3D Building Models, Production and Application

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June 2017
Abstract

3D models have been widely used in many areas since decades ago. When BIM (Building Information Modelling) and VR (Virtual Reality) become popular recent years, 3D model, as an essential part of it has been frequently asked or even required, which is both a challenge and opportunity to a surveying engineer.

Through investigation of three different alternatives to create 3D models: image based, terrestrial laser scanning based and airborne laser scanning based modelling, the author aims to help a surveying engineer to choose the proper method and tool. Workflows, costs and applications have been discussed for each approach and the results show that image based modeling is most time and cost efficient but with lower accuracy which is suitable for visualization while thanks to the high resolution of data capture, terrestrial laser scanning based modeling can be utilized for detailed as-built modeling or BIM. The weakness of such method is the high initial cost and much time demanded; for large area city modeling, the airborne laser scanning approach is the most efficient way with limitations of the low level of details and expensive equipment.

However, it should be critical to understand that there is no automatic way to reconstruct a controllable 3D object at present. Due to the limited accessibility of equipment, the photogrammetric 3D building reconstruction method is not included in this study and thus, a future study may continue with this method. 3D object may be converted to a format that can be used in BIM, such kind of format exchange can be an interesting topic for further study.

Keyword: 3D Modeling, Laser Scanning, ALS, Modeling, Sketchup
Acknowledgements

This thesis has been taken a long time, partly because I am working full time after the education. But now it is time to finish it. I would like to thank my colleagues from Geocama Consulting AB who provided me the working position, dataset for this thesis and other supporting during the years I am working there.

I also thank my supervisor Dr. Milan Horemuz for his support and guidance.

Of course, I give my thanks to my family and especially for my parents who struggled to support my study in Sweden mentally and financially. Thank you so much.

Peng
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# Introduction

## 1.1 Background and Motivation

3D model is a digital representation of the physical and functional characteristics of an object. Nowadays they are widely utilized in industries, e.g., game development, media, government, military, archaeology, manufacturing, and product design. 3D model is also a fundamental element of BIM (Building Information Modeling) though not all 3D modeling solutions utilize BIM design technology (Eastman, 2011). In ACE (Architecture, Construction, and Engineering) industry, standards experts have determined that with BIM, the stakeholders will benefit in among others lower risks and management costs, better decision making and quicker respond (Web Open Geospatial). To have a BIM ready before a project getting started is very common, even for larger infrastructural projects, for example, Stockholm Bypass. The main purpose of using BIM is to ensure a project will be accomplished in the light of corresponding budget and schedule (Nilsson, 2014).

A terrestrial laser scanner is not new to a land surveyor. It has been widely used in tunnel construction since almost two decades ago. Point cloud database usually contains millions or billions of 3D points which is very hard for software such as AutoCAD, Microstation or Revit to handle. Thanks to the development of software, a number of plugins can bring point clouds into a CAD environment and take advantage of the various tools or functions. Even the standard software along the scanner are now very powerful and many modelling work can be performed directly by them.

Together with the terrain models, 3D building models in a large scale of region can be generated from airborne laser scanning data in an automatic or semi-automatic way, which will most benefit urban planning and Smart City development which includes applied innovation, better planning, a more participatory approach, higher energy efficiency, better transport solutions etc. (EU Commission, 2015). Due to the large coverage of area, airborne laser scanning is more often required in larger civil or infrastructural projects in which land surveyors are fully involved.

All these above have resulted in many changes of work flows and deliverables in surveying engineering, which have been both challenges and opportunities for a surveying engineer. Thus, this leads to an initiation of this study of investigating 3D model producing methods and their applications.

## 1.2 Literature Review

According to a number of publications, the weaknesses of architectural 2D drawings have been widely recognized. Traditional as-built practices are mainly based on graphical standards for 2D drawings (Cory, 2001) which is time consuming and requires many times of re-measuring. Eastman et al. (1974) argues that since they are two-dimensional while the buildings are three-, at least two drawings are required to characterize any part of the building arrangement and thus, at least one dimension must be depicted twice. A General Building Description System (BDS) was first initiated by Eastman et al. (1974) to eliminate the weaknesses of the drawings which is the beginning of BIM. Today, BIM is expected to drive the construction industry towards a “Model Based” process and gradually move the industry away from a “2D Based” process (AGC, 2005).

With the proliferation of building information modeling (BIM) in architectural design, a need to create accurate as-built BIM data for existing buildings is rapidly increasing. Having an accurate as-built model of the existing structure allows owners to visualize and analyze proposed retrofit. The increased awareness of
saving building energy consumption, reducing green gas emissions, as well as LEED (Leadership in Energy and Environmental Design) also call for new as-built documents based on BIM (Woo, et al., 2010).

The process of as-built information modelling can be divided into two main phases: data acquisition and building information modelling. Traditional as-built practices are mainly based on graphical standards for 2D drawings (Cory, 2001) which is time consuming and required many times re-measuring.

Image based 3D modeling method gives a very low cost and effective solution (Singh, et al., 2013). Four main software of image based 3D modeling method (i.e. SketchUp, CityEngine, Photomodeler and Agisoft) have been tested and compared by Jain, et al. (2013). But the methodology is described not very clearly.

Another popular implementation of as-built modelling is based on terrestrial Lidar systems. Sepasgozar, et al., compared this approach with the traditional model construction and have concluded that the accuracy of terrestrial laser scanning is higher than the traditional model construction.

In the recent years, several researchers have observed the increasing demand of 3D city models for various purposes. One of the latest development in sensor technology, airborne laser scanning, offers a new efficient data acquisition method for measuring urban objects directly in three dimensions and storing the results digitally which shortens post processing time enormously. (Vögtle, 2000). 3D city models can be generated from the high-resolution satellite images (Kocaman, et al., 2008) or semi-automatically reconstructed from airborne laser scanning (Overby, et al., 2004).

1.3 Objective

Since 3D modeling newly becomes both challenges and opportunities for surveying engineers, the author would like to investigate the production and applications of 3D as-built models of buildings together with the terrain under. There are many modelling methods and the author selected three of them which a surveyor is most familiar with: modelling based on images, terrestrial laser scanning and airborne laser scanning. Workflow, cost, applications will be studied and compared. Through discovering the different features of the three workflows and their strengths, weaknesses, this study aims to help the surveyors who are interested in the modelling to choose the most efficient solution to accomplish corresponding tasks.

The three modeling methods mentioned above cover most of the modeling tasks, for instances:
A. high level of details model of single building
B. industrial plant reconstruction
C. quick and photo realistic visualization
D. city models in a large scale of region

Typical software that suit the tasks mentioned above is tested in the manner that important functions are listed, explained and modeling is realized.

1.4 Thesis Structure

This thesis is organized into five sections: Section I provides an introduction of the background, motivation and literature review; In Section II, the workflow of three modelling methods (i.e. Based on image, TLS and ALS) are briefly discussed together with the advantages and weakness of respective method; A detailed investigation of the three methods is presented in Section III through testing of modelling with suitable software as well as the precision of the models; Section IV provides a final conclusion and suggested work for future studies; And the Section VI lists the references of this study.

2 Methodology

2.1 Image Based 3D modelling

The image based modeling creates photo realistic models that are mainly for visualization purpose. With such models, graphic, and animation, a comprehensive simulation of buildings or products in a manner as it
would appear in real world will be represented. Many software can create this kind of models, for instance, SketchUp, ImageModeller and AutoCAD 123D. It should be noted that the latter two software perform a photogrammetric modelling and the 3D objects created by this method are hard to modify.

2.1.1 Data acquisition
Primary data sources for image based modelling are photos. Aerial photos are applied as a background map for geo-referencing and recognition of the shape, structure of objects (buildings). Images of surface (façade) can be utilized as texture as well as materials for a better understanding of details on objects (buildings).

Further, it is easy to reach aerial images from online map providers such as, Google Maps, Bing Maps, Eniro. A higher resolution helps to make a relatively more accurate and detailed model. Bird’s eye image, an elevated image of object from above with a perspective, can be used for texturing. In addition, a single-lens reflex camera (SLR) is suitable and handy for collection of images of surface (façade) if bird’s eye images are not available.

2.1.2 Photo correction
Aerial images from online map providers are usually orthographic and georeferenced, and therefore no corrections are needed. But for all perspective images such as bird’s eye view or SLR images if they are utilized as textures, corrections are always necessary. Differences between a perspective projection and orthographic projection is shown in Figure 2-1.

A simple orthographic projection on to Plane z=0 can be defined by the following matrix:

\[
P = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 0 
\end{bmatrix}
\]

For each point \( v = (v_x, v_y, v_z) \), the transformed points would be:
\[ P_v = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \]

Often, it is more useful to use homogeneous coordinates. The transformation above can be represented for homogeneous coordinates as (Bloomenthal, et al., 1994):

\[ P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

For each homogeneous vector \( v = (v_x, v_y, v_z, 1) \), the transformed vector would be:

\[ P_v = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \\ 1 \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \\ 0 \\ 1 \end{bmatrix} \]

In computer graphics, orthographic projection are fined by left, right, bottom, top, near and far. These planes form a box with minimum corner at \((-1, -1, -1)\) and a maximum corner at \((1, 1, 1)\). For approximate modeling based on images, realization of orthographic projection through calculation is not necessary. Image processing software such as PhotoShop, GIMP are able to do most of the corrections. For instance, through drag and move with the Perspective Tool in GIMP.

2.1.3 Modelling and Texturing

Footprint of objects (buildings) can be digitalized from orthographic aerial images and extruded with a reasonable height which can be either gained from measurements or from estimation depending on the application of the model. Textures are applied to extruded 3D objects and detail structures of objects (building) will be modeled with help of the textures. The different LoD (Level of Detail) shown in Figure 2-2 can be archived since the photo realistic textures contains all the information that is needed. However, it can be difficult to create image based models on LoD4 since the interior objects such as furniture are not usually modeled in such way.

Irregular shapes of objects such as a terrain can be represented by a mesh which is a collection of vertices, edges and faces that defines the shape of a 3D object. A mesh can be modeled in an exact way with data for example contour lines or a proximate way from the images of the object.

![Figure 2-2: Level of Detail. Image Source: Biljecki et al. (2016)](image)

2.1.4 Workflow

A modelling task starts with a comprehensive understanding of target objects (buildings), for instance, site visiting. Many photos are taken and corrected to make sure all surfaces (facades) are covered and all interested detail structures are included. Footprint of the objects (buildings) is drawn according to aerial image. It is also necessary to apply photo realistic texture and model the detail structures against the texture. Terrain model (ground model) is needed especially when height relationship between several close-by objects are required. The terrain model can be generated either by measuring data or by contour lines.
from archived maps or created by approximate height differences between objects (buildings). The model should be able to be exported to different formats that can be read by various CAD software. A brief workflow of image based modelling is shown in Figure 2-3:

![Workflow of Image Based Modeling](image)

**Figure 2-3: Workflow of Image Based Modeling**

### 2.1.5 Advantage and Weakness

There are several advantages of image based modeling: firstly, it is cost effective. The data can be gained easily from digital camera and correction of images can be done in open source software. The modeling process is based on the understanding and images of the building while architectural drawings contribute to higher precision of model. Time efficiency is the other advantage since no measurement is needed. All these advantages make it possible to easily and efficiently visualize and explain an object which can be difficult in a literal way.

However, there are weaknesses of this method. Firstly, the accuracy of the model is low since no dimension data for example height, width is involved in the approximate modeling processing. Even with architectural drawings, the dimensions of the object are from design drawings which may differ from the reality. Secondly, texture quality depends largely on the image resolution and the correction. Foreign objects that are not edited out cannot represent the actual texture of a model. Thirdly object for instance, roof of a building, where the photos are not available is hard to model.

### 2.2 Terrestrial Laser Scanning Based 3D Modelling

#### 2.2.1 Introduction

Laser scanning or LiDAR (Light Detection And Ranging) is an optical remote sensing technology that measures properties of scattered light to find range information of a distant target. Rather than conducting a single measurement as what traditional instruments do, laser scanning collects millions of measurements.
during a very short time, for example, in several minutes. The data is densely spaced points with 3D coordinates: point cloud.

The scanners can be sorted into phase-shift scanner and time-of-flight scanner according to measuring principles. The phase-shift scanner compares the phase of the laser source with the same when the radiation comes back again to the scanner after its reflection on object’s surface (Alonso, et al., 2011). This type of scanner is fast and accurate while reliable range is short. The measured distance can be calculated as:

\[ r = \frac{1}{2} \left( \frac{\Delta \phi}{2\pi} + n \right) \lambda \]

Where \( \lambda \) is the wavelength, \( n \) is the integer number of the waves and \( \Delta \phi \) is the phase difference.

A time-of-flight scanner calculates the distance by measuring the time of the round trip of a pulse of light. The accuracy of this type of scanner depends on how accurate the time is measured. It is usually slower but can measure a very long range. The following equation describes the measuring principle of time-of-flight scanner:

\[ d = \frac{1}{2} ct \]

Where \( c \) is the speed of light and \( t \) is traveling time of the light pulse. Figure 2-4 below shows the principle of these two types of scanners.

![Figure 2-4: Principle of Distance measurements of ToF and Phase Scanner.](Source: UC Davis AHMCT Research Center)

According to the various statues of a scanner when scanning is being performed, it can be classified into static scanner and mobile scanner see Figure 2-5. Terrestrial scanner that is mounted on the tripod is static scanner while handheld scanner, or scanner mounted on a moving platform such as vehicle, helicopter, UAV is a mobile scanner. Clearly, the selection of an appropriate scanner depends on the application. For instance, a handheld scanner is suitable for short range and small objects with many details while a car based mobile scanning is mainly used for road mapping. A terrestrial scanner is widely used in for example industrial pipe running modeling due to its high accuracy, large coverage and flexibility compared with a mobile and handheld scanner.
2.2.2 Data Acquisition

This part of the study focuses on data acquisition with terrestrial laser scanning.

Efficiency and accuracy are the two main factors considered in relation to laser scanning data acquisition. A higher resolution of dataset could give a better picture of objects while the size of dataset is larger and the period of conducting scanning is longer.

The term "resolution" is applied in different contexts when the performance of laser scanners is discussed. From a user’s point of view, resolution describes the ability to detect small objects or object features in the point cloud. Technically, specifications of two different laser scanner specifications contribute to this ability, the smallest possible increment of the angle between two successive points and the size of laser spot itself on the object (Boehler, et al., 2010).

Most scanners allow manual settings of increment by users. A typical level of resolution is shown in Table 2-1:

<table>
<thead>
<tr>
<th>Level of Resolution</th>
<th>Ultra-High</th>
<th>Highest</th>
<th>High</th>
<th>Middle</th>
<th>Preview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increments (Degree)</td>
<td>H=0.009</td>
<td>H=0.018</td>
<td>H=0.036</td>
<td>H=0.072</td>
<td>H=0.0228</td>
</tr>
<tr>
<td></td>
<td>V=0.009</td>
<td>V=0.018</td>
<td>V=0.036</td>
<td>V=0.072</td>
<td>V=0.0228</td>
</tr>
<tr>
<td>Point Spacing over 25 meters (mm)</td>
<td>H=3.9</td>
<td>H=7.9</td>
<td>H=15.9</td>
<td>H=31.4</td>
<td>H=125.7</td>
</tr>
<tr>
<td></td>
<td>V=3.9</td>
<td>V=7.9</td>
<td>V=15.9</td>
<td>V=31.4</td>
<td>V=125.7</td>
</tr>
<tr>
<td>Dataset size (MB)</td>
<td>2400</td>
<td>800</td>
<td>200</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Duration of scan (Minute)</td>
<td>26.5</td>
<td>6.6</td>
<td>3.5</td>
<td>1.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

For instance, it takes about 3 minutes 30 seconds to perform a 360° scan in horizontal and 270° in vertical directions with a ‘High’ resolution, which means 250,000 points per second. The average space between points is 15.9mm both in horizontal and vertical directions 25 meter away. Scanning without computer will largely increase efficiency. However, in cases like nuclear plant which can only be access once, it is very important to check scanning data directly after scanning is performed to ensure that interested area and targets are included. Terminology ‘Target’ used in laser scanning refers to an object that is placed in an area to identify a specific known location in laser scans and are often used to integrate laser scan data (Hoffman, 2005). A regular form such as sphere or pattern, checkerboard that can be easily recognized and the center of which can be accurately extracted is suitable as a target. The materials of a target can be paper, metal or plastic. Figure 2-6 shows two different types of targets.
An accurate target acquisition is essential to the registration and geo-referencing, it depends on the identification algorithm, but also largely on the quality of the point cloud which is derived based on the individual point precision per scan and the individual point signal-to-noise ratio (Ge, et al., 2015). The noise level of the recorded scan points on a target surface then depends largely on the surface reflectivity and the distance between the target and scanner. For example, a white dull spray paint has a reflectivity 90% while a black dull spray 8% (Boehler, et al., 2003). A typically recommended distance of distribution of targets can be found in Table 2-2.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Recommended target distance at angle of incident approx. 90 degrees</th>
<th>Maximum target distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>1-10 m</td>
<td>15 m</td>
</tr>
<tr>
<td>High</td>
<td>1-15 m</td>
<td>20 m</td>
</tr>
<tr>
<td>Highest</td>
<td>1-20 m</td>
<td>25 m</td>
</tr>
<tr>
<td>Ultrahigh</td>
<td>1-25 m</td>
<td>30 m</td>
</tr>
</tbody>
</table>

### 2.2.3 Registration and Geo-referencing

In practice, it’s rare to sufficiently capture a site or structure with a single scan. It’s either too large to be captured with one scan or key parts of the site/structure are obscured from the line-of-sight of the scanner’s first set-up. Hence, the scanner must be physically moved into a second location to capture parts of the site or structure obscured in the previous scan. This process is repeated until all sites or structures are captured (Geoff, 2005). Each scan station has its own coordinate system with the origin at the center of the laser emitter and all the scan stations can be aligned through registration.

Registration is a process of integrating the different scanning for a project into a single coordinate system as a registered dataset. This integration is derived by using a system of constraints, which are pairs of equivalent or overlapping objects that exist in two scanning datasets.

Generally, registration is realized by rotating and moving an origin of coordinate system of each single scan to an origin of a desired coordinate system. The process can be described by a rotation matrix. A two-dimensional rotation can be described as in Figure 2-7.
The rotation matrix can be easily derived and written as:

\[
\begin{bmatrix}
  x \\
  y
\end{bmatrix} = \begin{bmatrix}
  \cos \theta & \sin \theta \\
  -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
  X \\
  Y
\end{bmatrix}
\]

Where \( \theta \) is the counterclockwise rotation angle, \((X, Y)\) are the coordinates to be transformed. If the origin of two coordinate systems are not the same, e.g., with translation \((\Delta X, \Delta Y)\), the rotation matrix can be written as:

\[
\begin{bmatrix}
  x \\
  y
\end{bmatrix} = \begin{bmatrix}
  \cos \theta & \sin \theta \\
  -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
  X + \Delta X \\
  Y + \Delta Y
\end{bmatrix}
\]

Similarly, in a 3D right-hand coordinate system, a rotation about the x axis with angle \( \omega \) will have a rotation matrix:

\[
M_x = \begin{bmatrix}
  1 & 0 & 0 \\
  0 & \cos \omega & \sin \omega \\
  0 & -\sin \omega & \cos \omega
\end{bmatrix}
\]

Rotation about the x-axis by \( \omega \)

While the rotation matrix can be derived for y and z axis as:

\[
M_y = \begin{bmatrix}
  \cos \phi & 0 & -\sin \phi \\
  0 & 1 & 0 \\
  \sin \phi & 0 & \cos \phi
\end{bmatrix}
\]

Rotation about the y-axis by \( \phi \)
$$M_Z = \begin{bmatrix} \cos \kappa & \sin \kappa & 0 \\ -\sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{Rotation about the z-axis } \kappa$$

Thus, the new coordinates after above rotation and the translation (\(\Delta x, \Delta y\)) can be written as:

$$\begin{bmatrix} X_i' \\ Y_i' \\ Z_i' \end{bmatrix} = \begin{bmatrix} \cos \kappa & \sin \kappa & 0 \\ -\sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \phi & 0 & -\sin \phi \\ 1 & 0 & 0 \\ 0 & \cos \omega & \sin \omega \end{bmatrix} \begin{bmatrix} X_i + \Delta x \\ Y_i + \Delta y \\ Z_i + \Delta z \end{bmatrix}$$

To solve the transformation parameters, thus, three rotation and three translation parameters, at least three common points in each coordinate system should be known.

**Registration of Point Cloud:**

(1) **Cloud to Cloud Registration**

A cloud to cloud registration uses a shape identifying algorithm to align point clouds from two different positions to each other. In this method, neither the target nor special features, for example corner of the roof are processed into modeled vertex. Here a vertex is simply a node created from a point in a point cloud or from the intersection of edges or faces. By selecting pairs of common points which are physically close to representing the same points within each overlapping scan, the two sets of point clouds are aligned. For instance, A1-A3 in Figure 2-8 shows the identical points on the corner of the window and box in two point cloud sets which can be used as common points for a cloud to cloud registration. This method is quite accurate since it uses actually thousands of overlapping points to calculate the rotation and translation parameters between two sets of point cloud rather than relying on a limited number for example five of targets.

![Scan Station 1 and 2](image)

*Figure 2-8: Cloud to Cloud Registration*
(2) **Registration Using Targets**
Registration using this method is realized by transforming coordinates of point cloud from one scan to the other and the principle is described in section 2.2.3. Six parameters should be solved, thus, at least three targets in common are required in adjacent scan stations. A registration can be performed in the following way:

Name all the targets in all scan stations respectively and by comparing the target ID, scan stations can be integrated. T1-T3 in Figure 2-9 are the identical targets in both point clouds. A new registration algorithm has been developed by software such as Leica Cyclone, Z+F LaserControl that the configuration of the spreading of the targets can be used for registration, thus, nomination of the targets is unnecessary.

Figure 2-9: **Registration with Targets**

(3) **Combination of Targets and Point Cloud**
This method is applied when targets are less than three and a combination of two methods above will be applied. This method can be very useful when there are not enough tie points scanned or one fails to measure all three targets. If a “good” point, for example, corner of a box, can be identified in both the current and previous or latter scan world, a vertex can be manually created. And the registration principle is the same with the above. Figure 2-10 below shows targets T2 and T3 are available in both scan stations and a natural point at the corner of a window is created as a vertex named A1.

Figure 2-10: **Registration with Targets and Point Cloud**
(4) **Visual registration**

Visual registration is a registration method developed for scans without any tie points. A 2D thumbnail image is created during data importing process and it provide a top-down and elevation view of each scan. The thumbnails are used to visually recognize various scans for commonalities to identify overlapping areas. Align the images in x,y plane by dragging and rotating of the thumbnails and switch to the elevation view for a vertical alignment. When the 3D alignment of thumbnail images is ready, a cloud-to-cloud registration is performed through the overlapping area of point clouds by ICP (Iterative Closest Point) algorithm. See Figure 2-11.

Since ICP algorithm was introduced by Besl and McKay in 1992, it has become the most widely used method for aligning three-dimensional shapes (Low, 2004). In Figure 2-11 the ICP algorithm is realized in the following steps:

Point cloud in orange color is set as a reference and is kept fixed, while the green colored point cloud is transformed to best match the reference point cloud. For each point in the green point cloud, a closest point in the orange point cloud is found. An estimation of the rotation and translation parameters will be computed using a mean squared error, with which the green point cloud is transformed towards the orange one. The parameters are computed iteratively and the alignment is realized. The accuracy (Root Mean Square error) of the alignment is shown in the error histogram and table in Figure 2-12:
Geo-referencing of Point Clouds

As described in previous sections, each scan station has its own internal coordinate system with origin at the center of laser emitter. Most of the laser scanning products, e.g., point clouds, 3D models, 2D drawings are usually referred to a real world or a user defined coordinate system. The realization of such transformation of coordinate system is called Geo-referencing.

As explained in the above section, theoretically, only three points in common are needed for a coordinate transformation between two scan stations. As is shown in the Figure 2-13 below, if P1, P2 and P3 are measured with total station in a coordinate system, e.g., SWEREF 99 1800, and they are identified in a registered scan dataset, then it can be transformed towards the target coordinate system. Thus, a georeferencing is realized. Scan station 1 and 2 are aligned by T1-T3 three targets in common; scan station 2 and 3 are aligned with common targets T2, T4 and T5 and the aligned three point clouds are registered to an aim coordinate system by three targets P1-P3 which the coordinates are known. See Figure 2-13.

If a total station follows the scanning process and measures all the targets: T1- T6, see Figure 2-14, a registration and geo-referencing can be realized in the following way:

A new scan dataset is created where the coordinate of the targets measured by a total station will be stored. The coordinate system of this dataset is the aimed system of all the other point cloud datasets. By comparing the configuration of the spread of the targets in each scan with the aimed dataset, a 3D transformation is applied so that all the scanning datasets are transformed to the aimed coordinate system.

The advantage of this method is that all the point clouds will be registered in the desired coordinate system automatically and accurately without considering the number of targets in common in adjacent scan.
stations. Nevertheless, the limitation of this method is that two sensors are involved (scanner and total station), and it takes longer time to measure all the targets, which costs extra expenses.

![Figure 2-14: Registration with Coordinates](image)

2.2.4 Classification

A classification is a process of systematic arrangement in groups or categories according to established criteria. These groups or categories are called Classes. Distinctively from airborne laser scanning (See Section 2.3.4), the classification of terrestrial laser scanning is straightforward and application oriented. For instance, point cloud of a building can be classified into roof, façade, floor, terrain, wall, furniture, etc. A proper classification will help to increase the visibility of interested point cloud and release the memory of the computer. Figure 2-15 below simply classifies the point cloud into two classes: a, building and the terrain around and b, others (trees, pedestrians etc.).

![Figure 2-15: Before and After Classification](image)

2.2.5 Modelling

3D as-built models can be created using the point clouds. Most of the point cloud processing software e.g., Cyclone, offer the best-fit functions for geometrical primitives such as cylinder, patch, box, sphere etc. while irregular surfaces or free form objects can be modeled in other CAD software.
Terrain models can be created by triangulation of classified ground points. And the TIN (Triangulated Irregular Network) can be decimated according to the requirement of accuracy and level of details. An example of TIN is shown Figure 2-16.

![Mesh Model of a Terrain](image)

**Figure 2-16: Mesh Model of a Terrain**

### 2.2.6 Workflow

The workflow starts with data acquisition. A total station measurement can be necessary especially when geo-referencing and controlling is needed. Scanning in the site with different setups to ensure the coverage of interested area or objects. Export and import data from scanner to respective software before registration and classification are performed. Laser scanning production such as 3D modelling or 2D drawing can be done in different software, workflow is shown in Figure 2-17:
2.2.7 Advantage and Weakness

There are many advantages of modeling based on terrestrial laser scanning. First, data acquisition of large area with high accuracy makes TLS suitable an accurate 3D documentation. Secondly, the time spent for data collection is much less compared with traditional measuring methods and the measurements are done without touching the object which in some cases is not possible or desirable with the traditional method. Thirdly, a rich production out of scanning data makes it possible to fulfill various demands of the project or the client.

Despite all the above benefits, the weaknesses of a TLS method are: firstly, a high initial investment of instrument and software. Though due to the development of technology and competition, the price of a scanner has deduced largely, it may still cost twice as much as a high precision total station. Secondly, a demand of a high-end hardware for data processing of millions of points. And even a rugged laptop, for example, a Toughbook™ may be needed in a dusty, wet condition in the field. Thirdly, for outdoor data acquisition, most of the scanners are weather dependent since the scanning cannot be performed in the rain, snow or extremely hot or cold conditions and it lacks of building top information. Last, the modeling processes are time consuming and largely depend on the function of software.

2.3 Airborne Laser Scanning Based 3D Modelling

2.3.1 Introduction

The earliest airborne laser scanning systems were developed by NASA in the 1970s for mapping in the ice covered Arctic and Antarctic areas (Ackermann, 1999). And the popularization of ALS across disciplines including geography, geology, forestry, archaeology, natural resource management, and urban planning occurred in the late 1990s and early 2000s. Over the last twenty years airborne laser scanning (ALS) has
been established as a fully automated and highly efficient method of collecting spatial data (Balenović, 2010).

Since the ALS measurement covers very large area from the air, the point cloud can be used in many areas, typically in forestry and urban planning. Features of a forest, e.g., height, type of trees can be identified through many different algorithms. Xiaowei Yu, et al., investigated the possibility to detect the growth of the forest. 3D city models created from the point cloud are useful for various analysis in urban planning, for instance, disaster management, noise and solar simulation (Chen, 2011). DEM, DSM etc. can be generated and utilized in topographic survey.

There are many commercial software for LiDAR data processing, such as Overwatch, Merrick MARS, TerraSolid and etc. Most of these software packages contain the modules for coordinate transformation, point cloud classification, quality control, visualization, exportation and etc. Among which, TerraSolid is world-wide mostly used for ALS data processing (Perc, 2012). A detailed introduction to TerraSolid will be presented in Section 3.4.1

2.3.2 Data Acquisition
In most of the ALS systems, there are six major hardware components (Baltsavias, 2014):

a. Flight platform
b. Laser scanner and computing, data storage unit
c. GNSS
d. IMU (Inertial Measurement Unit)
e. Digital Camera (optional)

The laser scanner is mounted in an airplane or a helicopter and it emits laser pulses at a high frequency, e.g., 350kHz. The reflection of the pulse that hitting on the ground or object, e.g., building is received and detected by a receiver in the laser scanner. Then the difference of time and intensity of signal between emission and reception is calculated. With the same principle of ToF TLS discussed in previous section, the range between the laser emitter and the object can be determined. The attitude of the aircraft as the sensor is taking measurement can be determined by an IMU and simultaneously, differential GPS method is used to accurately record the position of the scanner. See Figure 2-18.

![Figure 2-18: Principle of ALS (Source: Terra Imaging)](image-url)
A typical ALS system as is shown in Figure 2-19 below:

![Figure 2-19: Riegl S560 ALS System (Source: Riegl.com)](image)

2.3.3 Calibration and Flight Line Matching

The ALS system should be calibrated by certificated facilities before the scanning task is performed. The objectives are to correct (Eero, 2013), for example:

a. the effect of varying range based on return signal strength.
b. the effect of varying AGC (Automatic Gain Control) value on intensity
c. systematic effects of this ALS System, e.g., the distance between components.
d. error of time basis (synchronization and interpolation error)

The errors in the roll, pitch, heading of the IMU or the errors in the position from GNSS data may result in flight line misalignment or mismatch. The misalignment must be removed to get a valid measurement. A surface to surface, point to point or tie-line matching can be performed with different software or algorithms. See Figure 2-20 below.

![Figure 2-20: Before and After Flightline Matching (Source: TerraMatch)](image)

2.3.4 Classification

As described in Section 2.2.4, a classification is a systematical arrangement of the points into groups or categories according to certain criteria. One of the most time consuming but important classification procedures in ALS data processing is to extract the bare earth from the point cloud of vegetation, building etc. (Sithole, et al., 2004). Many products of ALS e.g., DEM is based on a correct classification of the ground.

There are many algorithms for classification, e.g., Kilian et al. (1996) proposed a method to identify ground points using a morphological filter. A different approach is to generate a very coarse description of the surface, and continually add points to this surface. The new points must fulfill certain criteria e.g. distance to the momentary surface (Hansen, 1999).

The purpose of this thesis is not to go through the classification algorithms since classification is a necessary step before city modeling with ALS. But a correct classification ensures a completing and correct modelling. For example, points on vegetation should not be included and modeled as a terrain. Classification is a challenging process because different classification algorithms provide different approaches and various features of the scanned area requires a deep understanding even testing of different
parameters to get a reasonable result, thus, right objects in the right classes. The Figure 2-21 below show the point cloud before and after the building classification. Before a classification is applied, all the points are in a default class and color is in grey scale; after a classification, the ground is in “Ground” class with orange color; low, medium and high vegetation are in respective classes with a green color scale while the buildings are colored red in a separate class.

![Figure 2-21: Point Cloud Before and After Classification of Ground, Vegetation and Building](image)

2.3.5 Modelling

Many applications, such as urban planning, telecommunication, security services need 3D city models. Buildings are the objects of highest interest in 3D city modeling (Morgan, et al., 2000).

Compared with TLS, the ALS collects point cloud over large area and thus, 3D city models can be created. There are a lot of publications discussing about building reconstruction from point cloud. For example, Michel Morgan investigated the automatic building detection and roof extraction from DSM (Digital Surface Model) as obtained from ALS and so on. Figure 2-22 below shows the city models of the Södermalm area in Stockholm. The 3D block models are created from ALS data (3D data source: Stockholmstad). Commercial software such as LAStool, TerraSolid etc. provide tools to create such model. If oblique photos are taken during the scanning, texturing of buildings can be applied.

![Figure 2-22: City Model for Södermalm from ALS (Data Source: Stockholmstad)](image)
Rapid and high level of automation of data capture make it possible to create triangulated models of ground, soil etc. for a large area from a classified ALS data. Such topographical information is important to design projects such as tunnel, bridge etc.

### 2.3.6 Workflow

An ALS project starts with a planning of task. According to the task requirement, selection of ALS systems, planning of flight lines and season, control measurement on the ground and etc. should be well considered. Due to the influence of the vegetation, the ALS usually will be performed during early spring or late autumn to acquire data in leaf-off conditions so that as much as point on the ground will be returned. Data collected by the scanner, IMU, GPS etc. will be integrated and matched. Flight lines should be aligned (matched). Other corrections will be performed with the help of ground measurement with total station. Classification is one of the most important step in the ALS data processing procedure since many ALS products are based on the classification, e.g., DEM, orthographic photo, building reconstruction etc. Building models can be created in an automatic or semi-automatic way in many commercial software. A brief description of the workflow is drawn in Figure 2-23 below.

*Figure 2-23: A Brief Description of Workflow of ALS*
2.3.7 Advantage and disadvantage

The ALS collects massive data of an area in short flight sessions. The output can be topographic maps for e.g., large infrastructural project, orthographic photos, DEM, city models. The traditional measuring method, e.g., with total station cannot compare with the ALS regarding of time. Data of the sites such as high way with much traffic, dense forest, island, etc. which impossible or difficult to get with total station can be collected by the ALS. The data can be collected during night since ALS works in an active way compared to photogrammetry.

There are also drawbacks of the ALS. The initial cost of platform, scanning system etc. are usually much expensive. The accuracy needs to be increased and the data processing, e.g., classification still requires much of experience. Another problem with city models is the data format and quality need to be standardized.

3 Tests and Results

3.1 Image Based Modelling with Sketchup

3.1.1 Introduction

Sketchup is a 3D modelling software first developed by Last Software Company. It was acquired in March, 2006 by Google and then by Trimble in April, 2012. The software is developed for architects, civil engineers, and other related professions. It is regarded as a simple, powerful tool for creating, viewing 3D models, especially for photo-textured models for visualization or other purposes like interior decoration. Sketchup is one of the typical software for image based modelling and thus is selected as a modelling tool in the case study.

There are two versions of the software, Sketchup Make which is free and Sketchup Pro with a subscription of license. Generally, Sketchup Pro enables the users to import and export different file formats and create high resolution animations.

In this section, an image based modelling of the Swedish Museum of Natural History (Naturhistoriska riksmuseet) is tested with the software Sketchup (current version 16.1.1449 64-bit).

The Swedish National Museum of Natural History was founded in 1739 and now it locates on Frescativägen 40, Stockholm. The whole museum consists of eight buildings (Figure 3-1) dominated by a 25 meter high dome-topped central tower.
3.1.2 Features

With help of powerful tools in Sketchup, users may find it easy to model. A brief introduction of the most important features is given below.

**Edges and Faces:** Edges are lines and faces are 2D shapes which are created when several edges form a closed loop on the same plane. All the models are made up of these edges and faces. For example: a window is a rectangle face formed by four edges in the same plane.

**Push/Pull:** The method for three-dimensional design and modeling which allows users to draw outlines, or perimeters of objects in a two-dimension manner. Any flat surface can be extruded into a three-dimensional form. For example, users can push a rectangle into a box or a circle into a cylinder. It can be used to any flat shapes. This patented tool of Sketchup makes modeling easy and fast. Figure 3-2 shows 3D objects created by Push/Pull tool in Sketchup.
**Accurate Measurement:** This tool allows users to create precise objects, for example, an accurate length of an edge or height of a building. Models can be built as accurate as you need. This tool can be used to resize a model, image, or face in Sketchup. Figure 3-3 shows a measurement of length of the cube by this tool.

![Figure 3-3: Measurement of Height of a Cube](image)

**Follow Me:** A powerful tool to create 3D objects by simply extruding 2D faces along a predetermined path which is perpendicular to the face. Complex 3D shapes can be archived through Follow Me tool. Figure 3-4 shows a spring that is created by Follow Me tool.

![Figure 3-4: Spring Created by Follow Me Tool](image)

**Components and Groups:** Both can group different parts of a model together so that users can move, rotate, re-scale or copy the whole model. Copies of Component are related together, which means, changes that have been made to one will be automatically reflected in all the others. However, changes in one of the copies of group will not affect others. This is extremely useful when we model handrails, chairs, windows etc.

**Sections:** with this tool, users can see the inside of a model by temporarily cutting away parts of the design. One can create orthographic views which look exactly like a floorplan, or arbitrary view with any angles. Figure 3-5 shows different section views of a house in Sketchup.

![Figure 3-5: Section View of a House](image)
**Sandbox:** Sandbox is used to create terrain model from contour lines or approximately stretching the terrain up and down as well as projecting features such as road, base of buildings onto the terrain. Sandbox is useful when there are height differences between objects while no accurate terrain models are available. Examples of application of Sandbox are presented in *Section 3.1.6.*

### 3.1.3 Data Acquisition

As described in Section II, SLR photos of the museum and the orthographic aerial images are the fundamental data resources for this type of modelling. Aerial images can be obtained through different online map provider, for example, Google Maps, Eniro. Digital photos of buildings which will be utilized as textures can be taken by a digital camera. To perform a seamless texturing, special rules are applied regarding the data acquisition: Photos should be taken for each façade, including alleys and courtyards. Other objects like trees, cars should be avoided as much as possible, which could largely reduce the editing work for photo corrections. Camera positions are marked as white dots in Figure 3-6:

![Figure 3-6: Positions of the Camera](image)

### 3.1.4 Photo Adjustment

Perspective images (Figure 3-7) may be used as texture in Sketchup with the help of the function "Distort Image", while the quality of texturing can be poor depending on the camera angle. External image editing software such as GIMP, Photoshop can easily cut out the perspective and create approximate orthographic images. This work will briefly describe the workflow of photo adjustment in Photoshop.
Select a whole image and use “Transform” tool in Photoshop. There are transformations such as Skew, Distort, Perspective. Skew slant objects either vertically or horizontally. Distort allows users to stretch an image into any direction freely, while Perspective allows to add perspective to an image. Distort an image through stretching it into different directions and an approximate orthographic image can be produced. See Figure 3-8:

Only the image of the façade is necessary, therefore, undesirable objects such as windows from the other side of the wall should be edited out. Objects in the red circle in Figure 3-8 above are considered as undesirable objects. There are three ways to do so. The first way is to simply select a similar area and copy to the area with same texture to cover the obstructions, as what is shown in Figure 3-9:
Two other useful tools for editing out foreign objects are: Clone Stamp tool and Healing Brush tool. To use the Clone Stamp tool, users first select a source point then it works like a brush that paints from the source point. The source area will replace the undesirable parts. The Healing Brush tool works similarly.

After removing the obstructions, we get an approximate "orthographic" image that can be used as texture. See Figure 3-10:

3.1.5 Modelling

In this part, method of creating a 3D building from a 2D image and the ways to add details like stairs, handrails and overhangs are described. From section 2.1.1, we know that the data needed are aerial images and digital photos around the building. Other sources could be very helpful to comprehend the structure of the building, for example, images with higher resolution and different view angles.
From Figure 3-11, it can be found that the main body of the building is symmetrical. And the tower on both sides are identical. Some parts of roofs are similar to each other. Thus, the "Component " and "Group" function in Sketchup may help to reduce the modelling work.

**Create a Rough Model:**

First, users need to start Sketchup and grab an aerial image of the museum from Google Maps through location. By doing this, the coordinate information is automatically obtained which means the images is georeferenced. Aerial image from other map providers such as Bing Maps, Eniro etc. can be imported into Sketchup to get the outline of the museum without a geo-referencing. Similarly to a 3D Cartesian coordinate system, there are blue, red and green axis represent z, x and y axis. By moving and reorienting the axis, user can set up a UCS (User’s Coordinate System) where the axis is parallel with the outline of the building. Such resetting of axis helps drawing of rectangles, straight lines along the building conveniently.

Draw the outlines of the building by digitalizing the aerial image. Use "Push/Pull" tool to pull up the surface just created (Figure 3-12). The height of the building can be interactively entered, nevertheless, for the visualization purposes, the height may also be estimated.
Then offset the rectangular on top of the roof 3 meters inside and pull up the inner rectangular about 4 meters and connect the corners of the two cuboids to create the lower roof. Pull up again the smaller rectangular about 2.5 meters to create the wall under the upper roof (left image in Figure 3-13). Connect the midpoint of the short side of the rectangular on the top and move the line 3 meters along the Z axis, cut 5 meters on each side of the line and finally connect the four corners of the rectangular with two end points of the line to create the upper gabled roof. See Figure 3-13.

**Texture a Model:**
To get a photo-realistic model, a "Paint Bucket" tool in Sketchup is used. Starting with importing of the adjusted photo of a façade, then manipulate the size of the texture until the photo fits the wall of the model. Same photo can be used on the façade if the textures are identical. See (Figure 3-14).

Details can be modeled with help of textures. A surface can be digitalized for door, window, pillar etc. which are then extruded into 3D by push/pull tool. See Figure 3-15:
Texture the curved surface:
Curved surfaces like domed roof, fluttering flag are common objects in 3D models. They are easy to create but difficult to be textured. For example, a surface of a cylinder consists of many rectangles. The smoother the surface is, the more number of rectangles will be. It takes time to adjust the textures on these rectangles so that they can seamlessly match each other.

There is a better way to texture the curved surface, the idea is to project a texture on a flat surface onto a curved surface. We take the direction board in front of the museum as an example. The first step is to create a flat plane which is the same size and parallel with the direction board and texture the plane with corrected photo. Then adjust the size and position of the texture and change the attribute of the texture to "Projected". At last, use the "Sample Paint" to pick up the texture and paint it to the direction board. See Figure 3-16.

![Figure 3-16: Texturing Direction Board](image)

With the above methods, the rest parts of the museum are modeled and details such as stairs, lamp, and traffic sign can also be created. See Figure 3-17 and Figure 3-18.

![Figure 3-17: 3D Model of National Museum of Natural History](image)
Image based modelling depends largely on the photos, thus no site visiting is required. The advantage of this method is that an approximate model even with photo realistic textures can be created within a very short of time. Photos can be obtained from Internet so that one can create a model without actually visiting the site. For instance, the white buildings in KTH campus are created according to aerial images. See Figure 3-19:
A model created by Sketchup can later on been converted to CityGML format. CityGML is an open standardized data model and exchange format to store digital 3D models of cities and landscapes. It defines ways to describe most of the common 3D features and objects found in cities (such as buildings, roads, rivers, bridges, vegetation and city furniture) and the relationships between them. It also defines different standard levels of detail for the 3D objects, which allows us to represent objects for different applications and purposes (Source: citygml.org). With CityGML format, various 3D analysis can be performed in GIS platform such as ArcScene. Figure 3-20 shows two example of conversion tools: a plugin CityEditor for Sketchup (left) and software FME (right).

![CityGML Format Conversion in Plugin CityEditor and FME](image)

**Figure 3-20: CityGML Format Conversion in Plugin CityEditor and FME**

### 3.1.6 Creation of Terrain

As discussed in section 2, in some applications, terrain model should be created to describe the actual topographic features of the surroundings and the height differences between buildings. Together with the buildings, terrain models can be useful in, for example, shadow and flood analysis. Image based modelling method creates terrain model by using topographic maps or images.

Sandbox in Sketchup or other modeling software is commonly referred to as a *triangulated irregular network* (TIN) modeling terminology. There are mainly two methods to model the terrain: from contour lines or from scratching. Both are realized through construction of TIN. The former is with a higher accuracy since the terrain is created according to the elevation data that is stored in the attribute of the contour lines. With the help of plugin, users can convert contour lines from ArcGIS, AutoCAD into 3D terrain. The latter is an approximate method which is mainly used when additional terrain is needed to coincide with the buildings.

TIN can be created in four ways in Sketchup as followed:

1. Import an image of a site plan, or contour map, trace the contours with the Freehand tool. Then adjust the elevation with *From Contour* tool in Sandbox.
2. Extract the x, y, z coordinates into a text or spreadsheet file from surveying data, create the terrain with help of plugin such as *points2mesh*.
3. If the contour information is stored in the line attributes in CAD files, one can simply use a Sandbox tool: *From Contour* to convert the contour lines to a TIN mesh that represents the terrain.
4. Create approximate terrain by *Smoove* tool

The following describes the first way. An image with contour lines over a river area (Figure 3-21) is imported into Sketchup and the contour lines are digitalized by *Freehand* tool.
Figure 3-21: Image with Contour Lines. (Image Source: Texas Gateway)

Figure 3-22: Create Elevations

Figure 3-23: Create Terrain from Contour Lines with Elevations

The Figure 3-22 presents the elevation of contour lines. The next step is to delete all the plan and vertical faces so that only contour lines with actual elevations are left. Then, use the tool “From Contour Lines” to create terrain. See Figure 3-23.

At last, smooth and soften the terrain by setting the maximum size of the angle between normals that will be smoothed or softened. The higher the setting, the more angles you are likely to smooth or soften, see Figure 3-24. One can either use the photo-realistic textures from Sketchup or aerial images to texture the terrain model. Since the terrain is always curved surfaces, the texturing method for curved shape mentioned in 3.1.5 is used.
Extra 3D elements like trees, grass, houses, rivers, roads can be added to the terrain (Figure 3-25). Sketchup files can be converted to Shape format. This is quite useful to perform 3D analysis in ArcGIS or other GIS software. Trend, slope, area etc. can be calculated.

When digital contour lines are available, terrain models can be created in a precise way in Sketchup with "From Contour" tool. An example of terrain model created by such tool is shown in Figure 3-26:
Approximate terrain can be created by *Scratch* tool. First, create a grid network which covers the whole area. Then select all the grids and add details, by doing this, more grids are added thus, a more detailed terrain can be created. Set the radius of the Scratch tool, for example 3 meters. This means the area covers by a circle with radius 3 meters will be mainly affected. The center of the circle is the position of the Scratch tool (Figure 3-27). The terrain created by this way is approximate, which is very useful when the terrain is just needed to fit the buildings for visualization purpose. See Figure 3-27:
3.1.7 Cost
The cost of image based modelling of the Swedish National Museum of Nature History is investigated in this study, and the summary of cost is shown in Table 3-1.

<table>
<thead>
<tr>
<th>Time</th>
<th>Equipment or Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data acquisition</td>
<td>2 hours</td>
</tr>
<tr>
<td>Image correction</td>
<td>3 hours</td>
</tr>
<tr>
<td>Modelling</td>
<td>8 hours</td>
</tr>
<tr>
<td>Total</td>
<td>13 hours</td>
</tr>
</tbody>
</table>

3.2 TLS Based Modelling

3.2.1 Introduction
In this section, a description of the test of the TLS based modelling is applied on an old building on Maria Präsgårdsgatan 2 and Östermalmsgatan 72 in Stockholm. The initial purpose of the scanning is to create floor plans and drawings for the wooden beam structures. A testing of plant modelling is performed on an oil tank point cloud offered by Leica Geosystems. Finally, a test on a roller coaster in Gröna Lund, Stockholm is conducted for larger scale of pipe running. Leica HDS6000 and Leica Cyclone are utilized for the testing.

Leica HDS6000 scanner was released in October, 2006 with a maximum range of 79 meters and a scan rate up to 500000 points/second. Accuracy of single measurement is 7.9 mgon in both horizontal and vertical angles, and 4mm up to 25 meters in distance (Leica HDS 6000 Release Note). There are five levels of resolution which the users can choose from (See Table 2-1).

Cyclone is a scanning data processing software from Leica Geosystems composed of several modules, including Scan, Register, Model and Publisher. Plugins such as Cloudworx, Viewer are available for different CAD platforms. All the scanning data are stored in a database file with .imp extension. The current version is 9.1.5 (Build 5387).

3.2.2 Features
An attractive feature of Cyclone is the powerful visualization and point cloud navigation. Cyclone’s Level of Detail (LoD) graphics display and visualization modes allow users to “see through” walls, apply shaded rendering, or enhance edges for improved comprehension of dense point clouds.
Virtual Surveyor is one of the most useful tools in Cyclone with which users can digitalize the points and extract points, 3D lines to a user-defined format and layer.

Additionally, Cyclone offers a complete industry’s tool set which covers a wide range of High-Definition Surveying applications in engineering, construction, asset management and other areas, for example, continuous and fast pipe runs, cross sections, contour extractions, TIN/Mesh creation, etc. (Leica Geosystems).

Cyclone can also import and export data in different formats such as E57 scan format, binary point cloud format, images, CAD files, etc. This largely helps data exchange between different CAD platforms.

3.2.3 Data Acquisition
In the planning phase, several objectives should be considered: the project requirements, deliverables, proper instrument, type and number of targets, weather and light conditions, etc. During the scanning phase, we should consider the location of scan stations and the selection of resolution. Preview resolution in HDS6000 is only for the creation of overview of the site, thus no data should be used for modeling or measuring with this resolution. There are many factors that may influence the quality of scanning data:

A. Outer environment. Vibration, refraction, and other optical perturbations.
B. Scanning Objects. The surface of scanned objects, size, and orientation related to the scanner.
C. Scanner itself. Performances of distances and angles
D. Quality of Control. Number of tie points, scanning density, etc.
E. Method of Calculation. Target recognition, way of registration, parameter settings, etc.

Set the scanner in a stable status; turn the faces of targets toward the scanner; establish the necessary control network and properly register the point cloud. All the above will help to reduce the errors. We cannot control much about the outer environment, scanning objects, and performance of the scanner, thus control measuring by total station and proper registration play an important role in the final precision.

3.2.4 Modelling in Cyclone

Basic Modeling
Deliverables of a scanning project can be just point clouds, 2D drawings, 3D models, or results of calculations. As mentioned above, demands of 3D information are largely increasing especially from architects and constructors. With software such as Leica Cyclone, AutoCAD, 3D models can be created from point clouds. In Cyclone, there are three different kinds of modeling methods: fitting the 3D geometric primitives, meshing, and from polylines. Regular shapes such as cylinder, box, sphere, line, etc., can be directly modeled by fitting point clouds, while irregular surfaces can be modeled by meshing or based on polylines.

Classification should be performed before modeling so that unwanted disturbances like trees, cars, furniture, etc., can be turned off or removed for a clear and clean view, which will help a lot during the modeling procedure. Unify the point clouds will help to reduce the redundant data.

Fit Point Cloud
Take a project on Maria Prästgårdsgata 2 as an example. New windows will be installed between the wooden beams. No drawing is available for this building from 1900s and all the documents were lost. Relative positions between these 70 wooden beams should be determined.

Seven scans have been performed within two and half hours with ‘High’ resolution by HDS6000. Totally 250 million of points have been measured and 25 black and white targets are used for registration. The largest misalignment of the targets is 3mm. Classify the roof floor and wall in separate layers so that they can be turned off and only the wooden beams are clearly shown. Classification of floor is done by using the tool Region Grow/Smooth Surface. This command segments the points that represent a smooth surface.
from the rest points in a point cloud. Selection of the points on a smooth surface can be controlled by several parameters such as Region Thickness, Maximum Gap to Span, Angle Tolerance, etc. Use Cut Plane, Slice and Polygon Fence tool in Cyclone to select the points and assign them in separate layers. A registered point cloud is shown in Figure 3-29, different colors indicate different scan stations.

Select the part that is to be modeled by rectangle or polygon fence, copy to new model space, delete the unwanted data, and apply "Fit Fenced" or "Fit Point Cloud". Since these wooden beams are almost cuboids and only the positions are interested, the "Box" are used to fit the clouds. The model can be extended in six directions: left, right, up, down, near and far. Thus, only the point cloud with enough data is modeled and then the model is extended to the end. The walls and roofs are modeled by tool Region Grow Patch and then set to rectangular intersected with each other. See Figure 3-30.
The Figure 3-31 below shows a model of an apartment in central Stockholm. Obstruction such furniture is classified into a separate layer to ease the modelling work.

2D drawings such as floor plans, sections and elevations can be generated from the models and they are very important basis for documentation, renovation etc. 2D drawing can also be created by digitalizing against the point cloud with plugins to CAD software such as Cloudworx which makes it possible for AutoCAD to load tens of millions of points. Figure 3-32 below shows the elevation drawing of the façade.
Model surface with help of reference plane
Although millions of points have been captured during scanning, it is always easily to find some parts with “too many” points while other parts with “too few” points. For example, the roofs are easily covered by beams or the walls are behind the furniture. A reference plane can be used to model an area where there are less points.

We will draw a 2D polygon within reference plane then create a patch from the polygon. Afterwards, adjust the boundary of the patch to fit the coverage of the point cloud. The problem is where to set the reference plane. There are two ways. Firstly, if there are sufficient points from which we can generate a patch, then a reference plane can be placed on such object (patch); otherwise pick one point on a random object, set reference plane on it, move and tilt the reference plane until it fits the coverage of the point cloud.

Pipe Modeling with Region Grow
As described at the beginning of this section, one of the most important function in Cyclone is pipe running. With the improvement of the algorithm, the user can run “Find Pipe Automatically” to create cylinders. But the software cannot find all of the pipes, which requires manual work to create all rest of the pipes with function “Region Grow”.
Patch, cylinder and sphere objects can be easily created by command “Region Grow”. Differently from “Fit Fenced”, the user can control the area of the points that will be involved in the modeling. Basic settings are Region Thickness, Maximum Gap to Span, Angle Tolerance and Region Size (Figure 3-33). Select one or more points of the region to be modeled, manipulate the parameters until the expected region is covered. After creating the object, always optimize the model by adjusting the handles.

![Figure 3-33: Settings of Region Grow for Patch](image)

A modelling test of pipes for an oil tank has been performed by the author (Figure 3-34). Pipe running is straightforward and semi-automatic. Elbow, reducing elbow, flange, etc. can be easily created. 2D drawings, sections can be generated and collision detection can be performed based on the 3D models. Photogrammetry and 3D Imaging department in UCL (University College London) has tested pipe modelling with AR (Augmented Reality) technology for on-site design verification. Without a doubt, the 3D models for facilities with complex pipe running will largely contribute to an easy management of the piping database.
As described above, it is straightforward to create straight pipes or join them with elbow connectors. Roller coaster with many different bend ratios can be modeled in the similar way but much more time consuming. We firstly use the same function “Region Grow” to model a small part of the rail, backward and forward, and then add elbow connector between them (See Figure 3-35). It is important to select suitable bend ratio. Diameter of the same rail will differ if we run the “region grow” which is not correct. Same diameter should be used for the same rail. A modelled roller coaster at Gröna Lund in Stockholm is shown in Figure 3-36. The exact positions of the rails and supporting poles are very important to architecture or constructors since these factors affect the construction of a new roller coaster next to it. A rendering of the model is shown in Figure 3-37.

\[
\text{Bend ratio} = \frac{\text{BendRadius}}{\text{PipeDiameter}}
\]
Mesh Modelling (Terrain)
A mesh is a series of triangles, rectangles or polygons created with the points in a point cloud. For each of adjacent trio of points in a cloud, a triangle is created. This has the effect of generating a coherent visual surface from a point cloud. The triangles can be added, edited, or removed. Mesh objects can be decimated which allows the users to adjust and fine-tune the mesh (Cyclone User’s Manual). An irregular object e.g., in Figure 3-38, can be modeled as mesh if other modeling tools fail to fit the form. Mesh modeling can be applied on terrain features and the models can be used for calculation of volume, generation of contour lines and etc. See Figure 3-39.
A drawback of Cyclone is that it cannot handle vertical surfaces well. A mesh model for a mountainous area will be difficult. Thus, an additional user’s coordinate system is defined by rotating around the x axis 90 degree to get most of the mountainous area horizontal and then create the mesh.

3.2.5 Applications of Models Based on TLS

As-built models are the one of the most important deliveries of TLS projects. As discussed in the section two, the models represent the reality accurately which help for preservation, maintenance and future renovation. With the VR (Virtual Reality) technology, the users can experience, examine the facility in a very different way compared with traditional methods.

Volume calculations can be easily done by comparing meshes before and after filling or excavation. The meshes generated from point clouds exactly represent the object, e.g., terrain, thus an accurate calculation can be realized. See Figure 3-40 below.
Contour lines can be created on the mesh with any desired height interval which is difficult with the traditional measuring methods since side of the mountain is inaccessible. See Figure 3-41:

![Figure 3-41: Contour Line from Mesh](image)

### 3.2.6 Cost

The cost of TLS based modelling of the attic shown in Figure 3-31 is investigated, and the results of the cost is shown in Table 3-2.

<table>
<thead>
<tr>
<th>Table 3-2: Cost of TLS Based Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
</tr>
<tr>
<td>Hiring of Scanner Equivalent</td>
</tr>
<tr>
<td>Data acquisition</td>
</tr>
<tr>
<td>Registration and Classification</td>
</tr>
<tr>
<td>Modelling</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

The above cost investigation does not include the initial cost of instrument: scanner. A new HDS6000 scanner cost approximately 700,00 euro in 2007 and it is difficult to assess the cost of instrument on each individual project thus, this cost of scanner is usually divided and shared on each project, thus here the cost will be represented by “Hiring of Instrument” which is approximately equivalent to 6 hours of work.

### 3.3 Modeling in Sketchup by Drawings Created from Point Cloud

As discussed in the above section, 2D plan and elevation drawings can be exactly created in CAD with point cloud and then be used as base drawings for modeling if, for example, the original drawings are invalid due to the gross errors or are simply lost. An example of such modeling will be briefly described below.
3.3.1 2D drawing from point clouds

A house in north of Stockholm was scanned by 55 set ups within two working days. A control network was established outside the house. Paper targets, tilted black and white target, and a ball target were used as tie point. Total station followed the scanner and measured all those targets which later were used during registration. See Figure 3-42, different colors represent different floors.

![Figure 3-42: Registration of the Scans](image)

With the help of Cloudworx, a plugin of AutoCAD, user can create accurate 2D floor plan and elevation from the rich point clouds. Suitable UCS, User’s Coordinate System, which will help to conveniently draw the lines. See Figure 3-43 and Figure 3-44.

![Figure 3-43: Floor Plan from Point Cloud](image)
Besides, proper measurements from the point clouds are needed, for instance, the thickness of the wall, height of each floor, size of the window etc. Measurements can be done in both Cyclone and AutoCAD. Import the 2D drawings to Sketchup and use the method describe in Section 3.1 to create 3D models. See Figure 3-45.

Due to the old building technic, the size of the stairs differs, thus, it is time consuming to model exact height of the steps (and which is not interested by the architects either). One way to reduce the work is to measure the height between two floors carefully, count the number of stairs and assign the height of the stairs evenly.

The model will be divided into different parts and assigned to different layers. Turn on or off the layers will show or hide details. Model can be exported to the format of 3ds, kmz, dwg, dxf, obj, wrl, xsi which covers most of the 3D software. A rendered version of the model is shown in Figure 3-46.
3.4 ALS Based Modelling with TerraSolid

3.4.1 Introduction

In this section, a test of creating city models based on point cloud from ALS will be performed.

The study area is approximate 300 000 square meter urban area in Norrköping, Sweden. It is a part of a larger scanning area from Norrköping to Södertälje. The area comprises residential, commercial, recreational, and light industrial facilities. The roofs of the buildings are both flat and gabled up to 12 floors. Vegetation such as trees, bushes and lawns are also included. See Figure 3-47. The main task of the test is to firstly classify the ground, vegetation, and building, then create the models of the building with software TerraSolid. An overview of the elevation map is shown in Figure 3-48.
3.4.2 Features of the TerraSolid

TerraSolid software is developed by TerraSolid Oy which was founded in 1989 in Helsinki. The software suite includes powerful LiDAR and image processing modules such as TerraScan, TerraMatch, TerraPhoto, TerraModeler, TerraGas etc. All the modules are fully integrated with Bentley’s Microstation at present.

**TerraScan**

TerraScan software package is developed for processing raw ALS or MLS (Mobile Laser Scanning) data. The powerful routine based classifications enable the users to classify the laser points into any user-defined classes such as ground, water, building, overlapping etc. Fully three dimensional vectorized city models can be created by semi-automatically finding the planar points on the roof. There are other useful features such as coordinate transformation, adjustment of the elevation of laser points to geoid, detection of power lines using least squares fitting etc.

**TerraPhoto**

TerraPhoto module is developed for processing images captured during the ALS. Rectified orthographic images can be produced by TerraPhoto. With ‘Tie Point’, e.g., a common point or line seen in multiple
images, point or line with known easting and northing coordinates, the TerraPhoto is able to solve camera parameters and improve the positional accuracy of images. An example of mosaic images is shown in Figure:

**TerraModeler**

TerraModeler is a terrain modelling application in TerraSolid software suit. TIN (Triangulated Irregular Network) surface models can be created and visualized by contours, colored triangles, shaded surfaces, slope arrows and so on. Volumes of cut and fill can be accurately calculated between two surfaces with a grid based method.

**TerraMatch**

TerraMatch compares overlapping laser strips with each other and corrects orientation parameters to obtain the best fit and improved accuracy of the laser data. The adjustment is based on measured differences between the xyz shape or the intensity of laser points from different strips. The user can decide, if TerraMatch matches all the data points or only points from selected flight lines.

### 3.4.3 Data Acquisition

The ALS data was collected by Optech Titan laser scanner in July, 2015. The average flight height is 500 meters above the ground with a side overlap 20% and the average density of point is 50 point/m². There are three flight lines over the study area, the point clouds are color into cyan, red and blue respectively, see **Figure 3-49**:

![Figure 3-49: Three Flightlines](image)

Flight lines are matched and checked in TerraMatch by for example measuring the differences between laser surfaces from overlapping strips or differences between laser surfaces and known points. Eliminating of the mismatch ensures the data quality, Figure 3-50 visually shows that the flight lines are matched well between line 34 and 35, 35 and 36. A complete report of the matching result can be generated from TerraMatch.
3.4.4 3D City Model Generation in TerraSolid

Ground Classification:
Filtering of ground points is one of the most important routines of TerraScan. Many other classification tools such as low vegetation, compare the elevation of other points to the ground surface created from ground points. The ground classification is sensitive to low error points in the point cloud, therefore, low error points, e.g., points that are clearly lower than any other points on the ground should be classified before running the ground classification. The purple colored points in Figure 3-51 are low points.

The ground classification routine consists of two phases. At first TerraScan searches the initial points and builds an initial temporary TIN model from the searched points. Triangles in this initial model are mostly below the ground (error points) with only the vertices touching ground. In the second phase, TerraScan starts molding the model upwards by iteratively adding new laser points to it. Each added point makes the model to follow the real ground surface increasingly closely. Iteration parameters determine how close a point must be to a triangle plane so that the point can be accepted to the model.

Iteration angle is the maximum angle between a point, its projection on the triangle plane and the closest triangle vertex. This is the main parameter controlling how many points are classified into the ground class. The smaller the Iteration angle, the less eager the routine is to follow variation in the ground level, such as small undulations in terrain or points on low vegetation. Use a smaller angle value (close to 4.0) in flat terrain and a bigger value (close to 10.0) in mountainous terrain (TerraScan, Users’ Manual).
Iteration distance makes sure that the iteration does not make big jumps upward if triangles are large. This avoids ground points that are too high, for example within low vegetation or on low buildings (TerraScan, User’s Manual). Figure 3-52 below shows the definition of iteration angle and iteration distance. Figure 3-53 shows the parameter setting of Classify Ground routine.

![Figure 3-52: Iteration Distance and Angle (Source: TerraScan User’s Manual)](image)

The result of ground classification is a set of point clouds that contains points most likely on the terrain of the area. The orange points in the Figure 3-54 below are the classified ground points and all the other points are colored gray.

![Figure 3-53: Parameters for Ground Classification](image)
Vegetation and Roof Classification

The roofs of the buildings should be in a separate class for a successful building reconstruction in TerraScan. This classification is realized through "By height from ground" routine. This routine classifies points which are within a given height range compared to a reference surface. In this study, the reference surface is the ground which is classified in the previous section. A typical parameter setting is shown in Figure 3-55 where the Max triangle length is the maximum length of a triangle edge in the reference surface, in this study, is the maximum length of the building side which is also the "hole" in the ground point cloud. The Min height and Max height is the range within which the points will be classified to a target class. The parameters should be manipulated so that they fit the specific study area.

By using this routine, low vegetation, medium vegetation and high vegetation can be classified into respective classes. The main idea is firstly, classify all the point above ground (0-999 meters) to class: low vegetation. Secondly, classify the height points that are between 0.3-999 meters above ground to medium vegetation and lastly, classify the high vegetation for the points that are higher than 2 meters above the ground. See image a, b and c in Figure 3-56:
The roof classification is performed by routine "Building" which classifies the points on building roofs that can form a planar surface. The routine starts from "holes" in the ground class and searches the points on planar surfaces above the holes. The buildings in the study area is classified and shown in image d in Figure 3-56 above.

**Modify the wrongly classified point of buildings.**

As discussed above, the parameters of routines should always be manipulated and tested for a study area before the classification is applied since every area may differ in ground features such as vegetation, mountain etc. Thus, manual correction of the classification is usually necessary. TerraScan offers different tool to re-classify the points such as By Class, By Fence, and Above Line etc. The Figure 3-57 below shows the re-classification of building roofs.

**Reconstruction of Building**

Reconstruction of building in TerraScan is performed by the tool "Vectorize Buildings" the software searches the points in the roof/building class and forms planar surfaces as roof. Then creates the walls vertically from the roofs down to the ground surfaces. A typical parameter setting of vectorization of buildings is shown in Figure 3-58 below.
The wrongly constructed building models will be corrected manually with a ‘Building Edges’ tool set in TerraScan. Tools such as Apply Straight Line, Move Edge Vertex or Align Edge Segment, etc. An ortho image as a background or the bird view images taken along with the scanning process helps a lot for the building model modifications. Figure 3-59 below shows the correction of roof constructions of several buildings in the study area.
Manually check each of the building in the whole area until all the wrongly constructed roofs are corrected. See Figure 3-60 below. With the oblique images, which are taken with scanning process, textures of buildings can be applied on the roof and façades. This can be realized in TerraScan in a semi-automatic way. Terrain models can be triangulated in TerraModeler.

3.4.5 Ground Model Generation Based on ALS Data

As describe in section 3.4.4, a correct ground classification is crucial to many other ALS data products and ground model is one of them.

Due to the large number of laser points, a further "Modelkey Points" classification is applied on the ground points to thin the data. A Modelkey Point routine classifies the points on the ground that are necessary to create triangulations. Such as feature points on the edge or the bottom of a slope, ditch, etc. See Figure 3-61. The points that used to build the triangulated network are largely reduced after a modelkey points classification and thus the ground model will be easier to handle. Such generalization of the ground model reduces the accuracy, however, it can be controlled through settings in TerraScan.

A ground model of the study area created based on modelkey points is shown in Figure 3-62.
3.4.6 Applications of City Models Based on ALS

3D city models can be converted to CityGML format which is an open, multifunctional data format that provides a basis for 3D geospatial visualization, analyzing, simulation and exploration tools. These tools have been widely used in urban planning (Nouvel, et. al., 2014). It helps the planner, decision maker and other participants to understand the existing buildings, vegetation, transport systems and the terrain of the target area much better and easier. Noise, heat, or solar exposure analysis can be performed with different analysis toolsets. For example, a solar exposure analysis of the study area is shown below in Figure 3-63:

The city models with photo realistic textures, and other objects such as vegetation can be integrated with online applications for service-oriented industries such as hotels, restaurants, or tourism. With the VR (Virtual Reality) technology, the potential customers can “walk into” the facilities freely and even perform booking, paying etc. virtually. The City of Stockholm have tested the AR (Augmented Reality) with the 3D
city models, for instance, the planned buildings can be visualized at the future position with a smart phone or tablet (Source: the City of Stockholm).

3D map is another important application of city models. Map/navigation providers such as Google Maps, Apple Maps have been using the 3D maps for three years since 2013. Especially with the increasingly complex infrastructural facilities such as bridges, interchanges and tunnels, the users may easily get confused or lost. With the help of 3D maps, navigation becomes easier.

The large coverage and improved accuracy of the terrain models offer a new alternative to the for the large infrastructural project. With less manpower compared to traditional surveying methods, the terrain models generated from ALS data are much time and cost efficient.

3.4.7 Cost
The approximate cost of ALS based modelling is shown in Table 3-3. However, due to the large coverage of an airborne laser scanning project and many different equipment, such as scanner, airplane, total station, leveler etc. are involved, it will be hard to calculate the cost of data acquisition just for a very small part of the projects, such as the study area. It takes longer time to pre-process the data, such as flightline matching, correction and etc. The city model is reconstructed in a semi-automatic way and is just one of the end products of the ALS. It is not suitable to compare the cost with TLS and Sketchup based modeling in a simply way.

<table>
<thead>
<tr>
<th>Table 3-3: Cost of ALS Based Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Data Acquisition</td>
</tr>
<tr>
<td>Data Pre-processing</td>
</tr>
<tr>
<td>Classification</td>
</tr>
<tr>
<td>Modelling</td>
</tr>
<tr>
<td>Modell Correction</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

4 Conclusion and further study

The study investigated three different 3D modeling methods: image based, terrestrial laser scanning based and airborne laser scanning based modelling. Images and point clouds as data sources are familiar to a surveying engineer. Apparently, advantages and drawbacks of each method are shown in the case studies:

The great advantage of image based modeling is the ability to quickly create detailed 3D models with photo realistic texture at a very low cost. And a rendering process, simple analysis such as solar exposure simulation and geo-referencing can be done directly inside the software. The modeling work can be carried out without actually visiting the site if the images are provided, which allows the modelling and data acquisition work by different people and at different locations. Though it is not possible to assign attributes directly in the software, with plugins this can be achieved. Conversion to CityGML format is also possible by using plugins and software. The drawbacks of this method are the low accuracy and the lack of model inside the building. The location and size of the building are digitalized on aerial image, thus the resolution of which will largely affect the accuracy of the position and size of the building. Without an architectural drawing, the heights and the extrusion of features such as windows and doors are mainly from estimation. Even with construction drawings, the model created by Sketchup may still differ from the reality depending on the building technique. So the uncertainty of this type of model may up to several meters.

A terrestrial laser scanning based modeling is the most suitable method for reconstruction of as-built models. A HDS6000 Scanner manufactured by Leica Geosystems is used in this study. According to the
manufactory, the accuracy for a single measurement at 127000 points/second scan rate, is ±5mm up to 25 meter range and that of the modeled surface is ±1mm at the same range (The accuracy of the modelled surface is subjected to modelling method), thus, imperfection of the constructions for instances, the inclined walls, uneven floors etc. can be represented by models created based on the high-resolution scanning data and the point cloud itself has been widely utilized as documentation. With plugins, it is possible to bring the huge volume of point cloud into CAD platform such as Revit and as a result, a BIM model can be created. The drawbacks of the TLS modeling are the high cost and the difficulty to get advanced level of modeling skills. To be concrete, the initial investment of a scanner and software is huge, and unaffordable by individual users; in addition, to create detailed models demands a much longer time and more experience in modeling software than Sketchup approach. The lack of building top information is another limitation of TLS while it can be complemented by ALS data.

Airborne laser scanning covers a much larger area and provides more products such as topographic maps, DEM, city models based on the point cloud. Compared with the traditional data acquisition tools such as total station, ALS is faster and cost efficient. But due to the density of the reflected laser points, the city models are with a less level of detail. Dawid Botes (2013) studied that a typical accuracy for ALS is 5-10 centimeters and the error in height is directly correlated to altitude while according to Dahlqvist, et al., (2011), accuracy of a DTM (Digital Terrain Modell) can be in decimeters.

A general comparison on cost, time, level of details and accuracy is summarized in table 3-4. It should be noted that the comparison is only valid among the three methods discussed in this study. A plus sign shows a positive evaluation while a minus sign gives a negative and a “0” sign indicate a median value among the three.

<table>
<thead>
<tr>
<th>Method</th>
<th>Cost</th>
<th>Time</th>
<th>LoD</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Based</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>TLS Based</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>ALS Based</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

To summarize, a surveying engineers can be involved in a 3D modelling work with the data sources that they are most familiar with. However, it is important to choose a right method to balance the cost and requirements. An Image based modeling is apparently fast and cost efficient for small scale of project for visualization purposes, while TLS based modeling is accurate, detailed but more expensive. Such models can be applied in visualization, collision detection, extraction of drawings etc. Models generated based on ALS are with low accuracy and level of details. But due to advantage of the large coverage, it is widely used in for instance, GIS analysis and urban planning.

Most of modeling work in this study are still time demanding, thus an automatic or semi-automatic reconstruction of building models may be studied in the future. 3D models generated by a photogrammetry method is popular in recent years, due to the accessibility of equipment, it is not included in this study which can be very interesting for a further study.

Another interesting study would be the applications of these 3D models in VR (Virtual Reality) environment. Military training, virtual exhibition, etc have applied the technology and many potential applications are worth exploring.
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