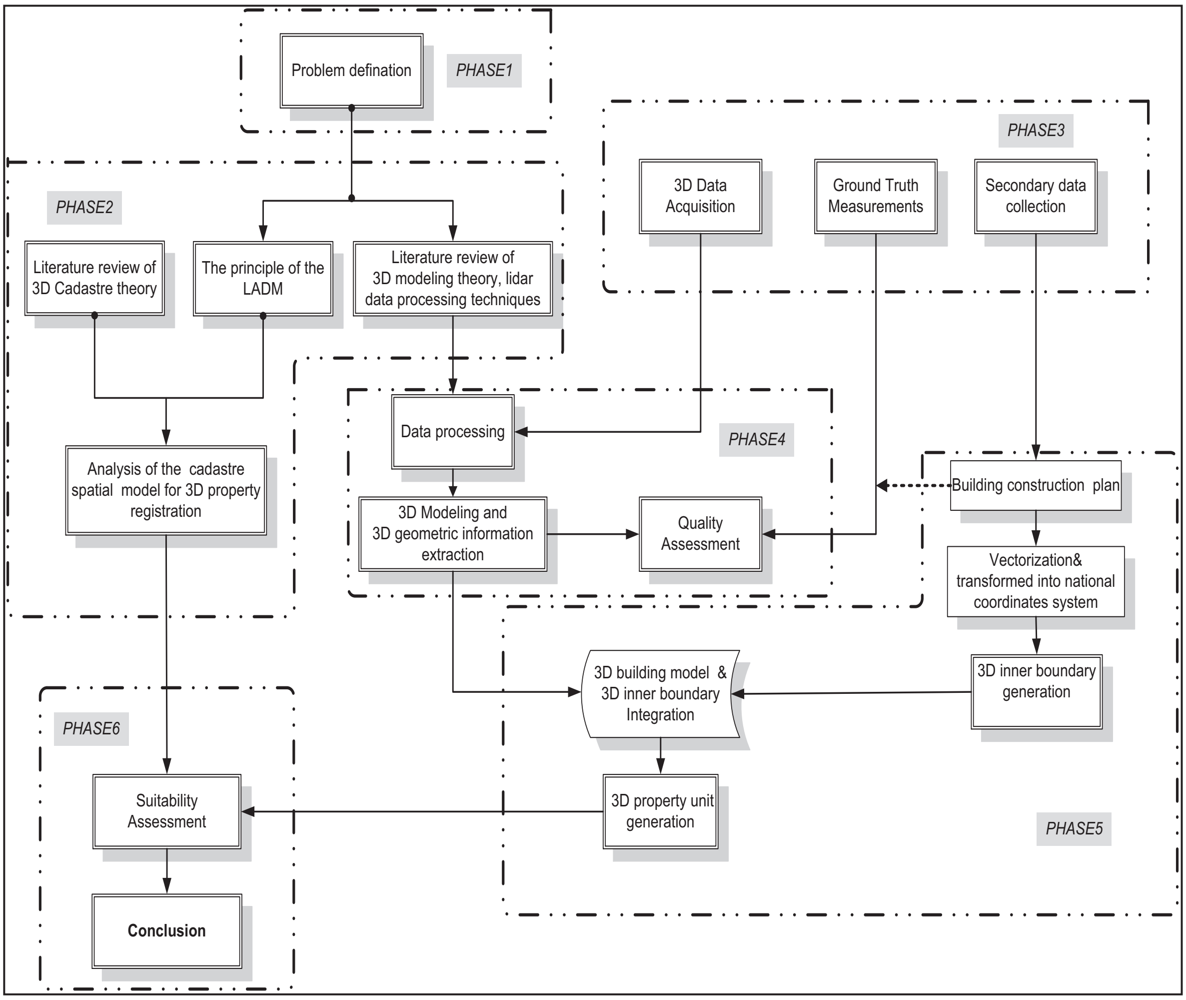


Figure 1.5.1.1 Research approach

To achieve the objective of the research, a study of the assessment of Lidar data in 3D cadastre in Istanbul is carried out. MLS data and facade mapping are used to reconstruct 3D physical objects and then the accuracy of the result and suitability of this approach in the 3D cadastral model are evaluated. The following section presents a more detailed explanation of the proposed approach.

Phase 1 Research proposal

In the stage of research proposal writing, the research problem, objectives and strategy for the research are formulated. To achieve the objectives of the research, the research questions are defined.

Phase 2 Desk research

This stage consists of literature review and background information analysis of 3D property registration in cadastral system. The aim of this stage is to analyze the different forms of the 3D property and to deepen the understanding of the legal requirement of the 3D property registration.

In the first step, the types of legal object existing in the legal and cadastre framework is reconstructed. Based on the cadastral requirements of legal object registration, the 3D data acquisition and processing approach will be selected. In this research, MLS data and building construction plans are used. The literature review of laser scanning technique and desk research about 3D spatial object modelling and processing are applied.

Phase 3 Field work and data collecting

The study area is located in the historic city centre in Istanbul. According to the accessible laser scanning data, a typical building is chosen as research object. In addition, the secondary data, including the building construction plan, cadastral map and cadastral database recording are collected for the 3D property unit model and registration.

Phase 4 3D physical object reconstruction and accuracy assessment

This stage involves the 3D object reconstruction, 3D geometric information extraction and accuracy assessment for cadastral purpose. MLS data are used to reconstruct 3D physical objects and then the 3D information such as floor position and balcony structure are extracted from the 3D model.

And then, a quality assessment is implemented. By comparison of the truth value of the build and the measured length from the 3D model (by calculate the mean value and the standard deviation), the accuracy of the geometric structure of the 3D model is assessed.

Phase 5 3D property units modelling

The fifth phase of this research focuses on the physical building modelling and the apartment units generation.. Here, these two data sources are proposed to manipulate separately by implementing different data processing methods. Firstly, the floor location on the building façade are extracted from the physical building model and generated into floor surfaces of the building. Secondly, the construction plan will be introduced and generated as inner boundary. By integrating these two models, the result gives a better understanding and demonstration for individual 3D property unit registration in 3D cadastral domain.

Phase 6 Conclusion and thesis writing

This research will be mainly conducted from 2 perspectives: the theoretical analysis of 3D cadastre spatial model and the experimental assessment of the application of MLS data in 3D cadastral domain. By analyzing the output model and result, the suitability of the proposed approach is concluded here. In addition, the research questions are revisited in this step.

1.5.2. Research methodology

Table 1-2 Research methodology and data resources

Research questions	Method	Data resources
What are the benefits of registering a property unit in 3D?	Review of 3D cadastre theory and analysis of the cadastral model for 3D property registration. Review the theory of 3D spatial modelling and defining the legal object will be modelled. Studying of the International Standard LADM	Scientific articles and publication.
What kinds of data should be introduced for representing building units in 3D cadastre model?		
What is the advantage of integrating the physical building model and spatial data into LADM for building units registration?		
What type of building information could be reconstructed from MLS data for cadastral purpose?	Processing of laser scanning data and modelling of 3D physical object. Studying of the output result.	***Data :*** MLS data Building façade map Cadastre records and cadastral map of the property from the local cadastral office The building construction plan from the local municipality Photographs of the buildings from field ***Software:*** ArcGIS AutoCAD Architecture
What is the geometric accuracy of the 3D information acquired the reconstructed building model?	Extraction and measurement of 3D geometric information from 3D model by comparing with the photographs of the buildings. Assessment of model data quality and studying of the output result. Comparison of the measurements of the 3D model with truth value from the building construction plan. Collection and extraction of 3D geometric information from : ---3D inner boundary generation from the construction plan; ---Wall and façade information extracted from 3D building model; --- Building footprint from cadastre map.	
What is the restriction of MLS data for 3D physical objects reconstruction? How the application of MLS data	Analysis of the output results. Suitability of the model to be assessed in 3D cadastral registration and recommendations.	Model outcome Quality assessment results

improves 3D physical objects acquisition for cadastre purpose?		

1.6. Structure of the thesis

The thesis comprises with 6 chapters:

Chapter 1 General introduction

In this chapter, introduction and background of the research will be discussed first. The research problem, objectives and questions will be presented. In addition, the conceptual framework and research approach will also be provided.

Chapter 2 3D property registration and representation

The chapter is based on the literature review. The scope of 3D cadastre and the 3D property will be reviewed firstly, and then the representation of legal space and physical model for 3D property registration will be analyzed.

Chapter 3 3D data acquisition and modelling

This chapter consists of 3D data collection and reconstruction approaches for physical objects, and the 3D modelling and representation schemes.

Chapter 4 Land administration domain model for building unit

This chapter deals with the implementation of the physical building model into the 3D cadastre spatial model.

Firstly, the principle and scope of LADM will be reviewed, and then the approach of integrating the physical building model into LADM will be proposed. In this research, the MLS data is selected for the physical building modelling, therefore the workflow of modelling physical building and generating apartment unit will be designed.

Chapter 5 Accuracy assessment and experimental result

In this chapter, the 2D line based quality assessment for the geometric structure of the building facade will be carried out first, then the physical building model and the apartment units will be reconstructed according to the proposed approach. By analyzing the output model and data quality assessment result, the suitability of the MLS data and the building facade map will be evaluated here. In this step, the applicability of MLS data in cadastral domain will be assessed, and the approach of generating 3D property unit by integrating building construction plan into the 3D reconstructed model for cadastral registration will also be examined.

Chapter 6 Conclusion and recommendations

This research will be mainly conducted from 2 perspectives: the theoretical analysis of 3D cadastre spatial model and the experimental assessment of the application of lidar data in 3D cadastral domain. The chapter will conclude the outcomes of the research from these two perspectives and provide the recommendations for the future research.

2. 3D PROPERTY REGISTRATION AND REPRESENTATION

2.1. Introduction

The main aims of this chapter are to understand the concept and scope of the 3D cadastre and need of representation the properties in the 3D.

Traditionally, the cadastre is 2D based. When the cadastral activities come to 3D, the right in the 3D situation, the right of 3D properties must be clearly defined. Therefore, in this chapter, the scope of 3D cadastre and the 3D property are reviewed first (section 2.2), then the forms of the 3D property situation and registration are described in section 2. The 3D registration must provide the sufficient information on the 3D extent of the right, and support the integration of the geometry and spatial information of objects in the cadastral database. The legal space and physical model are two forms of expression that relate to 3D properties, the importance of representing them in 3D was mainly discussed in section 2.4.

2.2. Cadastre registration and 3D property

2.2.1. The scope of 3D Cadastre

The 2D based cadastral registration has been conducted for many years. As has been described in International Federation of Surveyors Statement (FIG, 1995) , the Cadastre

> "[…] is normally a parcel based, and up-to-date land information system containing a record of interests in land (e.g. rights, restrictions and responsibilities). It usually includes a geometric description of land parcels linked to other records."

This definition describes the land parcel as the basic entity, the ownership and the limited rights on land are registered on the basis of the parcels. However, it has to be mentioned that, although the representation of the parcel boundaries is in 2D, the rights established on the parcel show a spatial component which has effects in the third dimension. As most of the countries give the legal definition of the ownership as "from the earth centre to the sky" (Stoter and Ploeger, 2003).

With the intensification of the overlapping building complex construction and the underground utility network, it has been approved by many researches that the 2D based cadastral activities are not applicable for the complex situation (van Oosterom et al., 2001, Stoter and Ploeger, 2003) . The FIG Bathurst Declaration (FIG, 1999) also concluded that "most land administration systems today are not adequate to cope with the increasingly complex range of rights, restrictions and responsibilities in relation to land".

The 3D cadastre is referred as to

> "[…] registering and giving insight into right and restrictions not only on 2D parcels, but also on 3D property" (Stoter and van Oosterom, 2005).

This definition extends the scope of cadastre from 2D plane to 3D space, hoping to register the right and restriction of the interested space for each property, as well as to represent the spatial location of each property unit.

2.2.2. 3D Property

When discussing 3D cadastre, it is preliminarily necessary to get insight into the meaning and scope of 3D property. As defined by the Dutch researchers (Stoter, 2004, Stoter and Oosterom, 2006), the 3D property refers to "The bounded amount of space to which a person is entitled in term of right and responsibility". This definition is more specific to the legal objects (legal space) that concerns to land, without pointing out the status of physical objects that relate to the land. Based on that definition, the parcel itself can be seen as a 3D property, the rights that refer to the parcel existing in the 3D space. The research of Paulsson (2007) has reviewed the international context of 3D property's definition and scope. The definition of 3D property in her research is "A real property that is legally delimited both vertically and horizontally". According to that definition, each property is considered as a three dimensional object, the boundaries of the object divide space at each dimension then form a bounded volume with length, width and height. This definition is more apt to reflect the spatial extent and the physical structure of property, and therefore it is suitable for the 3D representation of the physical objects.

2.2.3. 3D property situation

Originally, the individualization of the property began with the subdivision of the terrain surface into independent units via 2D land parcel boundaries (van Oosterom et al., 2005). Along with the growing population in the world, the consumption and the pressure on land in urban areas are dramatically increasing. As a result, the high–rise physical objects, such as the multi-function building complex, apartments and the constructions which interlock each other are now seen everywhere. Furthermore, as the extension and supplement to urban planning and development, the underground utility network such tram system, pipes as well as the telecom network play a more and more important role in city development. Differently from the building complexes or apartments, the underground facilities always intersect several parcels but are registered as a single property. Nevertheless, their existence limits the rights of the parcel owners and therefore should be represented in the Cadastral database.

In order to describe the spatial location and status of each property unit, and to registry their ownership in complex situations, the term "3D property situation" has been introduced. (Stoter and Oosterom, 2006). Usually, the 3D property situation can be grouped as (Stoter, 2004, Mingru, 2007):

(1).The above ground objects

- ✓ Apartment units
- ✓ The complex constructions (on top of each other)

(2).The underground objects

- ✓ The underground constructions
- ✓ The underground utility networks

2.3. 3D property registration

Based on the definition of 3D cadastre (see 2.2.1), it can be concluded that the right of land has spatial effects in three dimensions, which is not limited by parcel boundaries on the 2D surface. Practically, a property is always denoted as the building or construction associated with land (Kalantari et al., 2008). Therefore, not merely the demarcated land parcels have 3D characteristics, the real property objects, which locate above or beneath the land, also divide the space into individual property units. They also have spatial components and should be clearly defined in the cadastre system.

It has to be noticed that there is no standard or clear definition of the concept of 3D property. The scope and description of the 3D property "vary from country to country" (Stoter, 2004, Paulsson, 2007).

Therefore, whether a physical object has to be represented in the cadastre system is mainly determined by its national cadastral or legal framework. Paulsson (2007) discussed types of 3D property units registration in the context of the legal and international cadastral framework. Based on the extent of right, the (1) condominium property and (2) independently owned 3D property were introduced in her research.

2.3.1. Condominium property

According to the ECE Guidelines on Real Property Units and Identifiers (UNECE, 2004):"The third dimension facilitates subdivision into strata, creating separate 'parcels' above or under the original surface area". The building floors are the most common "parcels" that are erected above the land surface dividing the space into layers.

Currently, some countries have already amended laws and regulations in order to definitely demarcate the 3D space of properties in the vertical dimension. In most cadastral systems, the condominium or strata titles are used to represent the 3D property units within one physical object (building) (Stoter and Oosterom, 2006). Building complexes and apartment units are two types of condominium properties that can be defined as the follow:

(1) **The building complex** registration is mainly implemented in Germany, Denmark and Switzerland (Eriksson, 2005). Commonly, the building object is subdivided according to the different functions and registered in terms of floors. Mostly the ground floor is for commercial or industrial use whereas the upper stories are for residential purpose. Moreover, for each floor is composed of individual sections and shared property.

(2) As has addressed in many researches, **the apartment complex** is the most common form of 3D situations and it is a specialization of building complex (Stoter and Oosterom, 2006), and it is kind of shared property that is used for residential only. There are two systems to establish the registration of the apartment complex ownership: the dual system and the unitary system (Stoter, 2004).

The dual system is widely adopted for building registration in most of the European countries including Germany, Denmark and France (Paulsson, 2007). The apartment complex is composed of privately owned units and jointly owned parts. Each apartment owner has the full ownership of his unit, which is registered independently as a real property. The common part of the building such as the entrance, stairs and the ground land are held in co-ownership.

The unitary system is described as a co-ownership model, which means all the apartment units' owners jointly own the whole building and the land parcel. The ownership is not separated by the physical wall and floor; hence each individual is entitled to the right of using certain part of the building with the exclusive right. The unitary system is used in countries such as The Netherlands, Norway and Switzerland (Paulsson, 2007).

2.3.2. Independently owned property

The term of independent property exists in some countries is used to register the ownership of a property separately from the underground land and the rest of the real estate (Paulsson, 2007). Unlike the condominium properties that have strong relationship between the land and the physical objects, the "independent" emphasizes the status of one property that exists individually. The independently owned properties do not have common parts and their rights have no connection with the land beneath. There are two types of independent 3D property that can be defined: air-space parcel, and 3D construction property.

(1). The air space parcel could only comprise a volume of space in some legislation, without any bound to a physical object such as a building or a construction. This type can be found for example in Unite States, New South Wales, Australia as well as in Queensland, Australia (Paulsson, 2007).

(2). The 3D construction property is also defined as physical property, the owner of which is different from the intersected parcels. The constructions under, or above the surface are the most common examples of the 3D physical properties. They cross the neighbouring parcels and are represented in the cadastre system independently (Stoter and Oosterom, 2006). It is mainly applied to registry and to reflect the physical objects themselves, namely the object itself is registered in cadastre but not the 3D legal space. The typical example can be found as the construction property registration in Norway as well as the building registration in Sweden (Eriksson, 2005).

2.4. 3D Representation of legal space and physical objects

2.4.1. The need of 3D representation

In the 3D cadastre, both the land and the bounded space in three dimensions have to be taken into consideration when they are related to legal status of real property objects. The requirement of 3D arises because the location of these objects causes overlapping rights in a vertical dimension (Katerina et al., 2003). As mentioned in the section 2.2.3 , the main properties in cadastral registration have 3D characteristic are the building complexes, apartment units, the above ground constructions as well as underground objects such as tunnels, cable lines and network utilities. However, currently, the dominating cadastral registration systems are 2D based, the footprint of constructions and parcel boundary are marked on the plane in terms of their X, Y coordinates, and the height information is labelled as figures. This type of representation has shown the limitations in establishing the right for 3D constructions (e.g. locating the depth of the underground facilities, the absolute height information of apartment units) (Stoter, 2004, Stoter and Ploeger, 2003).

In order to tackle this issue and further fulfil the requirements of 3D cadastre "Registering and giving insight into the right and restriction on 3D property unit" (Stoter and Oosterom, 2006), the 3D representation of property structures as well as their situations, such as the physical objects are established vertically on the same parcel, become important. The 3D represented model reflects the geometric structures of the physical object, the introduction of which can help to clearly identify the 3D situation and the legal space of each property. More importantly, when it comes to building objects or constructions concerning the land, the geo-referenced 3D physical model could be used to identify the spatial position (coordinates X, Y, and the absolute height) and the 3D situation (see 2.2.3) of the properties, as well as their relative positions (e.g. next to, composed of). In the case of an apartment complex and a building complex, the 3D representation of a building object can demonstrate the 3D situation of properties; the physical volume of each object can also be defined or calculated.

2.4.2. The legal registration of the space

To be able to indicate the 3D property situation, the objects should be represented in the form of 3D model. Here, the difference between the description of the legal space required by a property and the representation of physical object itself should be defined.

The 3D property refers to "the bounded amount of space to which a person is entitled in term of right and responsibility" (Stoter, 2004). The legal space of the property is based on the registered record but not always the same as the real structure of the object itself. The typical example is the "air parcel" (see section 2.3.2), which could only comprise a volume of space in some legislation, or the registration of the networks/utilities (see Figure 2.4.2.1).

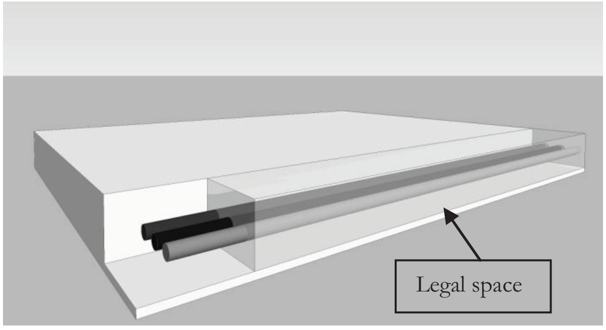


Figure 2.4.2.1 The legal space of the underground utilities

In the case of the Netherlands, the network of pipes and cable lines are registered and assigned identifiers (ID) in cadastre. The legal space (covering the safety zone) related to the utilities is recorded in the cadastre dataset. On the other hand, in order to realize the physical representation and define the accurate location of the actual objects, the spatial description of the underground utilities could also be maintained in the relevant databases (the physical model of the construction is registered in other systems and they can also be queried by cadastre database) (Stoter and Ploeger, 2003, Doner et al., 2008)

2.4.3. The physical representation of the spatial object

The legal space in the cadastre is defined as a space within which the physical object owner is entitled to a right of ensuring the property; the extent of legal space is not always the same as the physical boundary of the object (Stoter and Oosterom, 2006). In the converse, the 3D representation of a physical object is the geometric and spatial description of the unit itself (Stoter, 2004); it could be used for reference purposes and to support the cadastral task.

In the cases the physical property registration in some cadastre system, such as the 3D construction property in Norway (Stoter and Oosterom, 2006) or the building registration in Sweden (Eriksson, 2005), the 3D geometric information of the physical objects themselves are maintained in the cadastral datasets; the extent of the physical object is the equivalent of the legal space of the property unit. As for the case of the building complex or the apartment complex, each property unit within the building is a physical object which reflects a bounded volume of right in space. The position of each floor and floor to floor height affects the limits of the right at the upper and lower levels. For the accurate 3D representation and registration, the 3D geometric information relating to the property boundaries in all dimensions (including both the inner wall and the exterior structure of the building object) should be maintained or accessible in the cadastre dataset.

2.5. Conclusion

In this chapter, the scope of 3D cadastre and the 3D property were review first, and then the forms of the 3D property situation and registration were described. Finally, the importance of representing the property units in 3D was mainly discussed.

The legal space and physical model are two forms of expression that relate to 3D properties. The legal space of the property that is registered in a cadastre database relates to the administrative boundary or the required safety zone around the object. Therefore, for the 3D representation, the boundaries of the legal space are not always spatially overlaid with the physical structure of the objects.

In order to define the legal space that a cadastre requires, the 3D represented physical models could be used as the reference to define the legal space for the cadastre usage (such as the spatial operation "buffering", "overlay" in the geo-database). As mentioned by Van Oosterom (2006), land administration itself "Has a strong relation in the sense of legal space and physical object; the presence of physical objects leads to a restriction in area or space (2D or 3D) in the land administration" (which refers to the legal space). A 3D represented physical model with sufficient geometric information could reflect the 3D situation and define the spatial extent of the property units. Therefore, the 3D geometric information of physical object should be available in the cadastral dataset.

Buildings are the main objects in cadastral system with 3D characteristics. In the last decades, lots of studies have been conducted for the spatial information acquisition and manmade objects reconstruction. The approaches of 3D data collection and reconstruction for physical objects especially the building object are discussed in the next chapter.

3. 3D DATA ACQUISITION AND MODELLING

3.1. Introduction

Buildings are regarded as the most important objects in reality for this study. Modelling and reconstructing the building objects into 3D have been implemented in different domains such as urban planning and 3d city visualization. From cadastre point of view, a building model with sufficient geometric representation and spatial relationship is the premise of precise registering 3D properties. In this chapter, the 3D data collection and reconstruction approaches for physical objects especially the building object are reviewed first in section 3.2, then the 3D modelling and representation schemes are described in section 3.3;

3.2. The 3D data acquisition approaches

Remondino (2006) defines the 3D object modelling as the two step process, it begins with data and information collection and finishes with a reconstructed physical model which can be interactively viewed in the computer and accessed on the internet. In the recent years, the spatial data collection technique has shown a rapid development. Several methods and techniques can be applied for spatial data collection, from the conventional ground based surveys, photogrammetry, to different types of remote sensing scanners including panchromatic aerial photo, remote sensing images, airborne or ground based laser scanning. Meanwhile, the data quality has also enhanced. Based on the data acquisition mode, the following techniques are mainly applied for 3D data acquisition and the physical object modelling.

3.2.1. Image based approach

The image based modelling is the predominant approach applied in the 3D building modelling. Generally, the image-based 3D modelling approach consists of the following steps (Remondino and El-Hakim, 2006):

- Images orientation and calibration;
- Measurement of the corresponding points on multi-images of the same scene;
- 3D object modelling
- The texturing and visualization.

Depending on the imaging method and the imaging distance, two categories of images are mainly introduced for 3D building reconstruction: aerial images and terrestrial images.

3.2.1.1. Aerial image based 3D data collection

The aerial photogrammetry is an important tool to acquire the 3D data in the urban area; it usually refers to vertical or oblique images captured from long distances with airplane.

This approach is mainly applied for building detection. By interpreting the overlapping part of stereo pairs, the building height can be extracted. Moreover, in the work of building reconstruction from aerial images, the roof facets can also be modelled (Zlatanova et al., 1998). Currently, it still has difficulties for reconstructing the buildings by taking the aerial images as the single data source (Süveg and Vosselman, 2004). The approach of capturing and processing data using aerial images require human interaction (Malin and Light, 2007). Another factor that has to be considered is the incomplete representation of the building facades. Moreover, the flight plan as well as the image quality is strongly affected by the weather conditions (Collier, 2009). Süveg (2004)and Brenner (2005) mentioned the multiple data fusion combined different types of data sources like the remote sensing images, DEM data, Lidar data, cadastre map or the existing GIS file could improve the speed of the data processing; it could also enhance the accuracy and reliability of the extracted model.

3.2.1.2. Territorial image based 3D data collection

The territorial image based modelling is a technique for reconstructing 3D objects from the digital images or photographs which are captured at a close range from different angles. It is also call as "Close-range photogrammetry" (Collier, 2009). By using a sequence of overlapping images that taken from different position, the 3D coordinates of points can be measured then the 3D objects modelled.

Basically, the principle and procedure of terrestrial image capturing and 3D spatial object modelling are the same as the photogeometry. The advantage lies in the inexpensive equipments and the effective project flow (Remondino and El-Hakim, 2006). Moreover, the terrestrial images are taken from a close position thereby the resolution is higher than the aerial approach; it could also be applied in the indoor environment.

However, this method differs from the aerial photos which are mainly used for the building height and roof structure reconstruction, the ground based images show the limitation for modelling the top part of the high-rise construction. Taken from the ground, the roof part is not covered by the images. In addition, the reference points (corresponding points) must be covered by the overlaid images for the camera calibration, the whole process is semi-automatic and time consuming.

3.2.2. Laser scanning approach

Laser scanning technology for surveying and modelling has been extensively applied and developed in the last decades. This approach is based on laser range-finding measurements of the distance between the sensor and the targeted objects (Pfeifer and Briese, 2007). Operated from airborne platforms or from terrestrial platforms, the 3D scanners capture and record the geometric information of the object surface by using a closely spaced grid of points, namely the point clouds (Pfeifer and Briese, 2007, Vosselman, 2008, Palmer and Shan, 2002). By calculating the travel time of the laser, the position in 3D space of each scanned point on the object surface can be established. These point clouds data can be then exported into the 3D software and used for the objects extraction and reconstruction in the post processing stage (Arayici and Hamilton, 2005).

3.2.2.1. The principle of 3D measurement

Three kinds of approaches are mainly applied to detect the distance between the target object and the scanner: pulse round trip measurements, phase based measurement and the triangulation-based measurement.

In the pulse round trip measurements, the laser energy is repetitively emitted in forms of short pulses. Upon the emission, a time counter assembled in the system starts timing until receives the echo signal. The distance between the laser scanner and the detected surface is calculated by multiplying half of the time interval (Δt/2) and the light wave propagation velocity (Cg):

$$r = c_g * \Delta t \big/ 2 \qquad \text{(Equation 3-1)}$$

Together with the detecting angle which between the laser beam and laser emitter, the 3D coordinates (X, Y, Z) of the detected surface can be calculated (Vosselman and Maas, 2010a, Pu and Vosselman, 2010, Pfeifer and Briese, 2007).

Unlike the repetitively emitted laser pulses mentioned above, the phase based measurement applies a continuous wave laser as carrier for power or signal modulated on it (Pfeifer and Briese, 2007). By comparing the emitted laser beam and the received echo signal, the phase difference between two waves can be obtained, and then the time delay and range can also be calculated.

These two approaches can be grouped as "light transit time and estimation", which is based on the principle of light wave and its propagation velocity. Both of the measurements can achieve millimetre level precision (Pfeifer and Briese, 2007). With the character of continuous wave modulation, the phase based system tends to have high data rate (points per second), but the range is short than the pulse round trip measurements. For example, the phase based Leica HDS4500 has the scanning speed of 500,000 pints per second, the range of 50m and the range accuracy of 5mm/50m., whereas the scanning speed is only 1800 per second for the pulse based HDS4300 (Leica, 2011). Both of these approaches are applied in terrestrial laser scanners. As most ground based laser scanning projects are carried out on the streets which have relatively lower requirement of laser range (less than100 meters), the phase based system is more commonly applied.

The triangulation-based measurement follows the cosine law, and the range is determined via angle measurement. This approach has typically high 3D precision which can achieve 1mm or even less, but the range is limited within a few meters (Pfeifer and Briese, 2007). Therefore the triangular measurements is specified for the small products or artworks scanning (Pu and Vosselman, 2010)

3.2.2.2. Airborne Laser Scanning system (ALS)

To be able to record the 3D position of the airborne platform as well as the accurate attitude information, the GPS receiver, and the Inertial Measurement Unit (IMU) are composed together with the laser scanner in a ALS (Pfeifer and Briese, 2007, Vosselman, 2008). For each emission of the laser pulse, the position and orientation of the platform are recorded by the 3D measurement devices. By calculating these 3D measurement together the travel time of the laser pulse, the 3D coordinates of each reflected points (echo) can be acquired.

The ALS is primarily applied for the digital terrain model acquisition (Vosselman, 2008). In the meantime, with the improvement of the laser scanners technique, dense point clouds and sufficient information can be obtained from the returned laser pulse, ALS has been applied for 3D building extraction (Vosselman and Maas, 2010a). As each point is geo-referenced, the Lidar data can then be integrated with other data sources such as the cadastre map in the GIS environment for 3D city modelling (Palmer and Shan, 2002). Recently, the automatic approaches for point clouds data classification as well as for 3D geometric models of the buildings reconstruction have been extensively studied, the relative work can be found in (Vosselman. and Dijkman., 2001, Oude Elberink and Vosselman, 2006, Oude Elberink, 2010, Verma et al., 2006).

Surveying from the high altitude, ALS is feasible of providing information on 3D geometry of height of terrain and buildings, as well as the roof structure. However, same as the aerial image, the acquisition of building façade and the footprint from ALS data are not complete if the roof overhang presents (Rutzinger et al., 2009). Due to this reason, to be applied for the 3D building reconstruction in the cadastre domain which requires the façade information including the floor-to -floor height and the overhang balcony to define the property units as well as the legal space, the ALS data shows its limitation.

3.2.2.3. Mobile Laser Scanning System (MLS)

To reconstruct the 3D city model, including the detailed geometric description of the building facades, the ground based laser scanning technique became a promising approach. Mounted on the top of the vehicle, the laser scanners facilitate capturing and recording the spatial information of the urban facilities along the streets at vehicle driving speeds. Many researchers have been undertaken to ascertain its potential possibility for ground survey (Kersten et al., 2009, Barber et al., 2008, Arayici and Hamilton, 2005, Jiaxiang et al., 2008). Recently, the MLS technique has been applied in some digital 3D city model projects such as the "Historic Peninsula Project" in Istanbul (Buhur et al., 2008).

The full process of MLS data acquisition including: project mission planning, data collection, scans geo-referencing and registration, and post processing.

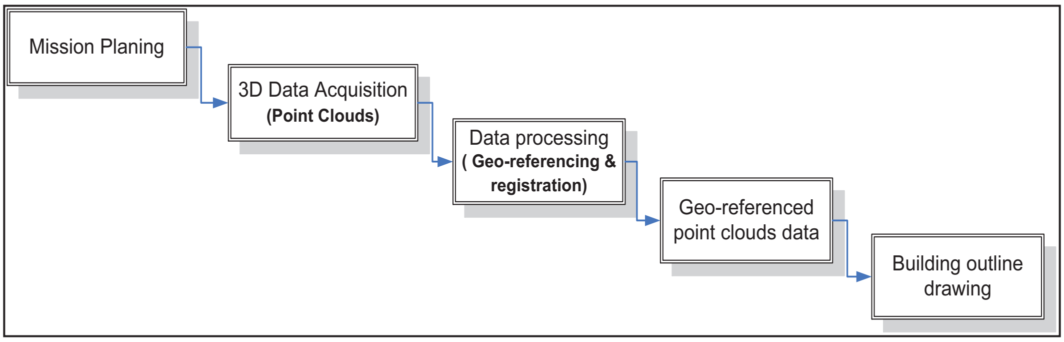


Figure 3.2.2.1 Mobile laser workflow

(1) 3D data collection

The MLS collects laser measurement data continuously throughout each MLS run. The systems use the devices including a laser scanner(s), Global Navigation Satellite Systems (GNSS) receiver and the Inertial Measurement Units (IMU) to produce accurate and precise geo-spatial data from a moving vehicle (Pu and Vosselman, 2010) (see Figure 3.2.2.2). When the vehicle is moving in the street, the GNSS and IMU data collection work is performed simultaneously during the scanning process. By combining the laser range, scan angle, the positional and orientation information of the vehicle platform, the spatial coordinates (X, Y, and Z) of each individual pulse can be accurately calculated. The geospatial data, in the form of point clouds, are generated by the laser scanner(s) according to the scanner positions (Pfeifer and Briese, 2007). In addition, to be able to capture the images of the scanned street, the system is also combined with digital camera taking overlaid photos along the street.

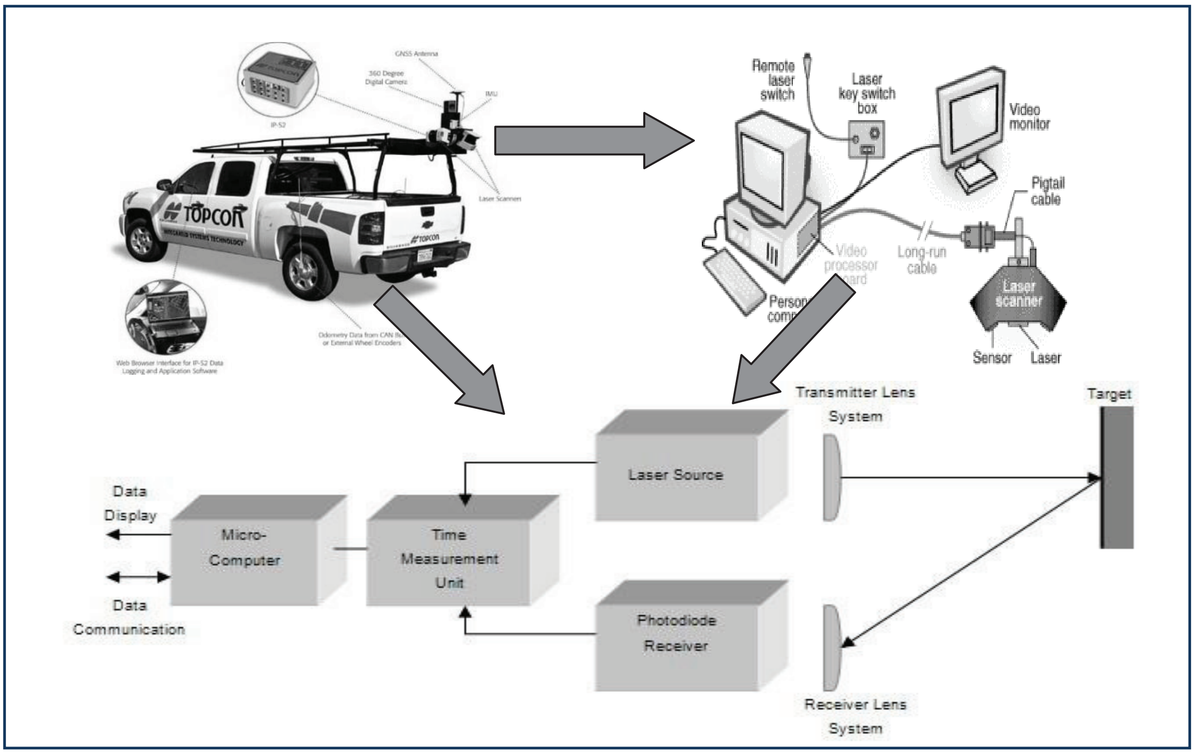


Figure 3.2.2.2 A standard design structure of MLS system (Pu and Vosselman, 2010, Topcon, 2010)

(2) Geo-referencing and registration

The registration is the procedure of integrating a set of scans of point clouds together or transforming them into the global or project coordinates framework (Shan and Toth, 2008).

When the mobile system drives on the street, the laser scanner is recording the reflected signals while the GPS and IMU devices are calculating the geo-spatial data at the same time. As mentioned in the section 3.2.2.1, the accuracy of the laser scanner instrument are within few centimetres, therefore the overall accuracy ()of the integrated MLS depends largely on the accuracy of the navigation solution (Ussyshkin and M. Boba, 2008). However, the GNSS or GPS shows vertical accuracy limitations, especially when the surveying and mapping project is conducted in the narrow streets of urban areas, the reception of GPS signals are always affected or even blocked by the barriers such as the high-rise buildings or trees (Zhao and Ryosuke., 2005, Ishikawa et al., 2007). To achieve the better accuracy of the collected and adjusted point clouds data, the control-points-based registration task should be conducted first.

Adding the artificial targets on the building walls as the control points along the street is the most widely applied method for MLS data registration (CALTRANS, 2010). Each artificial target is measured by total station before or after the MLS survey, and then its 3D coordinates can be calculated by using the geodetic methods. By computing the residential between the coordinates of the control points (targets) and the corresponding points from the laser scanning data, the transformation parameters including the translation, rotation and the scale factor can be defined. Afterwards, these parameters are applied to the point clouds to adjust the rotated or inclined planes (such as the building facade, see Figure 3.2.2.3, right) and then produce the geo-referenced spatial data.

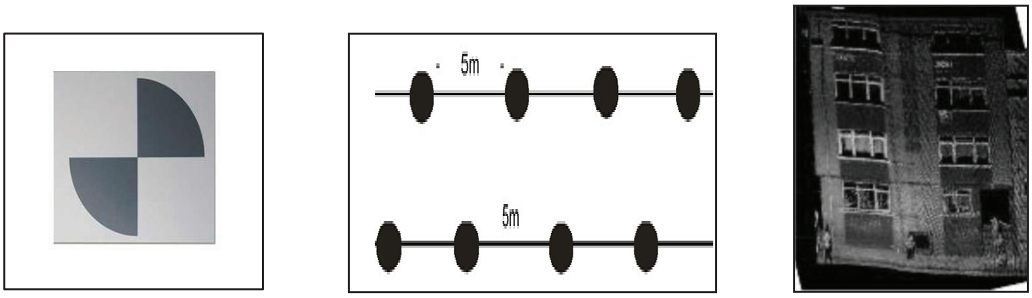


Figure 3.2.2.3 The artificial target (left); Distribution of targets in the streets for MLS scanning (middle); Inclined building facade caused by the incorrect scan data registration (right) (Buhur et al., 2008)

In the final step, the independent validation points are introduced to assess the geospatial data adjustment to control points (CALTRANS, 2010). The validation points are also placed in the surveying area and are measured together with the control points by using a total station. Their coordinates are used for the accuracy assessment. The final scan values are compared to validation point measurements to check whether the accuracy of the mapped façade fulfil the project requirements.

(3) Data processing

Unlike the raw data that directly exported from the scanner, the registered point clouds data are spatial adjusted by using the local transformation parameters, each of the point has the accurate spatial coordinates and therefore a series of scan can be integrated together for the post processing.

Currently, most 3D format processing softwares such as the AutoCad, ArcGIS, Z-MAP could be used for handling and further analyzing the 3D point data. The geo-referenced point clouds data can be imported into different commercial software for the interested objects detection and visualization (2D line-based building facade mapping or CAD models). Moreover, the post-processing manipulation with the imported point clouds can also be integrated with the photos or other types of data for creating value-added products.

Figure 3.2.2.4 shows the building outline drawing that extracted from the geo-referenced point clouds data. The detail geometric information and the structure of the facades are represented on the "façade map".

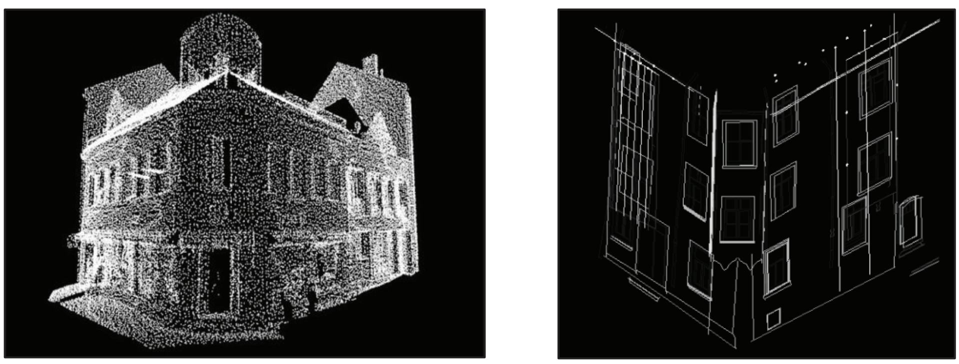


Figure 3.2.2.4 The registered point clouds data (left); The building facade mapping (right)

3.3. The 3D modelling of spatial objects

The principle and procedure of several approaches for 3D data collection have been described in the previous section. In the surveying and data acquisition stage, the observed data are saved as the raw 2D based measurements, aerial images, terrestrial photos or unstructured 3D point clouds. They are not suitable to be integrated in GIS or 3D environment with their initial formats (Koussa and Koehl., 2009).

To be able to represent the acquired objects of interest in 3D environment, the reconstruction task has to be executed in the second step. In the following section, the geometric and topological based modelling is explained first in the section 3.3.1, and then the concept about the semantic modelling is described in the section 3.3.2.

3.3.1. The geometric and topological modelling

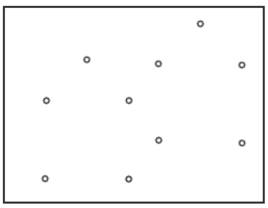
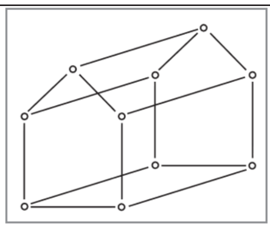
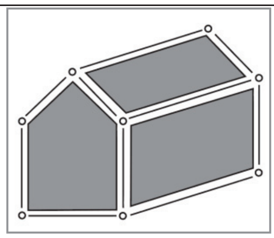
The geometric and topological modelling is defined as process of describing, manipulating and storing of the geometrical features of spatial objects by using analytical method or approximation methods (Rottensteiner, 2002). This approach describes the spatial objects from both shape and position perspective by means of the absolute geo-referenced 3D coordinates: each spatial object is abstracted as a set of vertexes in 3D space first, the geometry of a vertex is just its position in space as given by its (X, Y, Z) coordinates; the topological relationship is applied to structure lower level primitives by defining each other's neighbourhoods.

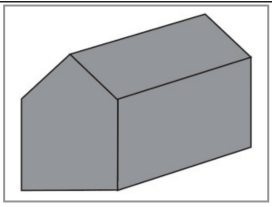
For each dimension, there is a geometric primitive that used for modelling. Based on the ISO Geographic information, Spatial schema (ISO 19107, 2003), they are defined as:

- 0-dimensional object: point (node, or vertex)
- 1-dimensional object: curve
- 2-dimensional object: surface
- 3-dimensional object: solid

Based on the topological relationship between the geometric primitives in different dimensions, four types of 3D object representations methods are defined (Rottensteiner, 2002). Table 3-1 illustrates the 3D representation scheme and characteristics of each method.

Table 3-1 3D object representation methods (Rottensteiner, 2002)

	3D object representation	Characteristics
Unconstructed set of points		• Defining an object by using a set of unordered vertices. • No topologic relationship between the points • 3D shape impression is only formed visually by the observers • Structure, size, volume cannot be recovered
Wireframe model		• Defining an object by vertices and edges. • For 3D representation, the wireframe is ambiguous
Surface model		• Defining an object by vertices, edges and faces; • Representing a spatial object in 2.5 D

Volumetric model		• Defining an object by vertices, edges, faces and volumes • Concerning with the representation of 3D solid primitives, especially for the building objects.

According to all the characteristics in the Table 3-1, for each spatial object, it can be abstracted as a set of geometric primitives and be represented in one of those ways. However, only the surface and volumetric models can be applied for the solid object modelling.

The volumetric model (solid model) defines the solid primitives, tetrahedrons in the simplest form (Koussa and Koehl., 2009). It concerns with the bounded space of the objects they occupied. Each primitive represents a closed 3D feature and it supports the calculation of volume. This approach is especially suited to the 3D building representation and 3D property unit generation in 3D cadastre (Figure 3.3.1.1).

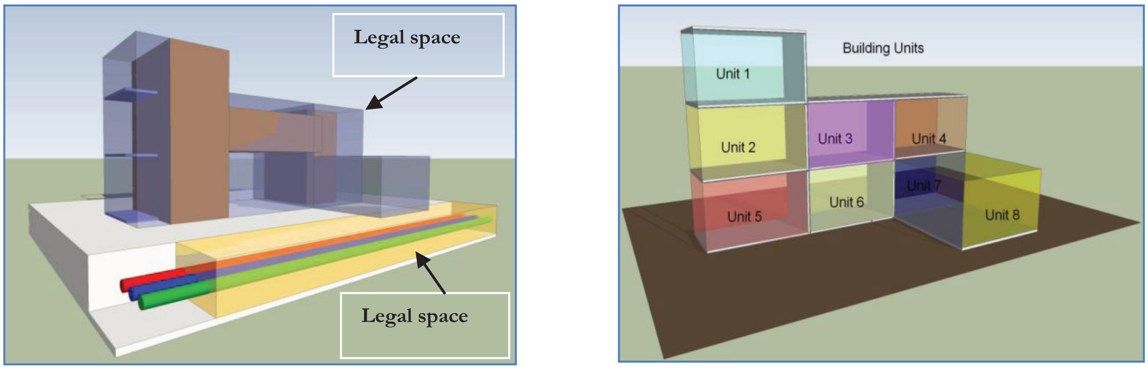


Figure 3.3.1.1 The need of solid model in 3D Cadastre: Physical building and the legal pace (left); Legal space partition by building units in cadastre (right).

Based on the form of data structuring, the same geometric and topological data can be represented in different ways. Here, two solid representation schemes, Boundary Representation and Constructive Solid geometry, which are mainly used for the regular shape modelling, are described in detail.

3.3.1.1. Boundary Representation (B-rep or BRE)

Boundary representation is the common scheme in the solid modelling and in the CAD design. In this representation scheme, each object is described in the form of the oriented surface boundary, while the surface boundary is composed of the lower dimensional elements including the vertices, edges and faces (Rottensteiner, 2002, Koussa and Koehl., 2009).

Figure 3.3.1.2 shows the geometry and topology components and their relationship in a boundary represented solid object: the model consists of geometrical data and topological data, geometry describes the exterior structure and position of each element by using the coordinates (X, Y, Z), while the topology organizes the neighbouring relationships (connectivity) among the geometric elements: faces, edges and vertices.

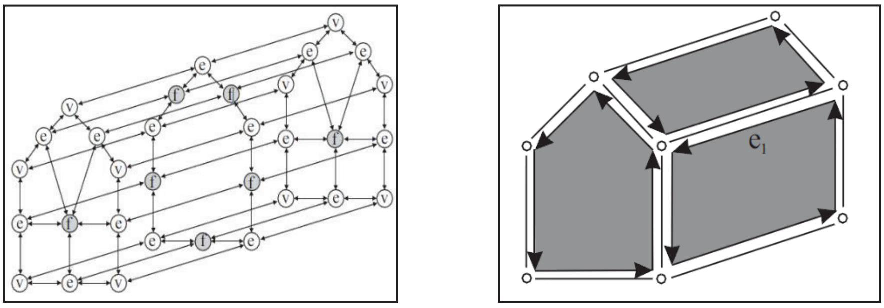


Figure 3.3.1.2 B-rep of a solid object (Rottensteiner, 2002): a model with nodes of f (faces), e (edges) and v (vertices) (left); the edges between neighbouring faces have to be saved in order, so that the surface normal of a face points toward the outside of a solid (right)

The B-rep model is a fundamental operation in the computer-aided design, the advantages can be concluded as (Rottensteiner, 2002, Koussa and Koehl., 2009):

- The B-Rep is suited to present complex objects. By defining the 3D coordinates (X,Y,Z) of each node and the topological relations, the geometric structure of the object can be well constructed;
- The volume of the solid can be calculated;
- The B-Rep model is bordered by a set of oriented surfaces; each feature (face) is explicitly stored and can be represented independently;
- The boundary faces are structured by a set of edges orderly, the inside and outside of solid are distinguished.

3.3.1.2. Constructive Solid Geometry (CSG)

In the concept of Constructive solid geometry (CSG) model, a solid is defined as a group of primitives in volumetric instances including cubes, boxes, tetrahedrons or cylinders. This modelling approach is mainly used to represent the complex construction according to geometric rules (Apel, 2004, Koussa and Koehl., 2009). The Boolean operations, Union (U), Intersection (∩) and Difference (\ ) are performed in CSG for the solid model construction (Rottensteiner, 2002).

The CGS is a powerful technique and it is especially suitable for the 3D building modelling. Theoretically, a solid object is a simple unit which is bounded by surfaces, whereas a complex solid (composite solid) is formed from a set of primitives connected by the shared parts according to the topological relations (Zhu and Hu, 2010). Based on this, a 3D building can be interpreted as the main body and the protruding part such as the eaves and the balconies (Zhu and Hu, 2010). Each unit is modelled as a volumetric primitive independently using CSG scheme, then the whole building is constructed through the Boolean operations (Figure 3.3.1.3).

Recently, in the study of building reconstruction from aerial and terrestrial imagery, the CGS was adopted. By calculating the optimizing parameters of through a set of measurements, the decomposed building objects can be modelled (Penninga, 2008).

The advantage of the CSG model can be concluded as (Penninga, 2008):

- The simple primitives can be parameterized through the scaling, translating or rotating the operation.
- Feasible to model the existing polyhedron objects.
- The CSG scheme is effective and simple for calculation with small storage space.

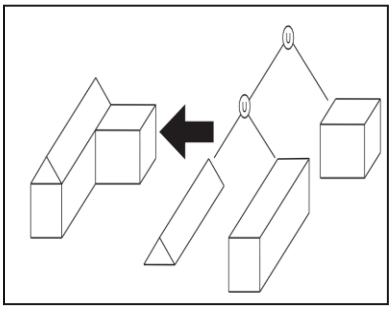


Figure 3.3.1.3 The CSG model is composed of three primitives by union (U) operation (Rottensteiner, 2002)

3.3.2. The semantic model

In the 3D object modelling, a spatial object should consist of a spatial description including geometry and topology, and a thematic description including the information or characterize that the object represented in the geographic space (Molenaar and van Oosterom, 2009). The geometric and topological based 3D object modelling has been described in the last section; this approach emphasizes the position accuracy (the X, Y, Z coordinates), the required geometric structure as well as the shape construction of the spatial object. On the other hand, when it comes to the thematic aspect, the spatial object class could also be defined first with of a group attributes on the basis of the applied domain, and then the geometry information is added.

Figure 3.3.2.1 shows the representation of spatial objects in the geo-database: the spatial objects with the same or similar characters are grouped into one object class; each object exists as an instance of a specific object class while the thematic attributes of the object class are common to all instances of that class; for each object, it is defined by a name, a thematic description, as well as a spatial description (geometry data).

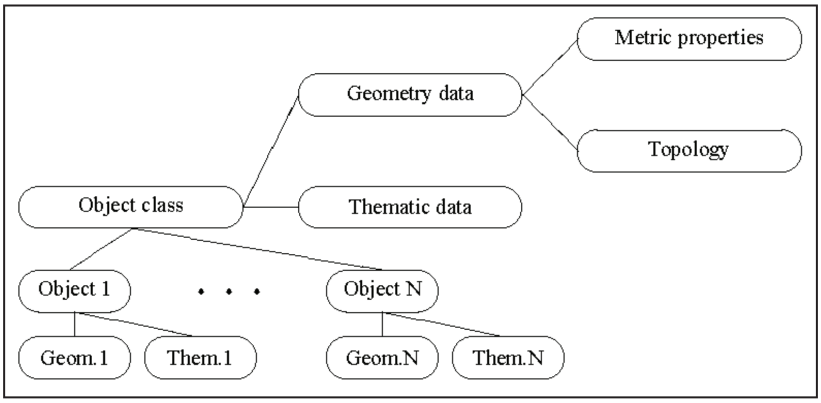


Figure 3.3.2.1 Spatial object definition according to (Apel, 2004)

Association, aggregation and classification are three types of relationship between the object classes (Molenaar and van Oosterom, 2009). The association simply indicates the thematic connections among the object classes. Aggregation is a special type of association which is used to construct a part-whole-relation between the elementary object classes. Such as the "Apartment unit–Storey-Building" for house property units registration (Zhu and Hu, 2010) or "Wall-Room-Building" relation for 3D building representation in CityGML (Kolbe, 2009). The concept of classification refers to the inherit ablity of the classes in the top-down level: the classes in the lower level inherit the identical attributes of the super class, and then the add its own unique attributes (Portele, 2004).

The semantic model represents the real-world entities by using thematic description, relations and the "part-to-whole" aggregation hierarchies between object classes. When apply it to the 3D spatial object modelling, the following rules have to be considered (Molenaar and van Oosterom, 2009, Kolbe, 2009):

(1). The thematically described objects classes divide the spatial entity into a group of segments, namely "spatial patition". In the case of classification system, each object is specified and used to represent an individual segment, therefore there must be no spatial overlap that exists between the objects in the same level.

(2). For each spatial object in the semantic model, both the spatial description (geometry data) and the thematic description are reqiured (see Figure 3.3.2.1). The selection of geometric primitive (point, curve, surface, or solid, see section 3.3.1) should coorespond to the thematic description as well as the aggregation level.

(3). For the spatial object in the semantic model, the accuracy requirement of the geometric data should defined. Such as the accuracy of the 3D location (X, Y, Z),or the precision of the measurements of the object boundary, or the required geometric detail for visualization (such as the "Level of detail" in the CityGML) (Kolbe, 2009).

3.4. Conclusion

The 3D modelling of the spatial object has been described as a two-stage procedure that consists of (1) data acquisition, and (2) the 3D object reconstruction by processing the collected spatial records in the 3D environment (Remondino and El-Hakim, 2006). In the recent years, there have been many studies on the spatial data collection and 3D object reconstruction (Remondino and El-Hakim, 2006, Malin and Light, 2007, Oude Elberink, 2010). There has no single standard to define whether an approach is good or not, or whether the reconstructed model is detailed enough. Selection of a 3D data acquisition approach should be taken under the consideration of the applied domain and the users' requirement. The factors such as the accuracy, the geometric detail, and the cost and time for data acquisition should be assessed.

For the cadastre requirements, the 3D represented model should be able to reflect the geometric structures of the physical object, and help to define the 3D property situation and legal space of the construction. In the cases of the manmade construction and building object, the overhanging eaves and balconies extent out of the footprint of the building, their existence affects the legal space or the occupied space of the object in three dimensions and therefore should be clearly modelled. Moreover, in the cases of the building complex and the apartment complex registration in the 3D cadastre, the multiple property units are established vertically on the same parcel. The position of each floor and floor to floor height affect the upper and lower boundaries of the established right for the building units in the cadastre system. Therefore, to represent each property unit, the geometric structure of the exterior wall of the building should be accurately modelled first.

Given the above requirements, the MLS which could capture and record the detail building facade information on the street level, shows its suitability of being applied in the cadastre domain. The principle and workflow of MLS data were explained in the section 3.2.2.1 and the section 3.2.2.3. The system collects the street and buildings' 3D information quickly and easily. The result could provide detailed geometry characteristics of the spatial objects with an ideal positioning accuracy (Jiaxiang et al., 2008). The table below concludes the characteristics of applying the MLS system for physical object detection in the urban environment.

Table 3-2 Advantages and disadvantages of 3D laser scanning technology (Arayici and Hamilton, 2005)

3D Laser scanning	
Advantage	**Disadvantage**
• Applicable approach for building façade detection • Rapid and effective 3D data collection • Predicable data precision • Ideal for 3D building modelling and visualization • The point clouds represent both 3D position and geometric structure of object	• Working environment and weather condition limitation (some system are not working in the sun or rain) • The post processing for an usable data output • Output needs manipulation for good recording quality • No common data exchange format in use for third parts • The complex control-points-based registration task

This chapter also reviewed the concept and different schemes about the 3D representation. Geometric structure and topological relationship, the thematic descriptions are two schemes that used to constrain and organize how the objects represented in the 3D environment. They can be concluded as (ISO 19107, 2003, Molenaar and van Oosterom, 2009):

- Geometric and topological description: describing the spatial object from the aspects of shape and location of the entity in the 3D coordinate system.
- Thematic description: including the information or characterize that the object represented in the geographic space. It should be pre-defined on the basis of the application domain.

The semantic based modelling covers both the geometric description, and thematic description of the spatial object, it can represent the same object differently according to the applied domain. This approach is mainly applied in the object based programming language and object oriented DBMS aspects (Molenaar and van Oosterom, 2009).

4. LAND ADMINISTRATION DOMAIN MODEL FOR BUILDING OBJECT

4.1. Introduction

The 3D modelling approaches have been discussed in the last chapter. The advanced data collection technique and modelling approach facilitate the reconstruction and representation of spatial objects in the 3D environment. In the processing stage, the data could be organized, stored and then represented according to the applied domain.

Land Administration Domain Model (LADM) covers various entities that relate to cadastre domain. Based on the Geographic information – Spatial schema (ISO 19107, 2003), the LADM provides a geometry and topology model for the description and representation of spatial objects that cadastre interests. A set of classes (LA_Point, LA_boundaryface string and LA_Boundaryface), which represent the geometry of the spatial unit by using the point, curve or surface primitives are presented in the LADM. Both the land parcel and the related physical objects can be described in form of 2D or 3D (Van Oosterom et al., 2006). An overview about the LADM is given in section 4.2. In the 3D cadastre, the 3D physical model provides important information for the determination of legal space and the representation of the complex 3D situation. Based on the relationship and between the legal space and physical model, a Surveying and

Representation_ PhysicalBuilding package of LADM is proposed in the section 4.3. Finally, the workflow of modelling physical building and property unit by using MLS data is presented in the section 4.4.

4.2. Overview of the Land Administration Domain Model (LADM)

The principles of Land Administration Domain Model (LADM) are mainly based on "Cadastre 2014" (Kaufmann and Steudler, 2001) and the concept of "Parcel- People- Right"(UNECE, 1996, UNECE, 2004). The model covers various entities that relate to cadastre domain; it describes the rights, responsibilities and restrictions which affect land and the spatial component (including the objects above and below the surface of the earth). More importantly, the model extends the cadastral registration from 2D base to 3D; the spatial data structure and representation scheme for 3D properties are introduced.

From the overall view, the LADM is design by using the Unified Modelling Language (UML). UML is a standard language which could structure the data model at the conceptual level; it is applied for the object-orientated or object-related model design. The LADM is defined as a conceptual scheme model and it is composed of three main packages and on sub-package. There are (1) Party Package (2) Administrative package (Rights, responsibilities, and restrictions), and (3) Spatial Unit Package. The Surveying and Spatial Representation package, which were presented as independent packages, are introduced in term of one sub_package of the Spatial Unit Package.

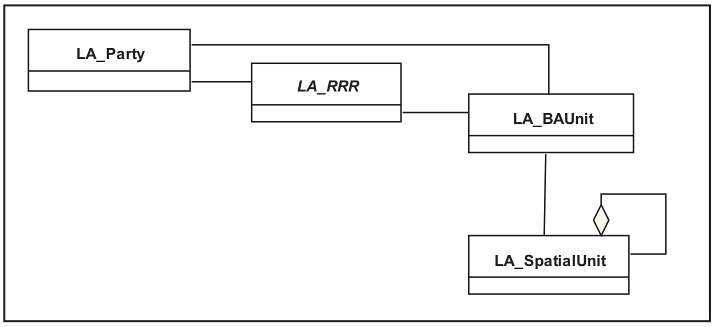


Figure 3.3.2.1 Basic classes of LADM (ISO/TC 211, 2010)

(1) Party Package

Party is defined as "a person or an organization that plays a role in a rights transaction"(ISO/TC 211, 2010). The party package contains LA_party, LA_GroupParty and LA_PartyMember. The LA_Party class is considered as the main class of the Party Package, while LA_GroupParty is a number of registered parties, each of them being a component of the group party. LA_PartyMember is an optional class here associating the LA_GroupParty and its' registered member.

(2) Administrative package

The Administrative Package of LADM, as amended and modified, contains LA_RRR and LA_BAUnit as main classes in the latest version. LA_Rights, LA_Restrictions and LA_Responsibilities are the three specifications of LA_RRR class. They have always been included since the earliest version of LADM, "Right" is defined as "a formal or informal entitlement to own or do something", whereas "Restrictions" and "Responsibilities" represent "formal or informal entitlement to refrain from doing something" and "the obligation to do something" respectively (ISO/TC 211, 2010).

LA_BAUnit (Basic Administrative Unit) is also called the Basic Property Unit, the definition could be found in (UNECE, 1996): "the extent of the land that is one unit of ownership is referred to as the basic property unit (BPU). It may consist of one or more adjacent or geographically separate parcels". In the current model (2010), the LA_BAUnit is introduced to register a group of spatial units, which under the same right (belongs to one party).

(3) Spatial Unit Package

The spatial unit of LADM is based on other ISO standards ISO19107(ISO 19107, 2003) and ISO19156 (ISO/DIS). Parcel is the classical cadastre unit. A cadastral parcel is single area of land, or it could be defined as a volume of space, under homogeneous real property rights and unique ownership (UNECE, 2004). During the development of the LADM, the class name "Parcel" has been extended into "Spatial Unit". The LADM supports multi-representation of the spatial units, from 2-dimensional (2D) or 3-dimensional (3D), to the mixed (2D and 3D). See Figure 3.3.2.2.

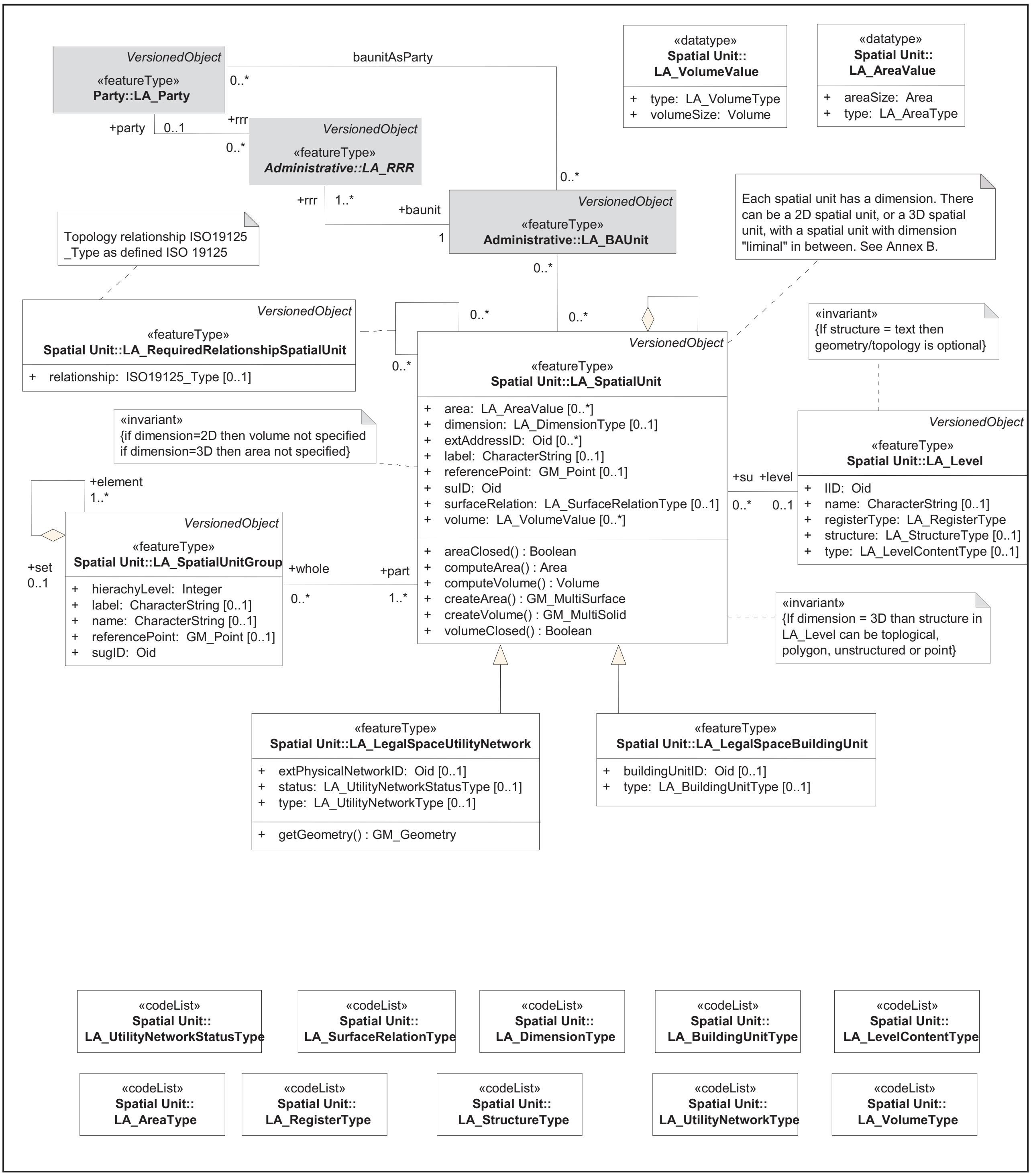


Figure 3.3.2.2 Content of spatial unit package with associations to other basic classes (ISO/TC 211, 2010)

LA_SpatialUnit is the basic class of the Spatial Unit Package; it can be grouped into:

- Spatial unit groups
- Sub spatial units

Buildings are the most important objects in reality that allocated on land parcel. In addition, together with the urban construction, plenty of public utilities and underground network are constructed. In some countries, these kinds of facilities are registered independently in cadastral system. Therefore, in the current version of LADM, two subclasses

- LA_LegalSpaceBuildingUnit
- LA_LegalSpaceUtilityNetwork.

are introduced as two specializations of the LA_spatial unit. These two subclasses share the same representation structure with the other types of spatial unit (2D or 3D parcels). Here, the building unit and the utility networks are defined from the legal entity perspective. The ISO/TC 211(2010) states that these two types properties concern legal space, which could be different from the physical structure of the building or the utility network (e.g. cable) itself.

(4) Surveying and Spatial Representation package

The surveying package is the sub package of Spatial Unit; it is composed of four classes:

- LA_SpatialSource class
- LA_Point class
- LA_BoundaryFaceString
- LA_BoundaryFace

Point is a 0-dimensional geometric primitive; each instance of LA_Point class represents an individual position in space. The points could also be used to generate boundary faces or boundary face strings. These kinds of approaches can be applied by generating LA_Point class, e.g., terrestrial surveying, aerial image/photo interpretation or existing map import.

Associating to the LA_Point class, the LA_SpatialSource is used to record a set of measurements with observations. It could be all kind of documents or information related to the survey (formal document, aerial/terrestrial photo, survey plan or the scanned paper based drawing). The Surveying and Spatial Representation package uses the classes of LA_BoundaryFaceString and LA_BoundaryFace representing 2D and 3D spatial units respectively.

In the current LADM (2010), the boundary face strings are introduced to demonstrate the boundaries of spatial units by using line strings in 2D, a typical example is the drawing of parcel on the cadastral map. This 2D based boundary could also be introduced into 3D land administration system depicting an unbounded volume, which fulfil the requirement of "supporting the increasing use of 3D representations of spatial units, without putting an additional burden on the existing 2D representations" in LADM (ISO/TC 211, 2010). A set of boundary faces are used to form a bounded volume in LADM. It is associated with the LA_SpatialUnit class, and the bounded spatial volume represents the legal space which defined by SpatialUnit.

4.3. The 3D representations of spatial object in LADM

4.3.1. The current work

To clearly describe the 3D situation and legal extent of each property unit, the LADM proposed the "LA_SpatialUnit" package with the sub classes LA_LegalSpaceBuildingUnit and LA_LegalSpaceUtilityNetwork. These three classes represent the land parcel, above ground building objects as well as the underground facilities separately. All these classes can be represented in 2D or 3D in form of LA_BoundaryFaceString and LA_BoundaryFace.

The current researches support the volume parcel and have extended the cadastre registration into the vertical dimension. In the work of Lemmen et al., (2010), the normal land parcel and the legal space around networks/utilities were represented in the LADM. The output model indicates that the 3D property unit could be displayed by a mixture of face primitives and face string primitives, and then visualized as a complete polyhedron. Moreover, the work also realizes the registration of legal space of underground facilities in 3D.

As mentioned by ISO/TC 211, the LADM should support "A very generic spatial representation model, as it has to be applicable world-wide, for a variety of spatial units" (Lemmen et al., 2010, ISO/TC 211, 2010), all spatial units may have a 3D representation. However, only the normal parcel unit and the utility network are explored in the cadastral system in some countries (Doner et al., 2010, Lemmen et al., 2010). Extending the 3D cadastre from terrain to the building unit level and registry the legal space of building complexes or apartment units have not been extensively explored. By studying the above mentioned literature, several reasons are concluded as follows:

(1) The different representation forms of the legal space and the physical object: the LADM refers to the "legal space", that is the bounding envelope of the physical object within which the owner could ensure the property of the object by means of right. The legal space could be equal to the physical volume such as the case of the registration of physical object (the construction, the building object); it could also be defined as a spatial volume which is "larger than the physical extent of the object itself (for example including a safety zone)" (van Oosterom et al., 2005). Note that the legal space or "safety zone" that cadastral defined could be invisible. They cannot be clearly defined without an accurate physical building model as reference.
(2) The complex geometric structure of the building object: the exterior structures of the building object or other man-made construction are not in a regular shape in most of the cases. The existence of the overhanging balcony affects the legal space that established for the property; moreover, it also brings difficulty for the vertical boundary modelling (the building façade cannot be represented by using a simple plane)
(3) The 3D property situation and the legal boundary: in the cases of the building complex and the apartment complex, multiple property units are established vertically on the same parcel. To clearly define the 3D property situation and register each property unit in a cadastre database, the 3D geometric information relating to the property boundaries in all dimensions should be maintained or accessible in the cadastre dataset. Currently, the apartment units are represented on the 2D based deed drawing or building construction plan, the 3D spatial information (such as the coordinates X, Y, and the absolute height) are not available.

Integrating the physical building model into the LADM provides a feasible approach for the above-mentioned issues. A 3D represented physical model with sufficient geometric information reflects the 3D property situation and defines the spatial extent of the property units. By associating with the "LA_LegalSpaceBuildingUnit", the spatial and geometric information from 3D survey products can be accessed by the cadastre dataset and used as references to support the property registration work.

4.3.2. The 3D Representations of physical building in LADM

To be able to introduce the physical model and the relevant information into cadastre dataset, a "Surveying and Representation_ PhysicalBuilding"package is proposed based on the framework of LADM in this step.

The Surveying and Representation_ PhysicalBuilding package shares the same representation scheme as the Surveying and Spatial Representation package (section 4.2); it aims to integrate the physical building model into LADM. The four classes of the Surveying and Representation_ PhysicalBuilding package are (1) Building_Point, (2) SpatialSource, (3) Building_BoundaryFaceString, and (4) Building_BoundaryFace. See Figure 4.3.2.1.

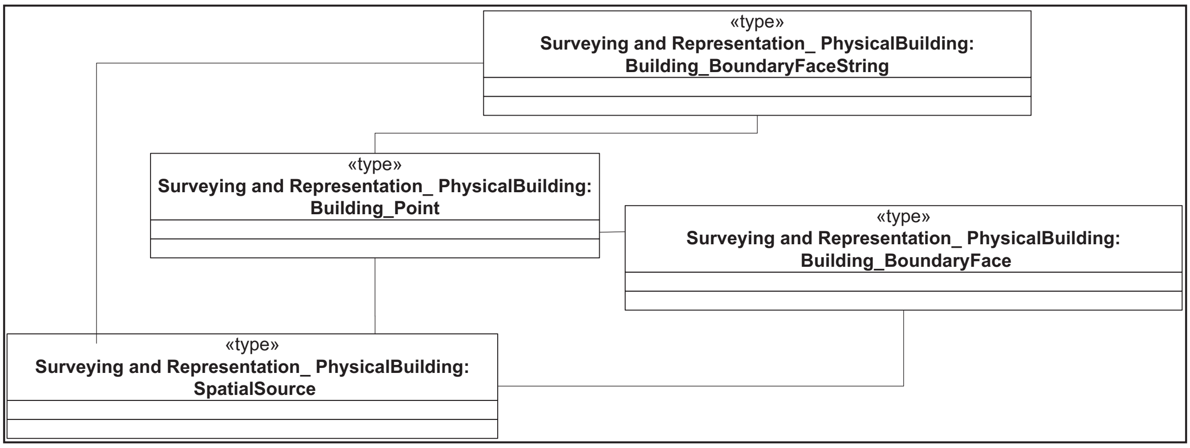


Figure 4.3.2.1 Classes of the Surveying and Representation_ PhysicalBuilding package

Building_Point is 0-dimensional geometric primitive, representing a vertex or a position on of building model. For the 3D physical building representation, the instances of the Buildingpoint class are used to record spatial information of the conjunction points (such as the corner of the floor, or the vertex of the boundary). By connecting a set of points in order, the physical structure of the building objects can be represented.

The same as the LA_SpatialSource described above, the SpatialSource class in PhysicalBuilding package is used to document the measurements of the 3D survey. The documents and data that relate 3D survey, including the project plan, the instrument calibration report, the raw data and the post processed products should be stored. Moreover, in order to integrate the physical building model into the cadastre data set for property registration, the geo-referencing procedure has to be applied. The accuracy assessment reports of both the 3D positioning accuracy and the geometric structure analysis should be documented.

The principle of Building_BoundaryFaceString and Building_BoundaryFace can refer to the LA_Boundaryfacestring and LA_Boundaryface that defined in LADM (section 4.2). They are associated with the Builing_point class and the SpatialSource class, representing the 2D boundaries (e.g. the upper or lower line of the wall) between the physical objects or the closed surface (e.g. floor surface, wall objects). In the physical building class, a set of boundary faces compose a bound volume which indicates the physical space of building objects, such as a room or one storey.

Figure 4.3.2.2 shows the content of Surveying and Representation_ PhysicalBuilding package with associations to the LA_LegalSpaceBuilding. The physical building model is maintianed in the geo-database separately and it is accessible when the cadastre required. Between LegalSpaceBuilding and PhysicalBuilding there is an optional association class: "LA_RequiredRelationshipBuildingUnit" (Table 4-1). An instance of association class LA_RequiredRelationshipBuildingUnit is a required relationship between the legal space and the relevant physical structure of the building unit.

Table 4-1 The attributes of LA_RequiredRelationshipBuildingUnit

LA_RequiredRelationshipBuildingUnit	
Relationship	The description of the required relationship
Value type	ISO 19125-2 spatial type
Multiplicity:	0..1

Note 1: Instances of LA_RequiredRelationshipBuildingUnit are based on relationship between the legal space of and the relevant physical structure of the building unit. The 3D representation of the physical building can be accessed and used for reference to support the cadastre work. The required relationship is established by performing the geospatial operation (such as the overlaying, buffering).

Note 2: For the registration of building, construction, and the property units within the building complex (e.g. the apartment units), the physical space of the properties coincident with the legal space that registered in the cadastre database. In this case, the 3D physical model as well as the spatial and geometric information can be inquired for the 3D property unit registration.

Note 3: The data collection and maintain of the physical model are not always the cadastre task. The data are organized in the other datasets in the relevant organization. The contained 3D spatial information and the 3D represented physical building model can be referred to cadastre use.

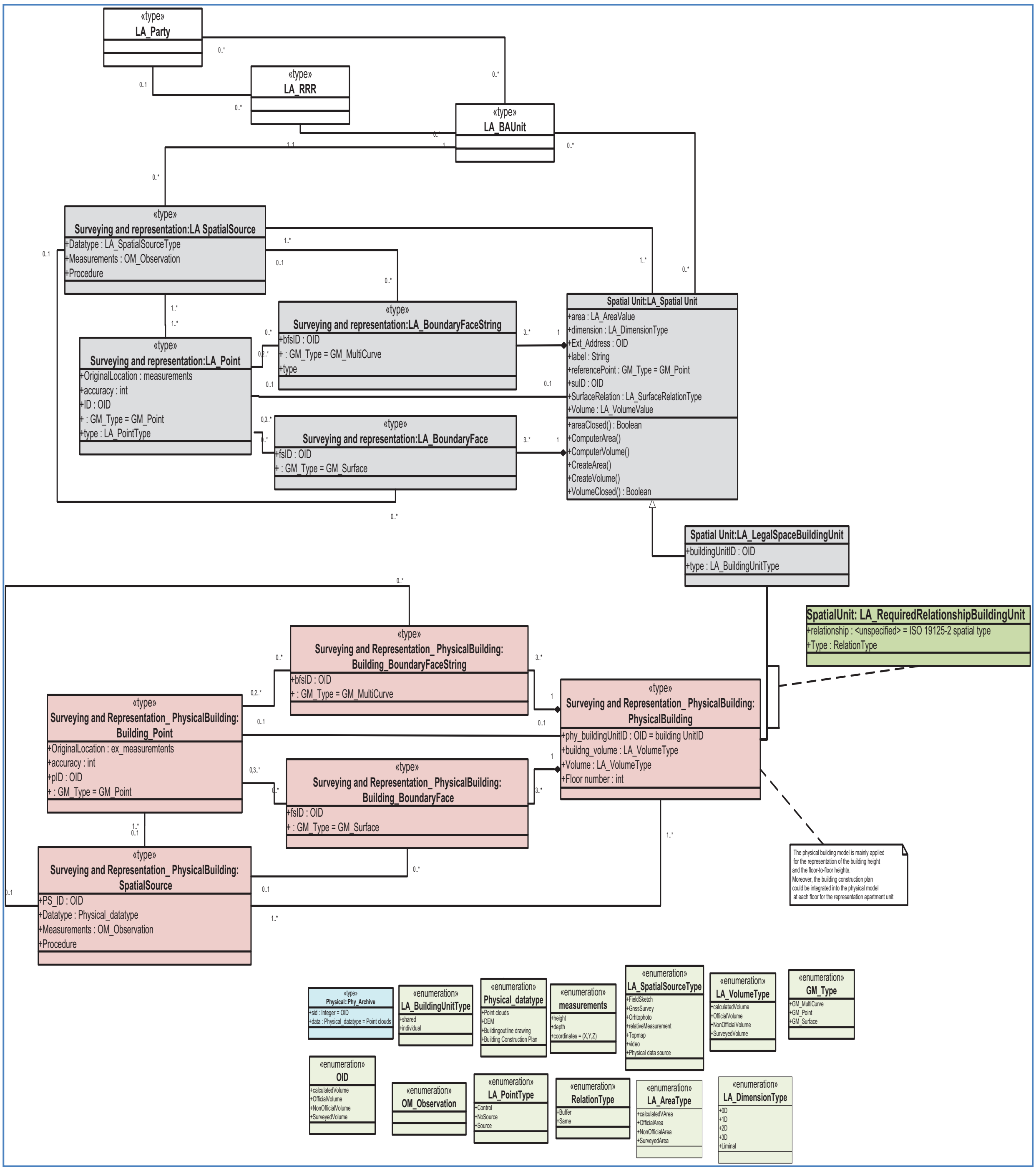


Figure 4.3.2.2 Content of Surveying and Representation_ PhysicalBuilding package with associations to other basic classes

4.4. 3D physical object modelling by using the MLS data

In the previous section, the application of physical building model and the spatial information into LADM has been described. With the integration of 3D physical building models into the LADM, the spatial and geometric description of the objects from 3D survey can be introduced as reference and the additional data source for the 3D building unit registration.

Developing with the technique of 3D data collection, many approaches have been applied for the building reconstruction. The principle and workflow of the MLS system for 3D spatial object collection have been described in Chapter 3. The MLS system could capture and record the detailed building facade information on the street level. In the post processing stage, the geo-referenced point clouds data can be imported into kinds of commercial software for the line-based building facade mapping or CAD modelling. In this research, the point clouds data and the processed facade map from MLS system are used for the physical building object modelling, then the suitability of applied the MLS data into 3D cadastre are assessed.

The implementation of MLS for 3D building reconstruction is composed of the 3 steps (Figure 4.3.2.1): quality assessment, the building object reconstruction, and the apartment unit modelling (by integrating with the building construction plan). This method will be executed in chapter 5. The accuracy report, geometric data and the physical model within each step can be integrated into the proposed Surveying and Representation_ PhysicalBuilding package in LADM. Table 4-2 shows the result of transferring the MLS data and the product into the LADM.

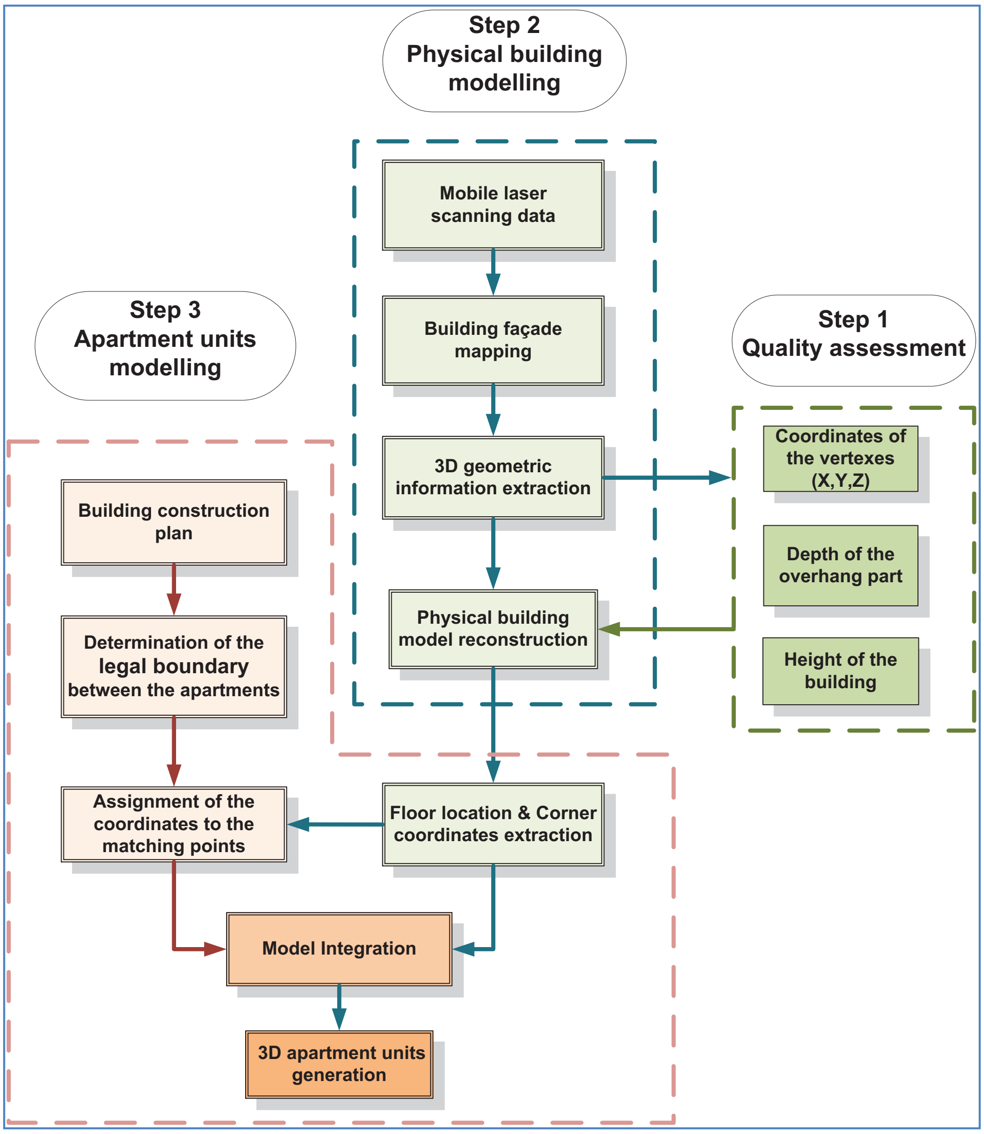


Figure 4.3.2.1 3D Property modelling procedure

Table 4-2 Transferring the MLS data and the product into the LADM

Result Step	Output	Integrating into the LADM	Note
Quality assessment	Accuracy report	Surveying and representation: Physical_SpatialSource	The accuracy report indicates the accuracy of the 3D position and the geometric structure of the building objects. It is documented with Physical_SpatialSource;
Physical building modelling	Physical model of the building object	Surveying and representation: Physical_SpatialSource; Surveying and Representation_ PhysicalBuilding: Building_Point class; Building_BoundaryFaceString class; Building_BoundaryFace class	• The extracted vertexes from building/apartment object can be recorded as a set of instances of the Building_point class and documented in the Physical_SpatialSource; • Associated with the point class, the boundary face string ,boundary face and the spatial unit can be formed in the LADM according to the the geometry and topology modeling scheme; • The generated floors, wall surfaces and the building/apartment modes can be documented individually in the Physical_SpatialSource class
The Apartment unit modelling (together with the floor plan)	Physical model of the building storeys; Physical model of the apartment units	Surveying and representation: Physical_SpatialSource; Surveying and Representation_ PhysicalBuilding: Building_Point class; Building_BoundaryFaceString class; Building_BoundaryFace class	

4.4.1. Quality assessment

Before introducing one kind of 3D survey data into cadastre database, the quality assessment procedure has to be implemented first. The issues about whether the positional accuracy of the 3D data could fulfil the requirement of cadastre, or whether the 3D data could accurately reflect the geometric characteristics and relative position of the features on the spatial objects should be analysed.

In this research, the façade maps from pinot clouds are taken for the building object modelling. Building height is an essential attribute that relates to the 3D building modelling. In the 3D cadastre and building registration, the building height or the floor to floor height is used to define the vertical position and volume of 3D property in space. As for the façade structure, the balcony and roof extend from the footprint on the cadastral map, they closely relate to legal space of the 3D property in the cadastral system therefore should be accurately modelled.

During the façade mapping stage, the positioning accuracy of each feature represented on the façade map has been defined by the mapping requirement, the result can acquired from the accuracy report; therefore the quality assessment is mainly based on the building geometric structure in this research. For assessing the suitability of the geo-referenced point clouds data and the mapping building façade for 3D cadastre, the building height based and the overhanging depth based quality assessment are carried out first.

4.4.2. Physical building modelling

In this research, the 3D geometric modelling of a physical building is carried out by using 3D polyhedron as the geometric primitive. When the registration of the physical object registries the building as an independent property, only the vertexes refer to the footprint, the roof and protruding part are required. The 3D primitives are constructed by composing the upper and lower corners of the building. In addition, for the overhanging part, each of them is modelled as an individual 3D primitive first, and then attached to the main building by using the Boolean operations including union, difference or intersection.

Furthermore, the MLSand the façade mapping show the limitation of the building footprint detection. To be able to detect all the façades and extract the complete building footprint, MTLS data collection mission should be conducted around each building. However, the surveying missions are carried out on the main streets in most of the cases, meaning that merely the front are covered during the surveying and mapping procedure. Practically, a group of parcels and the erected buildings are composed as one block, there is always no gap between the neighbouring buildings (see the Figure 5.3.1.1 in chapter 5). It brings the problem for building footprint extraction as well as the side and rear walls modelling. In order to determine the complete 2D footprints and record their 3D coordinates in the database for 3D primitive construction, the cadastral map should be able to be accessed. That is to say, when the laser data cannot afford enough spatial information for generating the 2D polygon of building footprint, the drawing that exists on the cadastral map can be used to extract the coordinates of missing endpoint.

4.4.3. Apartment units modelling

In the cases of the building complex and the apartment complex, multiple property units are established vertically on the same parcel. The cadastral registration should give enough insight into the ownership of the property, as well as the height attributes with the “upper and lower limits of rights established on one parcel” (Stoter and Oosterom, 2006). Therefore the floor location has to be defined firstly. Moreover, as has been mentioned above, for the registration of the property units within the building complex, the physical space of the properties coincident with the legal space that registered in the cadastre database. In order to represent each property unit as the independent geometric primitive, the boundaries of each property unit at all dimensions should be modelled, and then the coordinates of the corners can be recorded in the dataset.

(1) The floor surface

Different types of methods can applied to define the position of floors on the building façade. The most straightforward approach is to extract the bottom location of the overhanging balcony. From the perspective of building construction, the under surface of the balcony is in the same plane as the inner floor surface, thereby their Z attributes can be used to record the height position of the stories. In addition, the geometry of windows can be accurately detected by laser scanner and it can provide useful information to define the position of floor. During the process of façade mapping, the structure of windows can be modelled first, and then the boundary of stories can be easily recoded as the median line existing between the upper and lower windows. On the other hand, the relative height value can also be acquired from the building construction plan. By assigning the height to the footprint, the 2D boundary of each storey can be located on the facade.

(2) The inner boundary

3D location of the individual storey layer helps to understand the real situation of properties. However, since the point clouds data and the façade drawings limit to the detection of the exterior geometry and status, the complex intra-structure of apartment unit cannot be determined straightforwardly from the façade map, the geo-referenced and scaled build construction plan is essential in the case of apartment unit modelling in 3D.

The building construction plan is in digital format and modified by using the architectural and civil engineering (CAD) system (Figure 4.4.3.1). Amounts of information, referring to both the graphic shape including the exterior boundary of stories, the inner walls for room participation, balconies, windows, and the textual description such as the construction area and the usable floor area are available and can be inquired. It can be used to create detailed architectural as well as the in-door 3D models (Ross et al., 2009).

A room is considered as the smallest component of the building objects. Note that two kinds of inner walls are applied for the rooms and space participation. The first type is the normal walls that exist between the kitchen, bed room and the living room. These normal inner walls belong to one property and therefore are not considered in the property modelling for 3D cadastre. On the other hand, the apartments are composed of a group of rooms; the walls bound these rooms indicating the borderline between the legal spaces of adjacent units. To be able to represent the structure of the apartment units in 3D, the property-line walls (common wall) have to be generated.

Figure 4.4.3.1 shows the floor plan and the participation of apartment properties. Extracted from the floor plan, the legal boundaries of apartments are in the vector format. They can be integrated into the physical building model for representing the 3D property situation and spatial relationship of the apartment units.

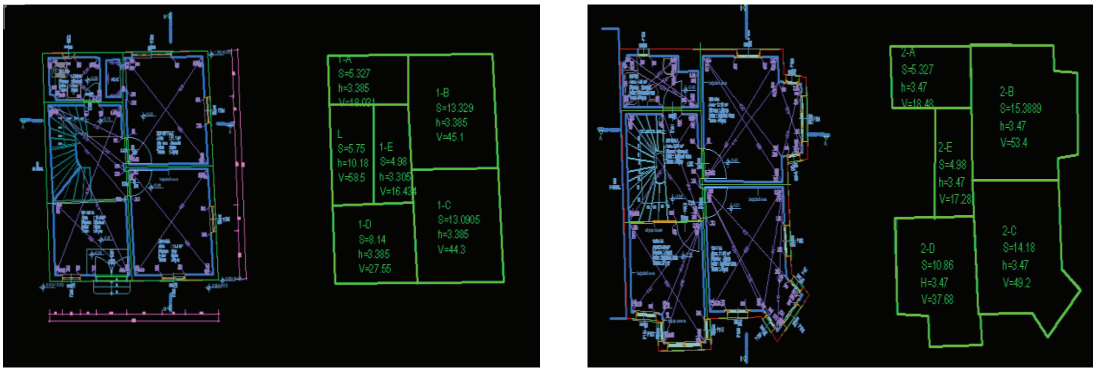


Figure 4.4.3.1 The floor plan of apartment complex and the generated apartment boundary on two floors: the ground floor (left); the first floor (right)

4.5. Conclusion

The legal space in cadastre and the physical representation of the spatial objects were studied in the chapter 2, the 3D geo-object that cadastre interested in does not always coincide to the physical object itself; the extra space such as the safety zone could be covered. The LADM describes this concept. As has been defined in the “LA_SpatialUnit”class, for the building objects or the urban facilities registration, the cadastral system records the extent of legal space but not the geometric structure of the physical object. However, in this case, the right limits of the space are invisible and therefore hard to be collected in the field survey. The feasible solution is to reconstruct the physical structure first, and then generate the required legal boundary by applying the spatial operation such as the “buffer analysis” or “overlaying” in the GIS or CAD environment.

To be able to introduce the physical model and the spatial information into cadastre dataset, a “Surveying and Representation_PhysicalBuilding”package is proposed based on the framework of LADM in this research. The extended package provides a clear relation between the legal registration and the physical representation of the building unit in the 3D cadastral system. The package inherits the representation scheme of the spatial unit in LADM: each physical building unit can be represented by using the geometric primitives of point, boundary face string or boundary face. Both the Building_BoundaryFaceString and Building_BoundaryFace classes are associated with Building_Point class and can be represented by orderly connecting a set of instances of Building_Point. Note that for the representation of the building object, the boundary face is more suitable than the 2D boundary face string. A set of the oriented boundary faces can form a bounded volume; therefore both the geometric structure and the volume of the physical building unit can be represented.

An association class LA_RequiredRelationshipBuildingUnit is introduced between the physical property and the legal space to define required relationship or indicate the value of buffering zone. By using this approach, it is possible to access and inquire the external source of the building unit for the property representation. Moreover, when the digitalized building construction plan or deed drawing is available in the cadastre dataset, the geo-referenced physical building model and the spatial information could be used for the 3D description the apartment unit (since the legal space equals to the spatial extent in that case).

To model the physical building unit for 3D cadastre purpose, the MLS data and the generated building facade map are chosen in this research. The experimental approach is composed of the physical building modelling and the 3D representation of the apartment units within the building. Within this stage, one should realize that the physical building model that cadastre required differs from the models for the 3D city visualization. Only the geometric structures and spatial information referring to the property registration have to be represented. Therefore, the modelling task addresses the features of wall and overhanging part. Moreover, to be able to provide accurate spatial information for property unit registration, the analysis of positioning accuracy and the spatial structure of the physical building model should be implemented first.

5. ACCURACY ASSESSMENT AND EXPERIMENTAL RESULT

5.1. Introduction

This chapter analyzes the results obtained by implementing the 3D property units modelling workflow that presented in the previous chapter. The experimental data of this research is collected from Istanbul, Turkey; therefore a brief background information description of the Historical Peninsula project in Turkey is given in section 5.2. The section 5.3 discusses the quality assessment for the geometric structure of the building facade map, and then the result of the property units modelling are presented in the section 5.4. Based on the results of the accuracy assessment of the mapped building façade and the reconstructed 3D property units, the suitability of integrating the physical building model into LADM for 3D property registration is discussed in the section5.5. The section 5.6 summarizes the finding of this chapter.

5.2. Background information

5.2.1. Study area

The study area is located in the historic city centre in Istanbul (Figure 5.2.1.1). The "Historical Peninsula project" of Istanbul Historic Peninsula was initiated in 2006. The main idea behind the project was to document this historic city and model it into 3D. In order to collect detailed building information and produce a realistic 3D city model, the data acquisition of the Historic peninsula was carried out by applying the MLS for building wall detection and the aerial photo for roof modelling. Approximately 48,000 buildings are scanned and recorded in the project (Buhur et al., 2008).

Figure 5.2.1.1 Istanbul Historic Peninsula (left), and the MLS data for building façade (right)

5.2.2. Mobile laser data acquisition

The project was carried out in the old urban residential districts in Historic Peninsula of Istanbul, Turkey. Three types of terrestrial laser scanning systems were applied in this project. The technical specification is summarized in the following table. Due to the limited surveying condition, the Leica HDS 4500 scanners were mainly applied for the mobile scanning (Kersten et al., 2009). The Leica HDS 4500 has the highest scanning speed (as high as 500,000 points per second) and the highest precision(5mm/50m); these characteristics “allow the user to collect accurate data of required ground point density within a very short period of time” (Leica, 2011, CALTRANS, 2010). It suits for scanning on the narrowed road and be little affected by noise.

Adding the artificial targets on the building wall as the control point is the most widely applied method for data registration. The project was carried out in the old urban residential districts in Peninsula, Istanbul. Due to the narrow street condition, the artificial targets were densely placed on the façades or the corners of the buildings every five meters along each side of the street (Buhur et al., 2008).

	Leica HDS4500	Leica HDS3000	Optech ILRIS-3D
Scan method	Phase based	Pulsed	Pulsed
Field of view [°]	360 x 310	360 x 270	40 x 40
Scan distance	< 53.5m	< 100m	< 1500m
Scanning speed	≤500000pts/s	≤ 1800pts/s	≤ 2000pts/s
Angular res. V/H	0.018°	0.0034°	0.001°
3D scan precision	5mm/50m	6mm/50m	8mm/100m
Camera	add-on	integrated	integrated

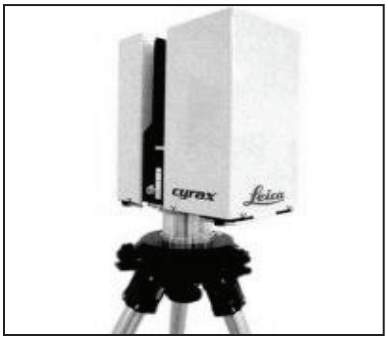


Figure 5.2.2.1 Technical specification of laser scanner(Leica, 2011) (left), and Leica HDS4500 (right)

5.2.3. Façade mapping

To extract the real structure of the building facade, the geo-referenced point clouds data can be used for the 2-D line mapping. As has been mentioned already, for the high density point clouds data, the accuracy of reconstructed building mainly depends on the result of the registration and the spatial geo-referencing. Since the HDS4500 Laser Scanner can emit up to 500,000 points per-second and produce a very dense collection of each measurement (Leica, 2011), the positional accuracies of each feature of the building façade that modelled from the point clouds are checked by comparing with the validation points.

The building outline drawing from the point clouds data is manual operation, the quality of the final result strongly depends on the skill and proficiency of the operators. Since the mapping procedure does not relate to the main objective of this research, the geo-referenced facade maps produced from MLS data are taken for the further 3D buildings and property units modelling processing. The generated building facade maps in this project are with the scale of 1:200. Based on the mapping requirement of the Historic Peninsula project, the positional error for each feature represented on the facade map should be within the range of 10cm both horizontally and vertically. According to the project accuracy report, this requirement has been achieved.

The building facade mapping accuracy according to the project report is given in the following table (Kersten et al., 2009):

Table 5-1 Façade mapping accuracy

	Mapping space	Object space
Scale factor	1	200
Relative position accuracy	0.2mm	4cm
Absolute position accuracy	0.5mm	10cm

Absolute positional accuracy is a measure of the average discrepancy between the true 3D positions of features and their mapped positions from the point clouds. According to the project accuracy report, for each feature that mapped from the point clouds, the absolute positional accuracy of 0.5mm in the mapping space can be achieved, which corresponds to 10 cm in the object space. The relative positional accuracy is a measure of the average discrepancy in distance between the facade features which are reconstructed from the point clouds. In this project, the relative position accuracy of 0.2mm in the mapping space can be achieved which corresponds to 4 cm or less in the object space.

5.3. Quality assessment for the geometric structure of the physical building

5.3.1. Data set

According to the accessible laser scanning data, the block 49 which is located in the Eminonu district, the area of historical Peninsula, was chosen as research object (Figure 5.3.1.1). This typical block consists of a group of independent land parcels and 16 multi-storey buildings. The whole area was scanned by the mobile laser in 2006, moreover, the point clouds data of the buildings and their footprint on the cadastral map were already geo-referenced in the Turkish coordinate system, and the processed building façade map were based on the accuracy requirement (Table 5-1).

For assessing the accuracy of extracted building features, the building construction plans are collected and the records that are displayed on the plan are introduced as the true value. In addition, the secondary data, including the cadastral map and DEM have been collected for the 3D cadastre building property modelling.

Figure 5.3.1.1 Aerial photo of the building block 496 (left); the Cadastral map (middle); the façade mapping and the roof structure of the building block (right).

(1). Building height measurements

The building height information represents the limits of right for each property unit in the vertical dimension; therefore it is the essential attribute for the 3D property reconstruction and the registration. In this step, the building façade drawings are mainly used. Extracted from point clouds, the intersecting line of the building footprint and the housetop are modelled on the façade map. In addition, the detail information, such as the floor number, the floor locations as well as the windows structures are also represented.

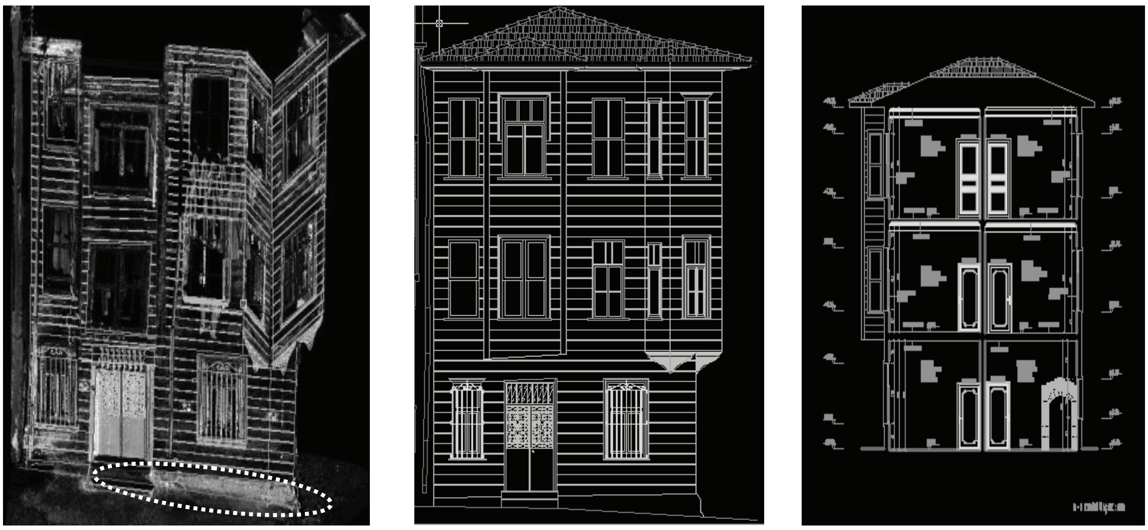


Figure 5.3.1.2 Point clouds and hand drawing of the building outline (left); Building construction plan of the building exterior structure (middle) and the geometric value (right)

In order to record the real height information of the whole building and each storey for 3D cadastre, the quality assessment of height value is carried out by measuring the perpendicular distance between the footprint and the top part of the building, or the perpendicular distance between two floors (see Figure 5.3.1.3).

Internal measurements for building height				
ID	3D Length	Average Value	Building construction plan	Difference
11-M1	10.3818	10.3693	10.3229	0.0589
11-M2	10.3776		10.3229	0.0547
11-M3	10.3737		10.3229	0.0508
11-M4	10.3695		10.3229	0.0466
11-M5	10.3654		10.3229	0.0425
11-M6	10.3613		10.3229	0.0384
11-M7	10.3555		10.3229	0.0326
11-M8	7.0924	7.0493	7.0600	0.0324
11-M9	7.0730		7.0600	0.0130
11-M10	7.0638		7.0600	0.0038
11-M11	7.0494		7.0600	0.0106
11-M12	7.0351		7.0600	0.0249
11-M13	7.0208		7.0600	0.0392
11-M14	7.0106		7.0600	0.0494
11-M15	6.9182	6.9089	6.8410	0.0772
11-M16	6.9148		6.8410	0.0738
11-M17	6.9114		6.8410	0.0704
11-M18	6.9080		6.8410	0.0670
11-M19	6.9047		6.8410	0.0637
11-M20	6.8965		6.8410	0.0555
11-M21	6.8979	6.8957	6.8410	0.0569
11-M22	6.8921		6.8410	0.0511
11-M23	6.8911		6.8410	0.0501
11-M24	6.8902		6.8410	0.0492
11-M25	6.8892		6.8410	0.0482
11-M26	6.8882		6.8410	0.0472
11-M27	6.9215		6.8410	0.0805

Figure 5.3.1.3 Example of one facade height measurements

Within this step, 17 groups of height measurements, which are sampled from 10 different facades, are calculated. Each group of measurements are sampled from 5 to 7 times and the calculated mean value is taken as the measured building height. By comparing with the value from building construction plan, the discrepancies and standard deviation of the measured height values are calculated then the accuracy is assessed.

Height measurements for building				
	Mean Value	Ground Truth	Difference	STDV
Height_1	6.8042	6.8000	0.0042	0.0189
Height_2	6.8102	6.8000	0.0102	0.0235
Height_3	9.1109	9.2500	0.1391	0.0163
Height_4	10.4243	10.3500	0.0743	0.0102
Height_5	6.1343	6.2000	0.0657	0.0069
Height_6	6.7746	6.7400	0.0346	0.0526
Height_7	6.0870	6.2000	0.1130	0.0263
Height_8	3.0477	3.0892	0.0416	0.0274
Height_9	2.8712	2.8333	0.0379	0.0100
Height_10	11.0387	11.0694	0.0307	0.0284
Height_11	2.8127	2.7735	0.0392	0.0009
Height_12	3.2780	3.4053	0.1273	0.0029
Height_13	10.3693	10.3229	0.0464	0.0093
Height_14	7.0493	7.0600	0.0107	0.0166
Height_15	6.9089	6.8410	0.0679	0.0077
Height_16	6.8957	6.8410	0.0547	0.0118
Height_17	7.0803	7.0600	0.0203	0.0266
Total	***Mean Difference***		***0.0540***	
	RSME		***0.0686***	

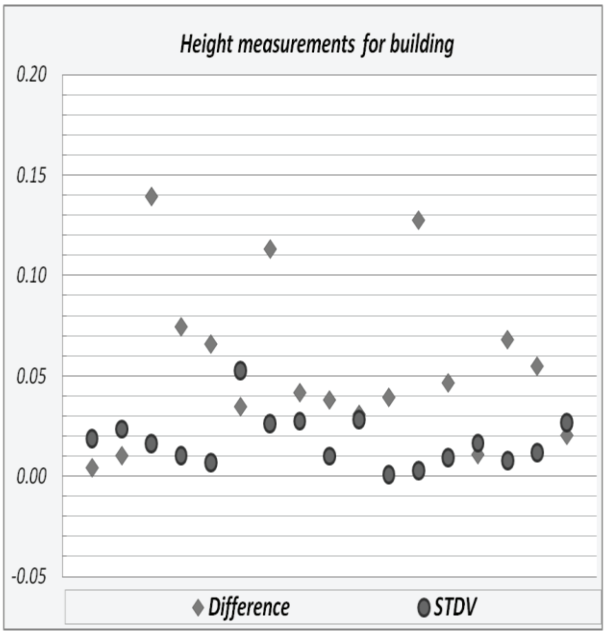


Figure 5.3.1.4 Height measurements for building

The results of the height value measurements for each façade are summarized in the Figure 5.3.1.4. The mean error of the height values varies from 0.5cm to 14cm, while the corresponding standard deviation is within the range of 5cm. In order to get a systematic accuracy assessment of the relative building height, the mean difference and the RMSE (Root Mean Square Deviation) are calculated based on the records in the "Difference" column. The overall results show a mean difference between the height which reconstructed from the laser points and the truth value is 5.4cm, while the RMSE is less than 6.8 cm in length.

The formula can be seen as follows:

Mean Difference

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n} \qquad \text{(Equation 5-1)}$$

RSME

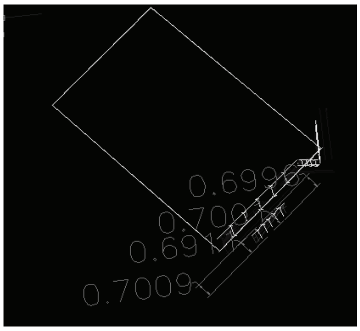
$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{d_i^{\,2}}{n-1}} \qquad \text{(Equation 5-2)}$$

For the depth measurements in this assessment, di= Difference in the Figure 5.3.1.4; n=17, n-1=16.

(2). Overhanging depth measurement

For the purpose of recording the geometric information and reconstructing the building facades for 3D cadastre, the accuracy of the depth of the overhanging part is also assessed in this step.

Internal measurements for building depth				
ID	Length	Average Value	Building construction plan	Difference
M1	1.5592	1.5604	1.6500	0.0908
M2	1.5748		1.6500	0.0752
M3	1.5504		1.6500	0.0996
M4	1.5518		1.6500	0.0982
M5	1.5286		1.6500	0.1214
M6	1.5973		1.6500	0.0527
M7	0.9174	0.8303	0.8500	0.0674
M8	0.8595		0.8500	0.0095
M9	0.8575		0.8500	0.0075
M10	0.7705		0.8500	0.0795
M11	0.8002		0.8500	0.0498
M12	0.7768		0.8500	0.0732
M13	0.9954	1.0307	0.8500	0.1454
M14	1.0130		0.8500	0.1630
M15	1.0342		0.8500	0.1842
M16	1.0532		0.8500	0.2032
M17	1.0578		0.8500	0.2078
M18	1.4887	1.5219	1.5500	0.0613
M19	1.4599		1.5500	0.0901
M20	1.5393		1.5500	0.0107
M21	1.5145		1.5500	0.0355
M22	1.5576		1.5500	0.0076
M23	1.5714		1.5500	0.0214
M24	0.9096	1.0277	0.8500	0.0596
M25	1.1137		0.8500	0.2637
M26	1.1106		0.8500	0.2606
M27	0.9639		0.8500	0.1139
M28	1.0490		0.8500	0.1990
M29	1.0191		0.8500	0.1691
M30	1.1276	1.0401	0.8500	0.2776
M31	0.9944		0.8500	0.1444
M32	1.0473		0.8500	0.1973
M33	0.9196		0.8500	0.0696
M34	1.0011		0.8500	0.1511
M35	1.1094		0.8500	0.2594
M36	1.0811		0.8500	0.2311



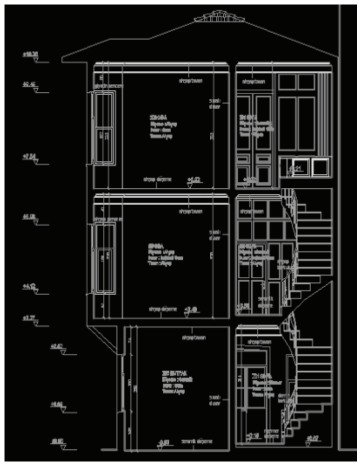


Figure 5.3.1.5 Record of one overhanging depth measurements (left); Top view of the data and the depth measurements (upper right); True value from building construction plan (lower right);

21 groups of measurements based on the length of the overhanging part from 10 facades are sampled and examined (Figure 5.3.1.6). Same as the assessment of building height, for each façade the distance between the footprint of the building and the overhanging part is measured 5-7 times, and then the discrepancies and the STDEV of the measured overhanging depth were calculated. Note that the depth value is recorded by measuring the perpendicular distance between the overhanging part and the edges connecting buildings and the terrain (the footprint drawing from point clouds). In some cases, the intersecting edges are hard to be detected by laser points and then cannot be represented on the façade map. The depth values are then measured between the overhanging part and the building footprint on the cadastral map. The results of the overhanging depth for each façade are summarized in the Figure 5.3.1.6.

Depth measurements for overhanging part				
	Mean Value	Ground Truth	Difference	STDV
Depth_1	1.3250	1.4500	0.1250	0.0328
Depth_2	0.7199	0.8500	0.1301	0.0637
Depth_3	0.4959	0.6000	0.1041	0.0052
Depth_4	0.7068	0.8000	0.0932	0.0229
Depth_5	1.5604	1.6500	0.0896	0.0235
Depth_6	0.8303	0.8500	0.0197	0.0320
Depth_7	1.0307	0.8500	0.1807	0.0265
Depth_8	1.5219	1.5500	0.0281	0.0323
Depth_9	1.0277	0.8500	0.1777	0.0810
Depth_10	1.0401	0.8500	0.1901	0.0734
Depth_11	1.4984	1.6000	0.1016	0.0548
Depth_12	0.7606	0.8000	0.0394	0.0480
Depth_13	0.9273	0.8000	0.1273	0.0478
Depth_14	1.3072	1.2700	0.0372	0.0195
Depth_15	0.8718	0.8700	0.0018	0.0015
Depth_16	1.0245	1.0000	0.0245	0.0533
Depth_17	0.9698	1.0000	0.0302	0.0567
Depth_18	1.6058	1.6000	0.0058	0.0008
Depth_19	1.6449	1.6000	0.0449	0.0265
Depth_20	0.9414	0.9000	0.0414	0.0149
Depth_21	1.0332	0.8500	0.1832	0.0779
Total	***Mean Difference***		***0.0846***	
	RMSE		***0.1072***	

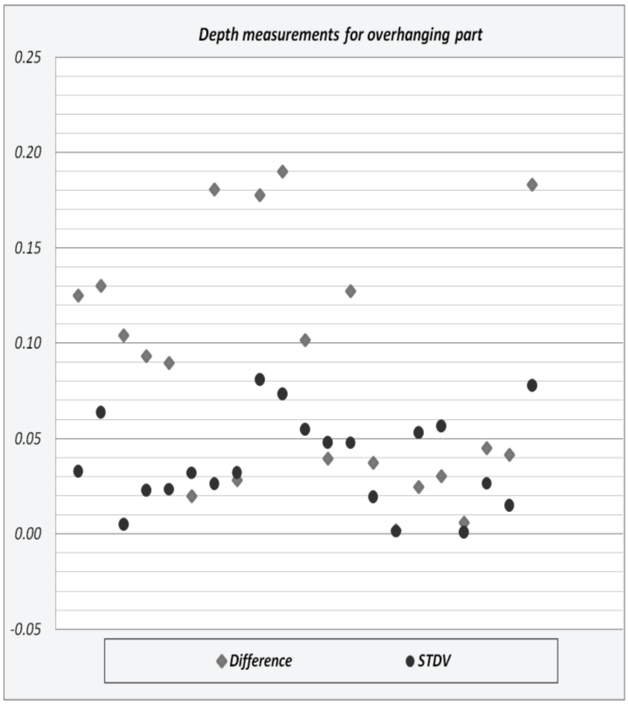


Figure 5.3.1.6 Depth measurements for overhanging

As illustrated in the Figure 5.3.1.6, for the depth value of the mapped overhanging part on the building façade, the differences between the mean value of measurements and the ground truth vary from 2cm to 19 cm, while their corresponding standard deviation are from 1.5cm to 8cm. Most of the differences are within the range of 15cm and the depth accuracy is lower than the height result.

The systematic accuracy for the overhanging depth value is also calculated (see the Formula 5-1, 5-2) on the basis of the 21 groups of measurement in the Figure 5.3.1.6. The result shows that there is 8cm mean difference between the overhang part which reconstructed from the laser points and the truth value, while the RMSE of the measured overhanging part is less than 11 cm in length. This error is also lager than the height value.

5.3.2. Quality assessment

For the features that mapped from the point clouds data, the theoretical accuracy of height and depth measurements are based on the positional accuracy that defined in the Table 5-2.

If σ_{z1} and σ_{z2} are standard deviations of the mapped features in the position, and $\sigma_{\Delta z}$ is for the distance measurement between the features on the façade map, then it can be calculated as:

$$\sigma^2_{\Delta z} = \sigma^2_{z1} + \sigma^2_{z2} = 2\sigma^2_{z} = 2\ S_d^2$$

Therefore,

$$\sigma_{\Delta z} = \sqrt{2} * 4\text{cm} \approx 5.657\text{cm}$$

The total error in the length measurement is due to both the positional accuracy tolerance of the point clouds data and errors during building construction process. Here, the assumed the standard deviation of building construction errors ($\sigma_{building}$) is 5cm. Thus the overall standard deviation σ_z is calculated as:

$$\sigma_Z = \sqrt{\sigma^2{}_{\Delta Z} + \sigma^2{}_{building}}$$

$$\approx 7.55\ \text{cm}$$

The overall quality assessment of the point clouds data for building façade mapping and the geometric measurements assessments are summarized in the following table (see Table 5-2).

Table 5-2 Accuracy assessment

	Theoretical accuracy	Assessed accuracy
Vertex (point)	4cm (Relative positional accuracy) 10cm (Absolute positional accuracy)	------
The length measurements	7.55cm	Depth: 10.72 cm Height: 6.86 cm

It can be seen that the RMSE of building height measurement is 6.86 cm which is comparable with the expected value of 7.55cm, while the RMSE for the overhanging depth error is around 11cm which is higher than the theoretical value. The primary cause is the occluded parts that are hard to be detected by the laser points and therefore cannot be represented on the facade map, such as the bottom layer of the eaves or the intersection part between balcony and the main wall of the building. In addition, the measuring was carried out from the top view by measuring the distance between the boundary, or the distance of the end vertexes of the overhanging part and the footprint of the building (see Figure 5.3.1.5, upper right). However, the intersection line of buildings on the ground is also hard to be accurately detected from the point clouds data (see Figure 5.3.1.2), which brings the uncertainty for the length measurement.

Moreover, only the positional accuracy tolerance and the building construction errors were considered in the theoretical accuracy calculation in this assessment. Practically, the overall error in the building façade mapping is due to the positional error, the building construction error and the errors during hand drawing or model reconstruction process. The last one is primarily based on the subjectively manual operation; hence the experience and proficiency of the skilled workers affect the quality of the final result as well.

5.3.3. Result analysis

The quality assessment of height and overhanging depth value on the façade map has been conducted in the above section. Spatial information from a direct measurement system is primarily obtained from the positions of the receiver of MLS system. The façade maps from the point clouds data show sufficient details to provide information about spatial and geometric structure of the building exterior walls. Both the 3D coordinates of the vertexes and the length value of the features on the buildings can be extracted. By comparing with the theoretical accuracy, the results show the feasibility of implementing the MLS data and the post processing product into the 3D property modelling. For each feature that extracted from the building façade map, the 3D positional accuracy is within 10cm while the accuracy of building height is better than 7cm. Though the RMSE for the overhanging depth is around 11cm which is out of the range of the theoretical value, the 3D features such as the protruding balcony and eaves which relate to the space of 3D property in cadastral registration can be detected. Moreover, the features on the building facades can be accurately represented (see Figure 5.3.1.2); the products can be used for the 3D objects modelling and visualization.

From the 3D cadastral property registration perspective, the geometric measurements of the façade map that assessed here relate to the physical objects, rather than the legal space that defined in the cadastral system. However, the referenced physical model afford both the real structure and the spatial information (X, Y, and height value) of each object, they can help to define the legal space of each property in the cadastre database.

While the currently applied approaches for 3D building reconstruction such as the aerial photo geometry or territorial image modelling show the limitation of building height and geometry structure representation, the ground based laser scanning technique could be applied for the detail building wall information acquisition, and for the real building property situation detection. The point clouds data and the facade maps can be integrated into the CAD environment for the further process or refinement for different purposes. In order to model and represent the complex property situation in the real 3D environment, the CAD based building object reconstruction and visualization are carried out in the next step.

5.4. 3D property modelling

5.4.1. Research object

To analyze the methods of data acquisition of 3D spatial information for the 3D cadastral purpose, a study object was selected. The building object which is located in the parcel 11 of the block 496, Historical Peninsula is chosen to reconstruct within this step. The object building is covered by 2 scans of MLS data (2 facades) and composed of 3 stories (Figure 5.4.1.1).

Figure 5.4.1.1 Research object, locating in the parcel 496_11, Demirtaş Mahallesi Eminönü, Istanbul

Several data were collected during the fieldwork in order to implement the building reconstruction and individual property representation. The building construction plan, which contains detailed information of the internal structure of the apartment unit, could be integrated into the physical building model. In addition, for the purpose of assigning the height to parcel and depicting the absolute z-coordinate of building objects, the cadastral map and DEM are also introduced in this step.

5.4.2. Physical building object modelling

Within the whole process, the entire physical object is constructed as a 3D primitive by linking the upper and lower vertexes of the building. Since the facade maps only cover the front wall of the building, the vertexes of the back wall are taken from footprint on the cadastre map. The roof and the balconies part are generated separately first and then integrated into the main building.

Figure 5.4.2.1 illustrates the result of the reconstructed overhanging components (left), and the whole building object (right)

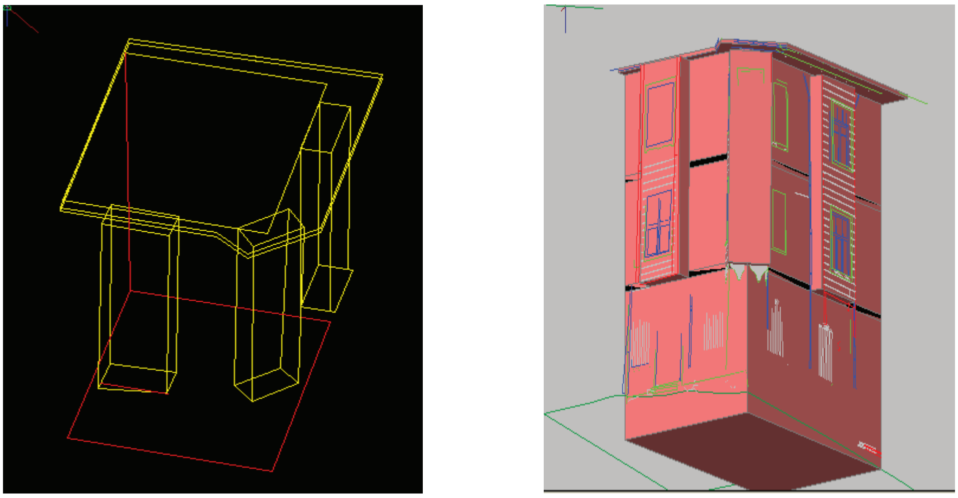


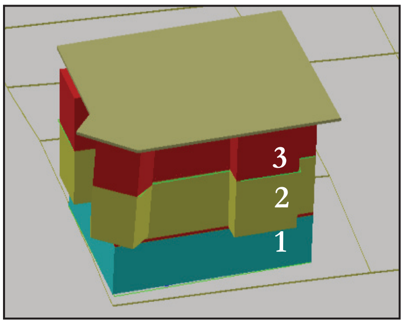
Figure 5.4.2.1 The 3D model of the roof and balcony (left); the 3D solid building object (right).

5.4.3. The building storey modelling

In the step of building storey modelling, the floor location on the building façade is extracted first, and then each floor is generated in form of 2D surface primitive by dragging along the 3D coordinate axes. The floor surface can also be extruded into a solid primitive by assigning the value of the floor thickness, thus the common area between the neighbouring properties can be displayed.

The physical space and 3D spatial information for each storey are as the following table. Note that in the "Absolute Height" column, the height information is displayed as a series of value at unfixed intervals, each of them represents (1) the absolute position of the objects in the Z dimension, and (2) the floor-to-floor height. The X , Y, Z record the coordinates of the centre point of each floor.

According to the result of quality assessment in the section 5.3, for each feature that modelled from the building façade map, the 3D positional accuracy is within 10cm and the accuracy of height measurement is 7cm. Hence, the accuracy of the reconstructed storey object can be expressed as: for each storey that represented on the 3D physical building model (Figure 5.4.2.1), its absolute location in the space has a 10cm positional error, while for the height value of the storey, the 7cm inaccuracy exists.



Properties within one building complex					
	Volume (m^3)	3D location (Centroid)			
		X	Y	Z	Height Range
Storey_1	152.2300	412823.1830	4543367.0810	38.7970	(37.279 -- 40.316)
Storey_2	211.2350	412823.2810	4543367.1210	42.2510	(40.316 -- 44.158)
Storey_3	191.2810	412823.2020	4543367.1490	45.8710	(44.158 -- 47.702)

Figure 5.4.3.1 The 3D representation and spatial information of properties in one building complex

5.4.4. The apartment units modelling

Once the building object has been partitioned into floors, the building construction plans for each storey can be integrated with the physical building through a matching point. Figure 5.4.4.1 shows the individual property units which are represented in form of the 2.5D: the 2D footprints of property units are established in the vertical dimension, while the line based inner walls are represented as the "Building_BoundaryFaceString" (section4.3.2) dividing space into different units.

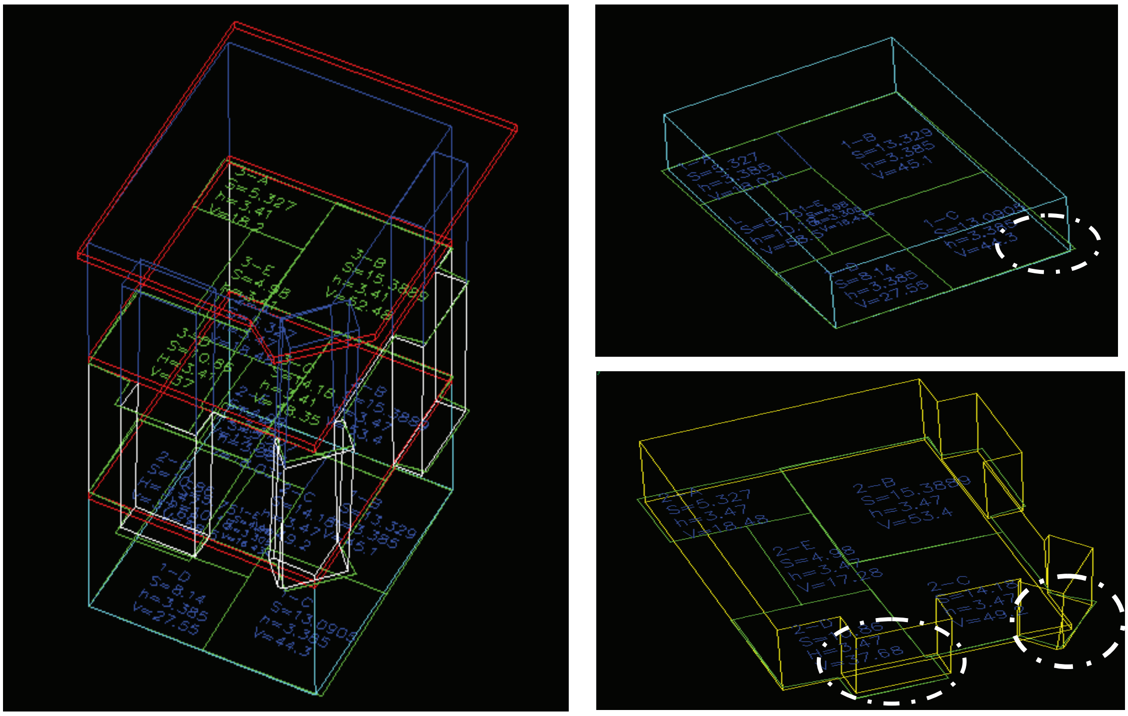


Figure 5.4.4.1 The result of the model integration. All apartment units within one building object (left); the ground floor (upper right); the second floor (lower right). Note the differences of the overhanging structure between two floors.

In the figure above the outline of the 3D physical building which generated from the façade map and the 2D floor plan are geometrically integrated as whole, but the minor discrepancies can be found at the corner and overhanging depth between two models (highlight in the Figure 5.4.4.1).

As mentioned before, for the 3D building model that was reconstructed from the façade map, the length measurement errors exist in the both the horizontal direction and the height value. They cause the discrepancy in the process of model integration. To be able to generate the apartment units from the integrated model, the following rules are adopted:

(1) Delineation of the exterior boundaries of each floor is conducted according to the vertexes from the physical building model (the model that reconstructed from the façade map).

(2) Delineation of the legal boundaries between the apartment units, only the property-line walls are extracted from the floor plan;

(3) Delineation of the inner boundaries between the apartment units is performed according to the corners on the integrated floor plan;

(4) Determination of the location of floor surfaces is based on the bottom surface of the overhanging balcony;

(5) Determination of the location of floor surfaces could also be based on the median line between the windows in the upper and lower storey. Moreover, the relative height of each floor can be acquired from the building construction plan. By assigning the height to the footprint, the location of each storey can be delineated on the facade. Note that these two approaches are applied in the cases of the buildings that do not have the overhanging balconies: the 3D positional accuracy of floor surface might be lower than what is determined by using the rule (4).

5.4.5. Representing the property units in LADM

The previous sections illustrate the reconstruction of 3D building object and the representation of apartment units in 2.5D. The extracted spatial information (Figure 5.4.3.1) as well as the physical model of the building and each storey (Figure 5.4.4.1) can be integrated into the Surveying and Representation_ PhysicalBuilding package in LADM (see the Table 4-2 in the Chapter 4).

Based on the result of the accuracy assessment, the vertex points which are extracted from the façade map could define the position of each property in the space accurately. Moreover, in the process of the model integration, the 2D boundaries of apartment units on the floor plan are transferred into world coordinate system automatically, and then the 3D coordinates of inner corner can also be extracted. In the step of building storey modelling, the floor height has already been defined (Figure 5.4.3.1). By assigning the height value of the floor to each vertex and boundary, the apartment unit can be extruded into 3D solid model, and then the volume of each property can be calculated. Table 5-3 shows the 3D coordinates of property vertexes and the calculated volume (the records in red colour indicate the vertexes which are acquired from the floor plan). The coordinates of the vertexes of unit_1 are highlighted in Figure 5.4.5.1(left).

Table 5-3 Apartment units within the building property in Parcel No. 496_11

Apartment units within the buidng property in Parcel No. 496_11					
	Volume (m3)	***3D location***			
		X	***Y***	***Absolute Height***	
				Lower value	***Upper value***
Unit 1	38.4800	412823.0490	4543362.1330	44.1580	47.7020
		412824.1490	4543363.0470		
		412824.7350	4543362.3430		
		412825.7960	4543364.4180		
		412823.5740	***4543366.2720***		
		412821.2270	***4543364.2560***		
Unit 2	48.7590	412825.7960	4543364.4180	44.1580	47.7020
		412827.2510	4543365.6280		
		412827.2490	4543365.5240		
		412828.2790	4543365.3700		
		412828.3120	4543367.2470		
		412827.2820	4543367.4000		
		412827.2770	4543367.1350		
		412825.5050	***4543369.2410***		
		412822.8540	***4543367.0520***		
Unit 3	54.3590	***412820.3070***	***4543370.0030***	44.1580	47.7020
		412822.8290	***4543367.0310***		
		412825.5050	4543369.2410		
		412825.0670	412825.0670		
		412825.7220	4543370.1930		
		412824.0900	4543372.0370		
		412823.4230	4543371.4470		
		412822.7920	4543372.1530		
Unit 4	19.5160	412817.9870	4543368.0260	44.1580	47.7020
		412819.0340	***4543366.6140***		
		412821.4680	***4543368.6410***		
		412820.3070	***4543370.0030***		
Unit 5	17.0070	***412820.3510***	***412820.3510***	44.1580	47.7020
		412822.3890	***4543365.2540***		
		412823.5750	4543366.2730		
		412821.4680	4543368.6410		

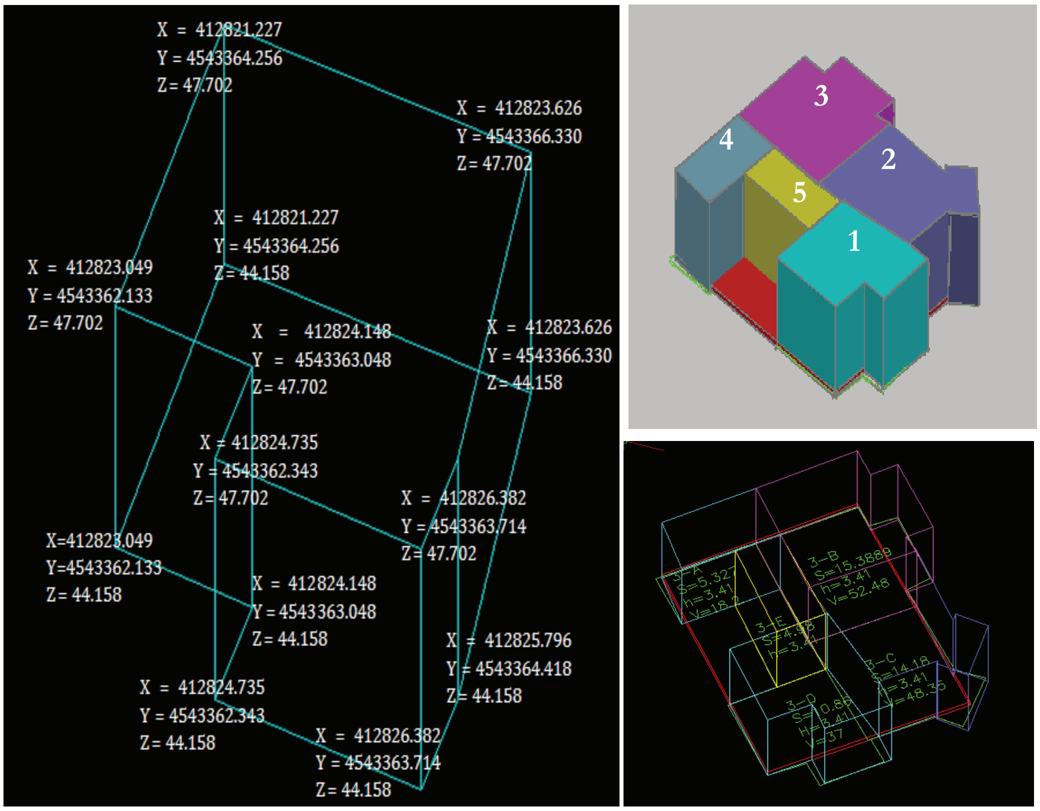


Figure 5.4.5.1 3D representation of the apartment unit_1 with the 3D coordinates of the vertexes (left); 3D representation of the property units within one floor (right)

As described in the chapter 4, the LADM is based on the spatial scheme ISO 19107(2003), the 3D representation of the LA_LegalSpaceBuildingUnit and the PhysicalBuildingUnit is supported. The geometry of building unit and the occupied space can be represented as polyhedrons by composing a set of boundary faces in order. According to the geometry and topology modelling scheme, the boundary face string and the boundary face of the physical building can be realized in the LADM by associating with the PhysicalBuilding_point class: a set of point instances, as the example in the Table 5-3, can be used to describe the floor surface and the wall object. Moreover, the instances of boundary face string and boundary face classes are also accessible if they are documented in the Surveying and Representation_ PhysicalBuilding: SpatialSource class, such as the 2D based inner walls represented on the floor plans (Figure 5.4.4.1).

5.4.6. Visualization of the 3D property units

The case of 3D property modelling in this research is conducted in the context of the world coordinate system. To be able to clearly describe the spatial relationship between the properties in 3D environment, the upper and lower boundaries of each property are recorded by using the absolute height value.

It has to be notice that the 3D building objects cannot exist in the air by themselves alone. Without the terrain model as the reference, the 3D definition of the property unit in the absolute height value could not indicate the spatial status of the object with respect to the land parcels on the 2D surface (Stoter and Oosterom, 2006, Ross et al., 2009). By assigning the absolute height values to the 2D parcel, the spatial relationship between the 3D physical objects (or the 3D property units) and the land surface can be illustrated.

In this step, the geo-referenced cadastral map and the DEM model are used (Figure 5.4.6.1). By projecting the cadastral map on the terrain surface, the absolute height value of the parcel boundary and footprint are defined.

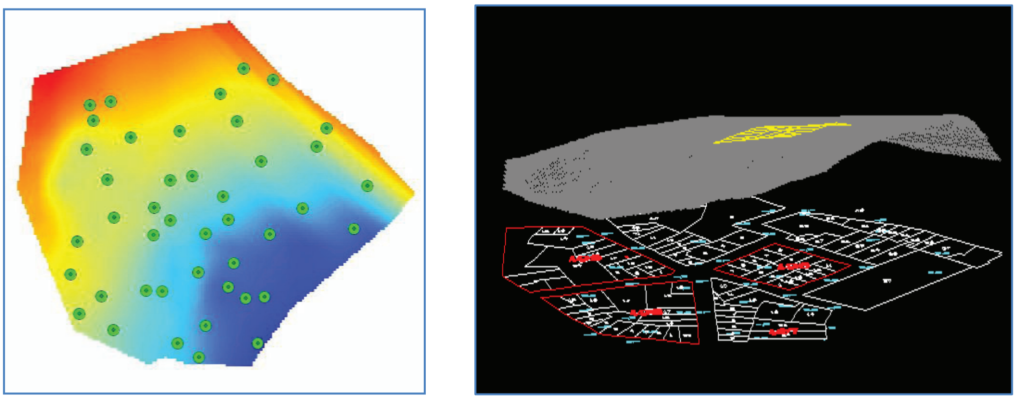


Figure 5.4.6.1 DEM data from the aerial imagery (left), and the parcel surface projected on the DEM (the yellow boundary) (right)

The 3D representation of this situation gives insight to the 3D parcel and the involved building property. Parcel boundary projected on the DEM helps to understand where the property units are positioned with respect to the terrain surface. With integrating the terrain model and the 3D property unit into one environment in the 3D cadastral model, it is possible to clearly registry not only which owners have a right referring to one land parcel, but also the position of the right volumes in the space.

The visualization of the generated right volume of apartment complex and the terrain model are presented in the Figure 5.4.6.2.

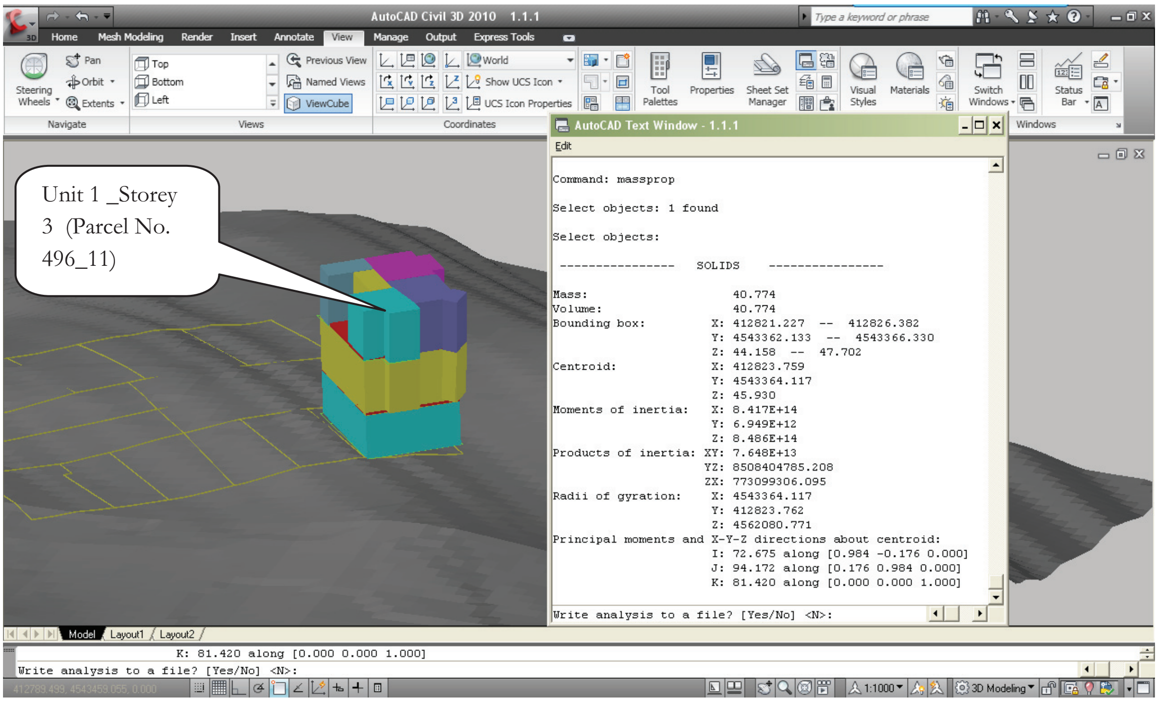


Figure 5.4.6.2 Representation of apartment units in 3D environment, the apartment units in the third floor are represented by using different colour.

5.5. Discussion of the experimental results

This section aims to summarize and analyze the experimental results and findings during the procedure of the 3D building reconstruction and the property unit generation for 3D cadastre.

5.5.1. The quality assessment of MLS data

Mounted on the top of the vehicle, the laser scanners facilitate capturing and recording the spatial information of the urban facilities along the streets at vehicle driving speeds. By implementing MLS technology into 3D cadastre, the exterior structures of the building as well as the real situation of physical objects are quickly mapped in the digital format. For the further process or refinement, the point clouds data can be exported into the CAD environment to produce the vector models.

In this research two criteria were applied to measure the quality of the MLS system. One is the accuracy of the 3D position of objects measured using the acquired point clouds data (Table 5-1 in the section 5.2.3). This accuracy is strongly influenced by the control data collected by the navigation system, geo-referencing and registration of scanner targets, and the point density of the mapping scanner (Li, 1997). Another criterion that has been considered is accuracy of the geometric structures that obtained from line-based façade drawing (section 5.3).

Methods and the accuracy of deriving geometric information of 3D physical objects from point clouds and façade map were discussed. For each feature on the building façade, its spatial information can be measured either using the coordinates of the vertexes or the realized features on the building exterior wall. The relative positional accuracy for the features can achieve 4cm according to the project accuracy report. In addition, the experimental calculation of the 3D length measurements between the features on façade map gives an accuracy of 6cm for relative height, while it is 11cm in the horizontal direction which is more than the required 7.55cm. However, the surveying environment and the situation of the research objects should be taken into the consideration. The facade maps assessed in this research are produced from the old, wooden houses which are located in the Historical Peninsula. Both the oblique building wall and the narrow streets reduce the quality of the data.

The quality assessment, the building model reconstruction and the experimental result of 3D model integration show the applicability of implementing the MLS data into 3D cadastre. The overhanging balconies, extending from the 2D footprint boundary and affecting the legal space of the property, can be accurately detected by point clouds data and represented on the façade map. They were modelled from the façade map separately and then attached to the main body of the building by using the Boolean operations. In addition, the eaves parts strongly affect the legal space around the building object as well. In this research, the eave depths (the measurements between the walls of the building and the vertex of the eave) were also derived from façade map. From the top view of generated model, it can be seen that most of the eaves exceed the boundary of the land parcel and projected on the neighbouring street.

On the other hand, in the vertical dimension, the building height as well as the distance between floors can be acquired with a higher accuracy. However, due to the ground based data acquisition approach, the MLSshows the limitation for the roof detection. The top structure of the buildings cannot be represented in the façade map, thus it affects the result of the total height detection for the buildings to some extent.

5.5.2. Generation of the 3D property units

(1) Generation of the 3D property unit in this research was carried out by integrating 3 datasets: (a) façade map, (b) building construction plan, and (3) cadastral map. During the whole process of the property modelling, several rules relate to the legal boundary determination have been proposed. First of all, it has been found that the point clouds data and the processed facade drawing could reflect the outer structure of the real objects with the estimated accuracy; therefore they are mainly applied for the building height, the overhanging part and the exterior boundary extraction.

Secondly, the building construction plans were used as the secondary data for inner structure modelling. In the process of the data integration, the floor plans were associated with the 3D physical building model that reconstructed from the facade map, consequently the 2D based inner boundary were geo-transferred into the world coordinates system. The result of the model integration shows the feasibility of defining the vertexes and inner boundaries based on the building construction plan. By extracting and recording the 3D coordinates of vertexes, the spatial and geometric information of the 3D property units can be maintained in the geo-database.

(2) In this research, the boundaries such as the floor surfaces and the inner walls between apartments are represented in the form of surfaces. The planimetric position of the boundary surface indicates the median line of the walls while the thickness of the wall is not represented.

In the property unit generation phase, it has been found that the floor position relates to the limits of the rights assigned to one property at the vertical dimension, therefore the consideration of wall thickness could improve the accuracy of the right volume that registered in the cadastre system. In addition, the floor surface and the inner wall that are located between properties and divide the space into different units; they should be classified as the common property. That is to say, the apartment owners have full ownership to occupy the unit, while only the limited right is assigned to use wall due to the collective ownership.

In the 3D representation, the surface can also be modelled a solid primitive by assigning the value of the wall thickness, thus the common area between the neighbouring properties as well as the accurate right volume of each unit can be defined.

5.5.3. The visualization result

In the last phase of this research, the generated 3D property and terrain model were integrated into one environment. As can be seen from the visualized result, after the integration step, the spatial situation of 3D property with respect to the land surface is presented. By using this approach, it is possible to registry not only which owners have a right referring to one land parcel, but also the bounded right volumes locating in the space. Note that the introduction of the DEM data in this research is only for the visualization, the terrain model is not involved in the LADM currently.

During the step of integrating the building model in to the DEM, the problem arose that because of data are taken from different sources (ground based laser scanning and the aerial imagery), the directly spatial overlaying causes the geometrical inconsistencies. In our research, there is a mean discrepancy of 3 meters that exists between the absolute heights of two models, which makes the building appears as if "flying in the air". To adjust the inconsistencies of height value, the terrain model was revised by using the altimetric points on the cadastral map in this research. A "difference DEM" was established first according to the absolute height value of corresponding points on the two model, then the final terrain can be generated through subtracting the "difference DEM" from the initial data.

5.6. Conclusion

In this research, the difference between the legal space and the physical representation of building object is discussed. The 3D cadastre defines building object from the legal entity perspective, the legal space is mainly addressed in the 3D property registration. On the other hand, the geometries of the physical building could be introduced to reflect the real situation and structure of the properties. Based on this idea, the "Surveying and Representation_ PhysicalBuilding" package for adding the physical model into cadastre dataset LADM is proposed in this research. The extended PhysicalBuilding package gives a clear illustration of the relation between the legal registration and the physical representation a property object.

To realize the geometric structure of the physical object and further afford the spatial information for the property representation, the applicability of MLS data in 3D cadastre was discussed in this research. The accuracy assessment procedure was implemented first, both of 3D positional accuracy and geometric structure on the building facades were considered. By comparing with the theoretical accuracy, the result shows the feasibility of using MLS data for physical objects modelling. In the procedure of physical buildings modelling, the geometric information including the 3D coordinates of the points, the structure of building boundary and the floor surface can be extracted; it is possible to document them as the instances in the classes of SpatialSource, Building_Point, Building_BoundaryFaceString, and Building_BoundaryFace respectively in the LADM (according to the Table 4-2). The 3D represented physical building model can either be recorded in the PhysicalBuilding_SpatialSource class, or can be realized through the geometric and topology modelling scheme by associating with the geometric primitive classes. The spatial information can then be applied to examine or support the legal space representation of the 3D building units.

Moreover, the integration of façade map and building construction plan shows the applicability of implementing the MLS data for 3D property (apartment units) modelling. By associating a set of 3D vertexes which obtained from the building facades and the inner boundaries extracted from the building construction plan, the apartment unit reconstruction can proceed in the cadastre database (see Figure 5.4.5.1). The result gives a better understanding and demonstration for individual 3D property unit registration in 3D cadastre.

6. CONCLUSIONS AND THE RECOMMENDATIONS

The main research objective presented in this research is to reconstruct 3D building objects and generate 3D geometric information by using MLS data, and to assess the accuracy and applicability of this approach in the 3D cadastral registration. Based on this objective, the research was carried out from 2 perspectives: (1) cadastral requirements: assessing an appropriate physical building model for implementing the cadastral registration of 3D property; (2) applicability assessment: assessing the applicability of reconstructing 3D physical objects by using MLS data for 3D cadastre.
This chapter first revisits all the questions that were raised in the general introduction part, and then lists the main conclusions in section 6.2. Finally, based on the research questions and the conclusion, the recommendation is outlined in section 6.3.

6.1. Research questions revisited

In the general introduction chapter the following questions were raised:

(1) What are the benefits of registering a property unit in 3D?

Through the literature review and the case study of the cadastral registration in some countries, two forms of 3D property situation were mentioned in this research: the above ground objects including the apartments and the urban construction, and the underground facilities. These properties are established on above of each other and create the separate “parcel” or “piece of land” above or under the terrain surface.

By registering the complex properties in 3D, the spatial information on right become available. Moreover, the depth of the underground facilities, the absolute height information of apartment unit can be clearly identified.

The condominium property has been described in the chapter 2. The apartment units and building complexes are the main objects with 3D characteristics that are registered in the cadastral system. However, in most of the registration systems, only the footprints of the buildings are displayed on the cadastre map, while the individual units within the building objects are not recognized. The strata titles are applied in some countries to identify the ownership of individual units within one building. The strata titles are maintained in form of the scanned drawing or the vector format file which can be further geo-referenced and used for the 3D spatial description of apartment units. By integrating the spatial information, the cadastral registration could provide the information not merely about who owns the property unit, but also the position and the boundaries of the property at all dimensions.

(2) What kind of data should be introduced for representing building units in 3D cadastre model?

There are two forms of building units that refer to the cadastre registration: the independently registered building object, and the condominium property including the apartments and building complex.

An independently registered building is represented as an individual object in the cadastre dataset, there is no subdivision of the legal space within the building. Therefore the information including the footprints, and the registration records which refer to the legal space of the building units should be covered in the cadastre set. Moreover, the physical model of the buildings could also be introduced for the exterior structure representation.

On the other hand, the apartments and building complexes exist within one building dividing the object into several spatial units. Each of the unit should then be individually represented. The strata title, which shows the division and the established ownership for apartment units, should be maintained in the cadastral dataset along with the building footprint. More importantly, to be able to define the 3D situation of each property, all the data should be expressed in the world coordinates system. Both the geometric description and topologic relationship between properties should be defined in the dataset.

(3) What is the advantage of integrating the physical building model and spatial data into LADM for building units registration?

As designed in the conceptual framework (section 1.4), the terms of "legal space" and the "physical structure representation" in 3D cadastre registration are the theoretical foundation of this research. The legal space and physical representation of 3D property in cadastre registration has been discussed in the chapter 2 and chapter 4. The legal space in the cadastre is registered as a space within which the owner of a physical object has a right to ensure the property, whereas the 3D representation of a physical object is the geometric and spatial description of the unit itself (Stoter, 2004). The design of "LA_SpatialUnit" class in the LADM inherits the concept of legal representation; it aims to record the legal space which is required by the physical objects.

Buildings are the main objects in cadastral system with 3D characteristics. A 3D represented physical building model with sufficient geometric information reflects the 3D property situation and defines the spatial extent of the building units, the introduction of which can help to clearly identify the 3D situation and the legal space of each property. Currently, the geo-referenced physical building model and the spatial information of urban facilities in more and more countries are available. They are maintained in the relevant datasets while cover the 3D spatial information of the physical object or the property units to which the cadastre dataset can referenced. Based on this idea, a "Surveying and Representation_ PhysicalBuilding" package, which consists of the SpatialSource, Building_Point, Building_BoundaryFaceString, and Building_BoundaryFace class was proposed in this study. The proposed PhysicalBuilding package provides an interface and representation scheme for integrating the physical building model and the relevant spatial information in the LADM.

(4) What type of building information could be reconstructed from MLS data for cadastral purpose?

In this research, the MLS data and the façade mapping data were selected for the building object and property unit modelling. As can be seen in the Figure 5.4.1.1, the detailed geometric description of the building facades are recorded by the point clouds data. From the cadastral perspective, the spatial information about building wall height, the floor to floor height relate to the vertical position and volume of 3D property in space; furthermore, the exterior structure of the building wall (including the overhanging balcony and the eaves) affect the legal space of the 3D property. All these information can be extracted from the MLS data and the building facade map.

(5) What is the geometric accuracy of the 3D information acquired from the reconstructed building model?

In this research, the façade maps which were produced from MLS point clouds data were selected for the physical buildings and the property unit modeling. Based on the project requirements, the mapping scale of the building facade is 1:200, while the positional error of each feature located on the map should be within 0.2mm/4cm (relative positional accuracy) horizontally and vertically. These facade mapping requirements have been achieved according to the project accuracy report.

The façade maps from the point clouds data show sufficient detail to provide information about spatial and geometric structure of the building exterior wall. Both the 3D coordinates of the vertexes and the length value of the features on the buildings can be extracted. Currently, there is no standard in 3D cadastre indicating the accuracy requirements for the building geometric structure. In this study, the theoretical accuracy for building height and depth measurements are calculated on the basis of the achieved 4cm relative positional accuracy and the building construction error. The calculated value indicates that: for each measurement on the façade map, the accuracy of 3D length should be within the 7.55cm.

The accuracy of the geometric information that acquired from the building facade map was assessed in the section 5.3. The experimental calculation of the 3D length measurements between the features on façade map gives an accuracy of 6.86cm for relative height of the building units, while it is 11cm in the horizontal direction. The former is comparable with the expected value of 7.55cm, while the inaccuracy of the overhanging structure on the building is out of the range of the theoretical value. However, the limited surveying environment and the poor condition of the measured buildings should be considered. The geometric accuracy of the 3D information acquired from the building model could achieve a better result if the research was carried out on the newly built buildings.

(6) What is the restriction of MLS data for 3D physical objects reconstruction?

During the process of quality assessment and the 3D building reconstruction, three main limitations of applying the MLS data and façade map into 3D cadastre have been found.

➢ The MLS and the façade mapping show the limitation for the complete building information detection. Firstly, because of the obstructions or the occlusions that block the signal from the laser scanner, the building footprint, the intersection lines between the main wall and other components on the façade in some cases are hard to be scanned.

Secondly, to be able to reconstruct a complete building model and acquired the footprint, the MLS system has to drive around the target object and scan all the façades. Practically, little space can be found between the intensive building blocks or residential areas. Such as the parcel block in the research, the buildings which are erected on the neighboring parcels adjoin and there is always no space for the vehicle driving. In addition, the targets placement work must be executed along the street which is time consuming and hard

to maintain. Due to these reasons, the MLS tasks are mainly conducted on the major roads and therefore only the front walls and the incomplete of footprint can be detected.
In this research, the 2D based cadastre map was used together with the laser data for the building object reconstruction. For the undetected back wall and side wall, the boundary of footprint on the cadastral map was taken.

- The MLS is ground based, which limits to the roof structure detection. In the step of façade mapping based quality assessment, the building height was defined as the vertical distance between the foot print to the eaves. The height and the structure of the roof part are not covered in the scan data then could be measured.
- The 3D building reconstruction in this research was mainly based on the vertexes and boundaries that extracted from the façade map. As described in the section 4.4, the 2D building façade drawing is based on the subjectively manual operation, hence the experience and proficiency of the skilled workers affects the quality of the final result.

(7) How the application of MLS data improves 3D physical objects acquisition for cadastre purpose?

This research was carried out on the basis of the concept of "legal space registration & physical structure representation". The MLS data was applied for the physical building object acquisition and modelling in this study. Mounted on the top of the vehicle, the laser scanners facilitate capturing and recording the spatial information of the urban facilities along the streets at vehicle driving speeds. The spatial information and the geometric structure of the building objects such as the building/storey height, and the overhanging part on the building facades are acquirable from the MLS products and they can be represented on the reconstructed model. These types of information involve the legal space of the building units and therefore should be integrated into the cadastre data set for property registration.

In the procedure of the building object and the apartment unit modelling, the 3D coordinates of vertexes, the boundaries of apartment units and the floor surface can be documented respectively in the classes of the "Surveying and Representation_ PhysicalBuilding" package which is proposed in this research. By associating with the "LA_LegalSpaceBuildingUnit" that defined in the LADM, the MLS data and the processed physical model could provide the spatial and geometric information about the real structure and the situation of the building units which are registered in the cadastre dataset. Moreover, the result of quality assessment (discussed in the section 5.3) and the output of model integration (building facade map and the building construction plan) indicate the applicability of implementing the MLS data into the 3D cadastre domain.

From the 3D data acquisition and processing perspective, one characteristic and advantage of laser scanning data is that the whole processing procedure, from data acquirement, data geo-referencing to meta or final product delivery is in digital format. The façade maps from point clouds can be imported, exported and processed by lot of 3D format programs like AutoCAD, ArcScence, Z-map and VRML. This advantage facility the integration of the lidar data and the post processing products into database for querying, manipulating, deep processing for cadastral purpose.

6.2. Overall conclusion

Based on the research objective and the conceptual framework, this study was accomplished through the literature review of the 3D cadastre concept and the 3D property registration, the study of the representation scheme of spatial units in the LADM, and experimental assessment of the feasibility of implementing the MLS data in 3D cadastre.

The importance of 3D cadastre has been addressed by many researches. This concept aims to register the situation and the amount of space of 3D property and brings the cadastral task from 2D parcel survey to 3D data collection. To have a complete registration of a 3D property unit, both the non-spatial information (right, responsibility, or restriction, the person) and the 3D spatial information should be contained in the cadastre system. The LADM is designed on the conceptual level and defines a standardized framework for organizing and representing the cadastre data (Lemmen et al., 2010). The spatial scheme ISO 19107(2003) is adopted for the property unit representation in LADM, both the 2D parcel boundary and the 3D legal space are supported and can be represented.

One step of this study is the analysis of how to introduce the physical model in the 3D cadastral system for the legal space registration. A "Surveying and Representation_ PhysicalBuilding" package for 3D building unit representation was proposed on the basis of LADM in this research; this package outlines the concept of "legal space registration & physical structure representation" and inherits the representation scheme of the spatial unit in LADM.

In this research, the MLS data and the façade map were applied for the extraction of vertex points and the generation of the 3D properties. In the implementation phase, the required geometric information including the vertex coordinates, the "Boundary face string" as well as the "Boundary Face" of the physical building which are designed in the Surveying and Representation_ PhysicalBuilding package were generated from the façade drawing and the building construction plan. Associating with these classes, the physical building unit can be reconstructed in the LADM. To provide the real structure and situation of the building unit for the legal space registration, the spatial and geometric information of the physical building can be further accessed by the "LA_SpatialUnit" via the association class "LA_RequiredRelationshipBuildingUnit". Moreover, the result of the apartment unit model (illustrated in Figure 5.4.5.1) and the accuracy assessment show the feasibility of introducing the MLS data for 3D property modelling and registration.

6.3. Recommendation

The recommendations are listed as follows:

(1). The 3D cadastre model: for the more advanced cadastre system which covers the construction registration and the building object registration, the physical model and the 3D description of the physical object can be maintained and organized in the cadastre dataset. That is to say, the physical data source is integrated into the cadastral dataset, and the physical model can be accessed by the original LA_Point, LA_BoundaryFaceString and LA_BoundaryFace classes. In that case, the external package for physical buildings that proposed in the section 4.3 will be included in the regular LADM system. The real situation of the land, physical objects and legal spaces can be much better reflected (see Appendix).

(2). The 3D data collection: the MLS data shows the limitation for the building roof modelling. To be able to reconstruct a physical object completely, the multi data source combination is a feasible option. The aerial image and airborne laser are known as "top-down" modelling, which have been applied in the 3D data collection for building reconstruction. Operated from airborne platforms, these two methods emphasize the roof structure reconstruction and could achieve ideal accuracy. By integrating the MLS data and the aerial data, the complete physical building could be modelled.

(3). The 3D model reconstruction: in this research, the facade maps were applied for the building units modelling. The building outline drawing from the point clouds data requires human interaction; the accuracy of the geometric structure of the building facades is strongly affected by the subjective interpretation and the experience of the workers. Moreover, the manual operation is time consuming and not really reliable. The further research should consider the semi or fully automatic methods for building reconstruction from the MLS data.

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APPENDIX: CONTENT OF SPATIAL UNIT PACKAGE WITH INTEGRATION OF THE “PHYSICAL_SPATIALSOURCE”