DELINEATION OF BUILDING FOOTPRINT OUTLINES DERIVED FROM VERTICAL STRUCTURES IN AIRBORNE LIDAR POINT CLOUDS

WEI SUN SUPERVISORS: Prof.dr.ir. M.G. Vosselman Dr.ir. S.J. Oude Elberink Enschede, the Netherlands February, 2014



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DISCLAIMER

This document describes work undertaken as part of a program of study at the Faculty of Geo-Information Science and Earth Observation of the University of Twente. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the Faculty.

ABSTRACT

Building reconstruction is of great interest since they play crucial roles in the 3D city, urban planning, infrastructure development and etc. As a relatively new technology, airborne LIDAR (light detection and ranging) provides a promising way of building reconstruction automatically. Current methods for building reconstruction use the roof as the footprint which hardly satisfied all the applications.

This research proposes a method for generating a true building footprint automatically by mainly using the wall data of building. The data was well classified by my colleague Sudan Xu. A connected components algorithm is applied to identify a single building so that each building could be calculated individually. For each building, the wall which is almost vertical is extracted and filtered by the structure as the rough footprint. Owing to the characteristics of LIDAR data, the point on the wall may have some gaps lead the incompleteness of footprint. Roof outline points which are generated by a position and density based algorithm will be used to complete the gaps by some logical rules.

An existing roof based map will be used to evaluate the result. The results are visualized by point cloud mapper (PCM) and statistically analyzed.

Keywords: Building reconstruction, true footprint, wall, point cloud, airborne LIDAR

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1 Introduction

1.1 Motivation and problem statement

Building footprint outlines are vital geographic information data in many fields, such as cadastral database updating, check quality of existing footprint outlines or maps, urban planning, DEM acquisition, vegetation monitoring, telecommunication, and 3D city modeling. And many potential applications, such as energy demand, quality of life, urban population, property taxes, disaster simulation and so on(Jensen, 2009). Furthermore, accurate building-footprint data are also critical for urban landscape models construction to evaluate the effects of the urban heat island and building base elevation for flood insurance(Zhang, Yan et al., 2006).

The traditional methods, take photogrammetric analyses as an example. It has been very well developed in method and the result is also considerable accurate(Brenner, 2005), as it suffers from several disadvantages: time and money consuming; huge amount of manual work; roof overhang in images and needed for experienced operators(Paparoditis, Maillet et al., 2001; Rutzinger, Elberink et al., 2009). Because of those reasons, people start finding a novel technology to fit the needs.

the principle of Laser scanning is to acquire geo-referenced points which based on the reflectance of terrain objects(Matikainen, Hyyppä et al., 2003). Laser scanning is being classified as terrestrial laser scanning (TLS), mobile laser scanning (MLS) and Airborne laser scanning (ALS). As ALS, combined of Laser range finder, inertial navigation system (INS), global positioning system (GPS), benefit from several aspects such as: applicability, the ability of using in large forested or beyond reach areas; weather independence compare to other data acquisition methods; highly automation in most of processing; less processing time and cost(Zhang, Chen et al., 2003). It proved to be a promising data source to extract building footprints(Matikainen, Hyyppä et al., 2003), and has received considerable attention in buildings automated extraction and footprint generation in urban areas.

With the rapid development of ALS technology, the points cloud becomes denser and accurate in recent decades. The original rough 3D model of buildings, reconstruction of roof shape combined with height data, in urban area is no longer meeting the needs. More accurate and automatically generated models are needed for more precise and urgent application and analysis. The automatic detection of vertical walls and the delineation of them are essentially part of a highly detailed model.

As ALS data are the promising approach to get building footprint outlines, there are many studies about footprint extraction has been done, however, they use traditional ALS data which only have an almost nadir view which has few points on the walls. So, most of existing approaches are based on roof edge, not the position of the walls. In other words, they use roof outlines instead of true footprints of buildings.

This thesis uses a more specific ALS technology which not only has the view of traditional data, but also has a forward and backward view such that there are a lot of points on the walls. By mainly generating the true footprint of building which imply the outline of walls of building intersect with grounds and uses the roof outline to complete it if there are no wall points available, instead of the traditional methods using roof area. The result of this research should give a more accurate footprint than traditional methods. The pre-processing is conducted by my colleagues. In this case, the input data I get is the classified point cloud which the roof and vertical walls of building already segmented and well extracted. So, this method will utilize a totally different way to extract the building footprints. Footprint regularization in this paper. Furthermore, the approach should only have minor manual work or even fully automatic.

1.2 Research identification

1.2.1 Research objectives

The main objective of this research is to develop and analyze an automatic and accurate algorithm for extraction and delineation of building footprint outlines based on vertical planes extracted from point clouds as well as classified roof. To accomplish the goals, following sub-objectives has to be fulfilled:

- Determine which vertical planes belonging to a certain component of roof points.
- Analyze the disadvantages and advantages of existing footprint refinement algorithms and use them properly in the new algorithm to increase the accuracy.
- Develop an algorithm to extract building footprints according to the vertical surfaces of buildings.
- Evaluate the algorithm and improve it.

1.2.2 Research questions

- Analyze existing building footprint outline refinement methods; what are the main factors affect their performance?
- How could we use the characteristics of most buildings to help in the approach? E.g. the roof outlines should cover the walls; most of the walls are parallel to opposite one and perpendicular to the joint ones; distance between parallel roof outlines to wall should be the same.
- How to select the vertical planes that are relevant for outlining a building by using a richer dataset? E.g. which walls belongs to a certain building; which walls intersect with the ground

surface.

- How could the roof help in retaining of small structure of building walls (I.e. small outstanding part or caves.) and complete the "data missing" area due to the material or occlusion?
- How is the newly designed algorithm performance in the real dataset comparing to the digital cadastral maps? E.g. correctness, completeness.

1.2.3 Innovation aimed at

- In this paper, the data set is richer than those used in most of the existing method. It has lots
 of points on the wall due to the forward and backward scan of the scanner. The existing
 methods using the roof edge as footprint, my method should deliver a true building
 footprint which is generated from the vertical walls.
- Due to the specifics of dataset, using roof outlines to help in extraction building footprints with incomplete wall data.

1.3 Thesis structure

This thesis is divided into five chapters.

Chapter 1

This chapter contains the motivation, problem statement, research objectives, research questions and the innovation aimed at.

Chapter 2

This chapter contains the basic principle of airborne LIDAR and related work in literature. First the data-driven extraction approaches are included, and then the objected-driven extraction approaches are reviewed.

Chapter 3

This chapter contains the research methodology which composed by four phases. They are pre-processing, vertical wall extraction, roof outline extraction and complete footprint with roof outline.

Chapter 4

This chapter contains the result of every step in the methodology tested with data and analyzes the performance of each algorithm and filtering.

Chapter 5

This chapter contains the conclusion which has been made according to whole research and recommendations for further improvement.

2 Literature review

2.1 Principle of Airborne LIDAR

Airborne LIDAR (light detection and ranging) measures the height of the ground surface and other features. The Airborne LIDAR system (see Figure 1) components by three main parts: GPS (Global Positioning System), INS (Inertial Navigation System) and a laser scanner. The ground base station of GPS may improve the accuracy by DGPS (differential GPS). Accuracy of whole system could achieve few centimeters.



LASER-SCANNING

Figure 1 Airborne laser scanning (Kao, Kramer et al., 2005)

The data generated by airborne LIDAR are 3D unstructured points which are also called point cloud. Compare to the traditional method, airborne LIDAR has its own advantages and disadvantages.

Because the system is mounted on an aircraft, it could easily accesses to many areas which are hardly for mobile laser scanning or terrestrial laser scanning such as forested areas or mountainous areas. And it is less weather dependent than traditional photogrammetric methods. The output points have extraordinary accuracy and more easily for automatic process. Furthermore, the cost per point of airborne LIDAR is much lower than geodetic survey. Most importantly, the laser beam could penetrate through the vegetation so that the survey not only generates the surface of vegetation, but also has some information on the ground.

Despite the advantages, the airborne LIDAR is not perfect. Even the point density and accuracy is increasing rapidly during recent years; texture of the data is still not as detailed as image. The absorbing of laser beams in water body area leads data missing in the production is also a drawback.

2.2 Main method for building footprint extraction

Extraction of building footprint outlines from ALS data has been a hot research topic for many years. There are two main kinds of approaches: data-driven extraction and object-driven extraction. There is more research on data-driven approaches because it is more flexible. According to the existing approaches, most of them follow a certain step: classification, rough footprint tracing, and footprint refinement.

2.2.1 Data-driven extraction approaches

Data driven approach means the progress in an activity is compelled by data, rather than by object or others.

 (Zhang, Yan et al., 2006) present a framework applies a series of algorithms which could extract building roof footprints automatically from airborne light detection and ranging measurements.

Author directly connects the boundary points to generate raw footprints. The coarse result is generated by the Douglas-Peucker algorithm which generalizes lines by shaping a line by connecting start and end points, and then selecting left point with the largest distance to line before a threshold is reached by recursively. This algorithm suffers from the zigzag pattern of raw footprint outlines and leads the remove of corner vertices. For recovering the removed vertices, two classes have been defined, dominant directions segments and non-dominant directions or multiple dominant directions. The author proposes a new method based on weighted line-segment lengths to estimate the dominant directions. At last, use four types of operations according to the different situation to refine the footprints. The algorithm has been tested in the data with resolution of 0.3 meter. The refine result could successfully recover the removed corner vertices in the first class, as for the second class, it doesn't work well. After the test data, 10% of the building footprints were incorrectly removed, and 2% of the footprints are added to final result due to some mistake. The omission error of a test data set of residential areas is 6%, as commission error is 5.5%.

(Morgan & Habib, 2002) use a breakline based method to estimate and extract the footprints of buildings. Input is a classified point of building and ground which the trees have been removed. Determine the breaklines by intersecting adjacent planar facades with building, then use the centers of the bounding triangles which are generated by connecting adjacent building and terrain points. It is a rough boundary estimation method due to the

low dense of points about 1.5 points per square meter.

The experiment by 1.5 points/ m^2 shows that this algorithm has the feasibility in the low point density situation. Building boundary detection algorithm is feasible to use.

 (Sampath & Shan, 2007) presents an approach use raw ALS data tracing and regularization of building footprints. After a series of pre-processing, author connects the point cloud with modify convex hull algorithm which restricted to a rectangular neighborhood. And then use hierarchical least squares solution to regularized rectilinear boundary with the help of perpendicularity constrains.

Author uses the point of spacing at 2.5 meter and 4 meter datasets to test the algorithm. As a result, with the dense of point cloud increase, the accuracy of the result improved. The final regularization uncertainty average is 18% to 21% of LIDAR point spacing.

(Dorninger & Pfeifer, 2008) present a comprehensive approach to determinate 3D city models from ALS data automatically. After some pre-processing, author defines the raw roof footprints as the boundary of orthogonal projection of all points of a building onto a horizontal plane based on mean shift segmentation and planar face extraction. Then generation by 2D alpha-shape and the angular deviation of detection of connected, linear component within it. As a result, the footprints of buildings are adjusted to either parallel or perpendicular to initial orientation which based on the longest line segment of the boundary.

The result of using a real dataset with 6 points/m² to test the algorithm, a definition of completeness contains closeness of segment, matching of shape of footprints, and height of footprints. The result shows 75% of the buildings are completely modeled and for another 15%, more than half of the footprints have been modeled correctly.

(Alharthy & Bethel, 2002) present a building reconstruction technology which is only use ALS data. In the footprint refinement step, the input data are generated by subtracting DEM from filtered DSM with a height threshold. Author makes an assumption that for each building there are two dominant directions which are perpendicular to each other. Then rotating each building to get four maximum cross correlations for them which are the two dominant directions. After a line segment extraction procedure, the slope of them will force to two dominant directions. Finally connect the gaps between the adjusted line segments. This work is only a simple and fast method for building footprint reconstruction using only ALS data. As the author believes that it is very useful for large areas of buildings whose share the same dominant directions.

2.2.2 Object-driven extraction approaches

The object-driven means the output is fitted by different pre-defined primitives.

 (Lafarge, Descombes et al., 2008) present an automatic building extraction method based on DEM. Use a marked point process to fit primitives to footprints and use Reversible Jump Markov Chain Monte Carlo (RJMCMC) for optimal connections between adjacent primitives. This method is fully automatic but the rectangle primitive generation and connection needs a long computation time. The refinement is based on fusion which author present 4 connection configurations by calculating the costs of DEM, recovering, and contour. Finally the raw footprint composed by rectangular primitives has merged into polygon footprints.

The algorithm has been tested on a 2 pixel/m² data set. The true negative (TN) which means missing detecting is quite high at 15.3% which could be caused by low flat buildings in inner courtyards that beyond to the proposed method. If those buildings have been expelled, the TN is only 4.5%. The author should improve the method of detection to prevent these kinds of situations. The false positive (FP) which means over detected is 9.7% which could also be improved by additional vegetation mask in the process to avoid the effect the detection of trees as parts of buildings.

(Weidner & Förstner, 1995) uses high resolution DEM to extract 3D shapes of buildings. After
a series of pre-processing, author defines two types of models to fit buildings. One for flat
roof and another one for symmetric and sloped roof. First, a basic algorithm to eliminate
points on a straight line. And then, use a merge algorithm to eliminate discretization noise.
The third step is a MDL (minimum description length)-based polygon simplification which is
to enhance the rectangle conditions of corner points.

As the result of the approach is not work well in a 0.5 meter resolution in x- and y- direction DEM data set. As the data show simple building footprints generation is possible using this approach.

 (Huang & Sester, 2011) has present a bottom-up and top-down approaches to generate and refine the footprint of buddings from ALS data. By using 3D Hough transform and joint plane detection, the raw footprint has been extracted with additional 3D information. Then use rectangle as primitives to match with the raw footprints with RJMCMC. Finally, use likelihood function to optimization the result.

Author tests the algorithm by 1 meter density urban scene data set. The method has reconstruct 89.78% of the building areas which imply the completeness of the reconstruction of footprints. As the rectangle primitives could not fit all kinds of buildings, more shapes of primitives should be used for further research.

(Wang, Lodha et al., 2006) present an automatic method to generate footprints of buildings based on ALS data based on Bayesian approach. After pre-processing, points on the boundary of buildings have been found by local neighborhood search. Then a rough boundary of buildings has generated by tracing a path between neighboring points. The rough footprints have been refined by skip highly offset points. The approximate footprints have been generated by applying a graph search algorithm. The final refinement is using Bayesian approach and annealing.

As the result, 86% of the 380 footprints have been matched. The 14% is mostly due to the tree overhang and miss-classification. The result is acceptable, as the effect of trees is also

considerable and some stairwells and awnings may be lost.

2.3 Summary

Airborne LIDAR point clouds have been using in building footprint extraction for several years by both data-driven method and object-driven method. Both of them have been well developed to reach an accuracy higher than 80% which could be used in building reconstruction. As they all suffer from low point density and generate a footprint only according to the roof outlines of buildings. The processing time of data-driven methods is less than object-driven methods and the data-driven methods are not limited by primitives. The traditional method offers some good algorithm for roof outline extraction, dominant directions generation and footprint refinement. Even the density of data has been increased; the main ideas of them are still the same and will be used in this research. Furthermore, the traditional algorithm assumes the outline of the roof as the footprint of a building which could be not that accurate, because some of the buildings could have a larger area of the roof than the area of the footprint. There are still a lot of improvement spaces for footprint extraction.

Before the data-driven algorithm has been used, data classification, individual building detection needs to be accomplished. Finally, the refinement of output and result evaluation is necessary.

3 Research methodology

3.1 Introduction

This research is an experimental research, so that the methods and algorithms are developed to process the datasets. The classification data which are used as input data of this research may have some errors, so the error propagation is inevitable. Each step, algorithms and parameters are modified and tested again if it doesn't performance well. As for the result evaluation, it is not only evaluated by digital cadastral map, but also the point cloud data itself.

3.2 Framework of the methodology

The procedure of this research is separated into 5 phases which including pre-processing, vertical wall extraction, roof outline extraction, complete footprint with roof outline and performance evaluation. The whole framework is shown in Figure 2. Each phase contains several steps.



Figure 2 Overview of working flow

3.3 Pre-processing

The datasets used in this research have been classified into several classes which including roof, wall, ground, trees and so on by my colleague (Xu, Oude Elberink et al., 2012) (Figure 3 (a)). Not all the classes are useful for the research, so only the classes which have relationship with footprint extraction will be retained such as roof and wall class (see Figure 3 (b)).

The roof is shown in yellow and wall is in red. Furthermore, classified data could not reach a hundred percent right which we could clearly see a tree shape object in the center of building in the Figure 3 (b), so that the further pre-processing of the data is necessarily to be done to decrease the incorrect classification.

The goal of whole pre-processing is to extract related data, roof finding and recognize each building individually. In another word, it is to define which wall and roof belong to the building and removing some of the small incorrect classification objects.





3.3.1 Size based filtering

After the points in related classes have been selected, the second step is single building reorganization. Proposition of this step is to define the relationship of roof points and wall points. I.e. define which wall and roof belong to a certain building.

This step could be achieved by 2D connected component algorithm which could connect the roof and wall points within a certain distance in 2D. After a connected component, there are some incorrect classifications points such as trees or some street furniture are also connected as a single segment. But compare to buildings, the size of connected incorrectly classified points is much smaller and without certain angle to the ground. According to the huge size and angle difference between incorrect classified point and right points, a size and angle based filtering could handle this task. As for the least size of a building has more than 20000 points and the biggest connected incorrect object has less than 1000 points. The angle has been generated by 3D Hough transform for each small segment and check if there are less than two angle of it. There is hardly confusion between them so the connected incorrect objects could be removed correctly (see Figure 4).



Figure 4 Segment of points after 2D connected component Each component was illustrated in one color

After recognizing each building, there are some balconies were incorrectly recognized as roof and wall which should not supposed to appear on the footprint. The best way to remove those objects is using a height based filtering. But some low roofs in the dataset could have even a lower height than balconies (see Figure 5). As a result, the height based filtering will not be used in this step.



Figure 5 The height confusion of balconies and low roofs

The small pieces of yellow rectangular surface are balconies. The big one have lower height is the

low roof of the building. It is obvious that the low roof have a lower height than balconies. Then, there is another approach could be used under this case which is a 3D connected component and followed by a size and structure based filtering. 3D connected component algorithm will connect the points within a certain threshold in 3D. Compare to 2D connected component algorithm using in the last step, it also takes height value into consideration. So that the balcony which doesn't have the same height with roofs will be extracted as small pieces of segments and roof area are more flat and continue will be extracted as very large pieces of segments. Then another size based filtering will be used after the 3D connected component algorithm to select the small pieces of segments. From knowledge of architecture and common sense, most of the normal balcony is small than 3 meters long and 2 meters wide. According to the point density of this dataset, the threshold of the filter has been set to 400. I.e. the segment which is less than 400 points will be selected from the roof data. Then from the selected segments, the wall points just below it within 1 meter will be searched. If there have fewer points than threshold in that area, the segment will be removed from dataset. After this step, most of the incorrect classification of roof has been eliminated compare to original roof. From Figure 6, it is obvious that some of the small objects have been removed from the roof label and the outline of building is more regular than before. This step could remove the incorrect points as roof in most of the extents.



Figure 6 Comparison the result of 3D connected component (a) the roof points before 3D connected component, there are a lot of small rectangular convex which is the balconies of building. (b) roof points after 3D connected component with size and structure based filtering, the small segments have been removed

3.3.2 Roof recovering

Some of the wall or other objects have been incorrectly classified as roof points, and there are also some roof points have been incorrectly classified as other classes. Most of incorrect classifications of roof points are classified as ground class or other classes. To recover those roofs, after using 3D Hough transform, the horizontal segments which are larger than 10 square meters, i.e. more than 600 points with higher than 2 meters to the real ground which defined by the lowest segments of nearby ground points larger than a threshold will be selected and reclassified as a roof (see Figure 7). According to the satellite image and aerial survey images, the roof after recovering is what it should be (see Figure 8). But the small pieces of roofs could not be recovered such as the small pieces of houses in the image. This step could recover some of the incorrect classified roof points.



(a) the building before roof recovering, (b) the building after roof recovering.



(a) (b)
Figure 8 Satellite image and aerial survey image of the building
(a) the satellite image, (b) the aerial survey image.

3.3.3 Data cropping

According to the structure of buildings, an assumption has been made that only the walls within the roof area are meaningful for the footprint. Proposition of this step is further removed some enclosure and incorrect classified walls. With refined roof data, the extraction in this step will be more accurate than the one from the original data. So, for each building its walls were cropped with roof area. From Figure 9, the black points indicate for roof and grey points indicate for wall points. It is clear that there are a lot of small objects which have been detected as balconies have been removed.

Due to the incorrect classification, not all the roof area could be recovered. So the extra wall data will be removed in this step such as the concave in the left of the building. Errors in the classification step have been propagated to this step and following steps.





3.4 Vertical wall extraction

Compared to the traditional method using roof outlines as footprint, the basic new idea of this research is to generate building footprint from vertical wall data of building. The dataset was generated by a very specific technology which not only has the view of traditional data, but also has a forward and backward view such that there are a lot of points on the walls(Fugro, 2014). After the first phase, the irrelevant points were removed. According to the definition of footprint which indicates the intersection outlines of building with ground. The vertical walls should be extracted to generate the true footprints of buildings.

3.4.1 Angle based filtering

The goal of this research is to generate footprints by vertical structure of building, so vertical wall segments were extracted as sketch of footprint. Even with the specific scanning technology and filtering in the pre-processing step, data missing on the wall and imperfect on classification are still inevitable, so that the angle based filtering is necessary to help in extraction of vertical wall and removing of misclassified trivial. There are many methods for plane extraction, among which 3D Hough transform in combination with surface growing (Vosselman, Maas et al., 2010) is used

in this research.

The angle of each segment is defined as the acute angle to the ground. After the angle of each plane is generated by 3D Hough transform, the angle attributes between 80 to 90 degrees compare to ground will be extracted. Because the point data may have some bias in acquiring, rather than only extract the vertical segment, give a small threshold may help extract more useful segments. And according to the regular angle of most buildings, this threshold works well for most of times (see Figure 10). The wall on the left side has not been selected is because it only contains one line of points which could not simulate a surface by 3D Hough transform. As mentioned before, even the new technology brings more points on the wall; there may also some point missing area in the dataset. After this step, all the vertical wall segments have been extracted, but not all of them are useful in the footprint. Such as there are some walls segments caused by multiple roof structure of the building like the down right of the figure.



Figure 10 Result of angle based filtering (a) before filtering, (b) after filtering

3.4.2 Structured based filtering

The structure of the buildings could be very complex. Some buildings have a kind of multiple roof structure which is indicated the building has multiple layers of stair like roofs. For this case, the walls appear above the roof area will have no help to the footprint and affect the accuracy because they could lead to some error in the logical rules and approaches of delineated wall lines connection. The structured based filtering is designed to remove those points.

The algorithm works like for all wall points will compare the height value with nearby roof points. If there are roof points lower than that wall point, the wall point will be removed from dataset (see Figure 11).



Figure 11 Result of structure based filtering

3.4.3 Delineation and refinement

To generate the footprint of the building, the filtered vertical wall has to be delineated. 3D Hough transform already divided all points into different planes and mark the points of each plane as different segment. Then for each segment estimates a line by Least Square method in 2D:

$$\frac{\partial S}{\partial \beta_j} = 2\sum_i r_i \frac{\partial r_i}{\partial \beta_j} = 0, j = 1, ..., m$$

And since $r_i = y_i - f(x_i, \beta)$ the gradient equations become $\sum_{i=1}^{n-1} \frac{\partial f(x_i, \beta)}{\partial x_i, \beta}$

$$-2\sum_{i}r_{i}\frac{\partial f(x_{i},\beta)}{\partial\beta_{j}}=0, j=1,\dots,m$$

 x_i is an independent variable and y_i is a dependent variable whose value is found by observation. The model function has the form $f(x_i, \beta)$, where the m adjustable parameters are held in the vector β . r_i defines the Ith residual, then S can be rewritten $S = \sum_{i=1}^m r_i^2$. S is minimized when its gradients vector is zero. The elegant direct estimation is based on second order moments of the coordinates.

The delineated line was presented by two edge points. So the footprint was presented by a set of points.

Before the next step, an assumption has been made that there are two dominant directions for each building. So the dominant directions of the building have to be defined and then adjust all the delineated lines. A There are two main methods to calculate the dominant directions of buildings. First one is simply set the direction of the longest wall as the dominant direction and calculates another one by the perpendicular relationship of them. Second one is calculating each direction of a wall and using their length as weight to calculate the dominant directions.

An assumption has been made by experience and logical that for the building in a certain area should have more potential to have the same dominant direction. By this assumption, two methods could compare with each other.

The second method is to calculate an initial direction by the direction of the longest segment at first. Then for each segment, a slope will be calculated and compared with initial direction and forced to classify into two parts.

$$\text{Dominant direction} \begin{cases} \frac{\sum_{i=1}^{n} direction_{i} * length_{i}}{\sum_{i=1}^{n} length_{i}} & direction_{i} \in dominant direction1\\ \frac{\sum_{j=1}^{n} direction_{j} * length_{j}}{\sum_{j=1}^{n} length_{j}} & direction_{j} \in dominant direction2 \end{cases}$$

Table 1 shows two dominant directions of each building in the study area and result has been retained three decimal places. The standard deviation of each column has been calculated which shows how much variation or dispersion from the average exists. The first method which takes longest wall's direction as the dominant direction has lower standard deviation than the second method.

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^2}$$

Which x_i indicate the value of each domination directions; μ indicate the mean value of dominant directions; N indicates the total number of samples; finally, σ imply the value of standard deviation.

	Longest wall as dominant direction		length weight direction	
building1	0.874	-1.144	0.922	-1.084
building2	0.886	-1.129	0.869	-1.150
building3	0.869	-1.150	0.892	-1.121
building4	0.876	-1.142	0.895	-1.117
building5	0.878	-1.139	0.884	-1.131
building6	0.885	-1.130	0.817	-1.224
Standard Deviation	0.006	0.008	0.035	0.047

Table 1 Compare of two method of dominant direction selection

Figure 12 shows the stability of two methods. The X axis illustrates the number of buildings; Y axis shows the dominant direction. The break line shows the method which takes the longest wall direction as the dominant direction, as the solid line shows another one. It is obvious that the break line which indicates the former method is more stable than the solid line which indicates the second method.



Figure 12 Comparing of two methods

Break lines indicate the method which takes longest line's direction as dominant direction; Solid

lines imply the method which takes all the direction of lines and using their length as weight The reason why the first method which set the direction of longest wall as dominant direction and calculates another one by the perpendicular relationship is more stable is that when classify the segments direction belong to which initial dominant direction, it will be forced to one of them. As the building could have some vertical walls which should not belong to any of the two dominant directions. They will affect the result of length weight method even they are not very long.

After analysis of the two methods, the first method which takes the longest line direction as the dominant direction is used, because the first method is more stable than the second one according to the assumption which has been made in this research.

After the dominant direction has been set, adjust the direction of each delineated line by the direction of the longest one. Then refine the delineated lines by calculating a new line which would instead of two nearby parallel lines.

Another assumption has been made that if two lines are parallel to each other, within a certain distance and have huge length difference, the shorter one will be considered as balcony or other trivial which misclassified as roof and wall and be removed. Proposition of this step is to refine the wall lines so that the further corresponding lines finding could be more accurate (see Figure 13).



Figure 13 Result of wall delineation and refinement

3.5 Roof outline extraction

Even the dataset is richer than the traditional one; the points on the wall may not be able to complete the whole footprint itself. Rather than simply connect the delineated vertical walls, using roof outline data to complete them could bring a more accurate result. In other words, the place where wall lines are shorter than the roof outline, the wall line will be extended; the place without vertical wall lines will be completed by the roof outline.

3.5.1 Outline extraction

This research uses a position and density based algorithm to extract the outline. For each point, the algorithm first selects all the point within a certain radius and cut the nearby space into 4 parts by 30° to the dominant direction (see Figure 14(a)). Then calculate the position of selected points. If there is no point in least one and as much as three parts, this point will be marked as outline point (see Figure 14(b)). The advantage of this algorithm is that it is simple to implement and could generate almost the same result with Alpha shape. As the disadvantage is for the points at the concave corner, they will not be extracted because there is no part is empty. How many points are missing at the concave corner depends on the half of the radius of selected circle. This algorithm works well on real data test (see Figure 15).



Figure 14 Principle of position and density based algorithm (a) distribution of 4 parts, (b) simple example





3D connected component has removed some balconies which have been incorrectly classified as roof and the data cropping has been removed some roofs which have been incorrectly classified as walls or other classes in multiple layer roof area. Ordered outline points could remove some small concave caused by incorrect classification which shown in the black circles in the Figure 16.



Figure 16 Trivial concaves caused by incorrect classification The black circle indicate the trivial concaves

After a simple line growing algorithm, the extracted outline points have been merged to different segment according to which line it belongs to (see Figure 17 (a)).

Start from X minimum value of segment number 0, calculate the distance to each point of the segment and give them ordered point number according to the increasing of distance then finds the next segment. To find the next segment, it will start searching at the point which has the largest distance in the last segment. From last point, the algorithm will find the nearest point in other segments within a threshold to be the beginning point of the next segment. And go on till there is no point could be found. Then start a new segment of those who haven't been iterated. Then continue with before steps until there is no point left in the roof outline points. Small segments with different order value with nearby segments will also be removed. After this, all the points were being well ordered.

Then is the filter of small concave or other kinds of small annular structures. The filter works if there is a point number jump in a certain threshold distance of any point. The points with point number within the jump points will be removed. In this case, small and illogical structures which caused in data acquisition and classification could be removed (see Figure 17). Finally, the filter may leads a more accurate and regular result.



(a) before order filtering, (b) order value based filtering

3.5.3 Roof refinement

After segment and refine the roof points, delineate each segment is necessary for further process. For a better view of what have been done in this step, the outline before 3D connected component will be used, because the roof of sample building outline after 3D connected component step is more regular and shows little change in the three rules. The segments have been delineated by Least Square method and set extreme order value to two points which define the line (see Figure 19 (a)). After the delineation, there are some overlap, gaps and cross of the roof lines. They are refined by three logical rules.



Figure 18 Three refine rules

(a) rule 1, (b) rule 2, (c) rule 3. Solid line indicate for roof lines; break lines imply for the lines which have been removed

Rule 1: if several lines are parallel to each other within a certain distance and have continued order value. They will be recalculated with a new formula from X minimum value to X maximum

value in those lines. The extreme order value is also saved into two points of the new line (see Figure 18 (a)). The implementation of rule 1 is illustrated in Figure 19 (b).

Rule 2: If two lines are perpendicular to each other with continued order value, they will be connected (see Figure 18 (b)). The implementation of rule 2 is illustrated in Figure 19 (c)

Rule 3: If several lines are parallel to each other within a certain threshold in perpendicular distance and have continued order value. Two lines which are perpendicular to the original lines will be added on both sides of the short line and connected with the other two lines (see Figure 18 (c)). The implementation of rule 3 is illustrated in Figure 19 (d).



(a)

(b)





(a) delineated roof outline, (b) result of rule 1, (c) result of rule 2, (d) result of rule 3

Compare the roof outline with roof points (see Figure 20). Most of the outlines are well delineated, but if there are some outlines which don't follow the two dominant directions will be force to one of the dominant directions which could leads some changes in the footprint.



Figure 20 Compare of roof outline result and roof points (a) roof points, (b) delineated and completed wall

3.6 Complete footprint with roof outline

Before complete the footprint with roof outline data, the wall data has to be removed if its roof outline was removed in the previous step which according to the pervious assumption that only the wall has roof above is meaningful in the footprint. The wall data has to be refined by removed points in the roof connected component step near both edges and order filtering step (see Figure 21). The small line which has been delineated in the vertical wall extraction step caused by incorrect classification has been removed because there are some points near both of its edges.



3.6.1 Find corresponding lines

After wall data refinement, the completion of wall lines could be started. This step is to increase the length of the wall lines by roofs. For each line of the wall may find one line in roof lines which are parallel and within a certain distance. If the roof line is longer that wall line, the wall line will be increased as long as the roof line (see Figure 22). Proposition of this step is to complete delineated wall lines by roof lines. So if there are some data missing in some part of the walls and with roof data nearby, they will be repaired.



Figure 22 Result of wall and roof corresponding

3.6.2 Complete missing data

After the corresponding, there are still a lot of lines which could not connect with each other. There is hardly any point on the walls supporting the low roofs and the low roofs will also remove the wall points which above them. This situation will lead break in wall lines. So to complete the rest of lines is still necessary. An assumption has been made that for each line, it should connect with at least two lines nearby and perpendicular to it. According to the assumption, for each line in the wall lines if there are not more than two lines which are nearby its two edges and perpendicular to it. The line will be marked and finding corresponding perpendicular lines in delineated roof lines. There will be three situations in this case.

The first situation is that one or both of the edges has no perpendicular line nearby, and one or two perpendicular roof lines were findable, the perpendicular lines will be marked as wall lines. The second situation is that if the wall lines are empty on both edges and could not find any line nearby and perpendicular to it in roof lines, it will be marked as trivial and removed. The third situation is that if the wall lines are empty on one edge but has a shorter roof line nearby, the length of wall line will be decreased as long as roof line and find the perpendicular lines (see Figure 23).



Figure 23 Two rules of complete missing data

(a) and (b) shows two cases of rule one, (c) shows the line remove of rule two, (d) shows the line's length decrease of rule three. The grey lines indicate the lines belong to roof lines; solid lines indicate the lines belong to wall lines; break lines imply the lines which would be deleted from wall lines

After this step, the sketch of footprint has been generated (see Figure 24). If the roof is not much larger than wall, the sketch will not have big difference after refinement.



Figure 24 Result of complete missing data in wall by roofs

3.6.3 Data refinement

After the data completion is done, the final step is to refine them. There are two rules for this refinement. First rule is to remove the illogical lines which generated by incorrect correlation or other reasons from previous steps. It defines that each line should connect with one

perpendicular line on both sides of it. There may have some lines which have more than two perpendicular lines nearby. So, the idea to deal with this situation is that if a line near more than two perpendicular lines, only the lines with extreme value are retained. In other words, the minimum value in X coordinate and maximum value in X coordinate of projecting points from the perpendicular line to the selected line will be retained (see Figure 25).



Figure 25 Result of first rule which remove multiple connected lines

The second rule is snapping all the lines nearby according to the logical that each line should connect with a perpendicular lines on each side of it (see Figure 26). After this step, a final refined footprint of building has been created by vertical structure of the building.



Figure 26 Result of second rule which snap the edges

3.7 Summary

In this chapter, the methodology of this research was presented. Four phases of the methodology were described exhaustively. The original dataset has been classified, so the input data of this research is unstructured roof and wall points which may contain some misclassified points.

Size based filtering was used after connected component with two dimension matrix to remove other objects which misclassified as roofs or walls and extract each building individually. Then a 3D connected component combined with a size and structure based filtering has been used implemented to remove balconies or other convex objects which should not belong to the footprint of the building. After that, some of the incorrectly classified roof points have been recovered by size, angle to the ground and height. For each building crop the data with its roof area according to the assumption that the walls out of the roof area should not be a part of the footprint of the building.

The innovation of this research is to generate footprint with wall data. Wall angle data which generated by 3D Hough transform were the acute angle to the ground, and then filtered by an angle based filter. As there may have misclassifications and biases in wall data, the threshold in angle based filtering has been set from 80-90 degree. There are some of the buildings in the study area have multiple roof structure which could influence the footprint extraction. The structure based filtering which could remove the wall data above roof area is necessary after a size based filtering. After that, wall data were delineated by Least Square method and adjust the

direction by the dominant direction of building which generated by direction of the longest segment.

Even the dataset is richer than the traditional ones, there are also some data missing for wall. Using the roof outlines to complete the gaps in delineating wall lines is the best way to generate the footprint of buildings. This research uses a position and density based algorithm to extract the outline point of the roof. There may be some small holes which could be caused by several kinds of situation and also be extracted as an outline of the roof. Therefore size based filtering is used after a connected component analysis. Then generate segment by line growing algorithm. Set the order value to all the points by giving sequence order value from the beginning of one segment to the end and goes to next nearest segment until all the segments have been iterated. Then if there is an order value jump in certain threshold, the points of having the order value within the jump points will be removed. Data set was refined by three logical rules after delineating the roof outlines.

The final step is to complete footprint by delineating roof outlines. Use removed points from roof connected component step to remove the corresponding wall data according to the assumption that if the roof area is small enough to be removed, its wall data are also useless. The lengths of wall lines are increased with corresponding roof lines which are parallel and nearby them. For those wall lines which could still not connect with other lines will be complete by corresponding perpendicular roof lines of empty edge. Then the lines which are empty on both sides will be removed as trivial data and the longer wall lines will be shortened. The rest of wall lines are refined by a simple constraint that each line could be only perpendicular with two nearby lines. If more than two lines are connected, two extreme lines will be retained. Finally, the sketch footprints will be connected with two near perpendicular lines. After the two rules, the final result of the footprint is generated.

4 Results and analysis

The data which used in this research are acquired by Furgo Aerial Mapping Company using their special surveying techniques, FLI-MAP 400(Fugro, 2014). This technique could offer a fast, accurate point cloud with more points on vertical structures. Because it uses an oblique angle scanning of both 7 degrees forward and 7 degrees back from nadir. The scan angle is 60 degrees with 150-250 scans per second. Point density of the dataset is 64 points per square meter which are denser than traditional methods. For some vegetation area, the density could be doubled because the multiple echoes of vegetation. The accuracy for the hard level surfaces is 3 cm.

There are two pieces of test dataset they all located in Rotterdam, Netherland. Because it uses an oblique angle scanning of both 7 degrees forward and 7 degrees back from nadir, so that there are more points on the wall. By using a richer dataset which has more points on the wall, the innovation of this research has been taken out that using the vertical structure to extract the footprint of buildings which should be more accurate than using roof outlines. The experimental data were acquired in February 10th, 2010. In the study area there are totally 42 buildings (see Figure 27) which totally 85,000 square meters building area are selected for testing this proposed algorithm. The yellow points indicate the roof of building; red points imply for the wall data; orange points shows the trees; the blue points express for the ground; green points mean the water area; cyan points indicate the stuff on the roof; white points represent the rest unrecognized points; There are totally 7 classes in the classified dataset. The result of footprints have been transformed into ARCGIS and compared with a digital cadastral map which was generated by the roof outlines of the buildings.

For a better view of the changes in each step, the following result only shows a small part of whole study area.



Figure 27 Overview of data of study area

4.1 Analysis of pre-processing

4.1.1 Result of size based filtering

The first size based filtering is using the size difference of buildings and misclassified trees, street furniture or other objects to remove the misclassified objects. This step increases the correctness of the classified data. It is obvious that some trees and other objects which not belong to the building are deleted from the small area in Figure 28.



Figure 28 Connected components and size based filtering (a) before size based filtering, (b) after size based filtering. The small pieces of incorrectly classified segments have been removed after the filtering

After the single building has been extracted, the 3D connected component with size and structure based filtering is used for each building. It could remove incorrectly classified roof segments such as balconies and other small objects. The result of this step is shown in Figure 29. It is clearly to be seen in the grey circle that there are some incorrect classification which lead more roof segments have been removed.



Figure 29 The result of 3D connected component with size and structure based filtering

4.1.2 Result of roof recovering

The mistakes in the roof class could be incorrectly identified and incorrectly rejected. The 3D connected component could remove some of the incorrectly identified points which indicate the points belong to other classes incorrectly identified as roof. This step could recover some of the incorrectly rejected points which imply the points belong to the roof class but incorrectly rejected to recognize as roof. I.e. they have been recognized as other classes such as ground class, other classes and so on. It uses the 3D Hough transform to detect the semi-horizontal planes larger than a certain size and 2 meters higher than the lowest pieces of nearby grounds and recover the back to the roof class (see Figure 30). According to the satellite images and aerial survey images, most of the recovered roofs are right. The false negative features areas which generated by using digital cadastral maps erase the generated footprints decrease from 5761 to 2399 after roof recovering. In another word, this step may recover more than half of the incorrect classified roof points back and increase the completeness.



(a) the footprints before roof recovery, (b) the footprints after roof recovery. The black circles show the obvious changes of the footprints. According to the satellite images and aerial survey images, the recovered roofs are right in the reality.

4.1.3 Result of data cropping

This step makes an assumption according to the reality that only the wall within the roof area is meaningful for the footprint. Under this constraint, data is cropped by roof area. Small objects such as a balcony which has been classified as wall and without a roof above will be removed in this step (see Figure 31). Even after last step to recover the roof segments, there may be some mistake in the classification. Some roof points were incorrectly classified as wall points because of multiple reasons such as the complex structure of the building. They could not be recovered and may lead more wall data be deleted.



Figure 31 Result of data cropping

4.2 Analysis of vertical wall extraction

4.2.1 Result of structured based filtering

After the angle based filtering, all the vertical wall segments have been extracted. As the footprint of the building indicates the wall data which intersect with ground. From both architecture and logical, for some building which has multiple layers of roofs, the wall just above the roofs will not be a part of the footprint. After a series of experiments, a constraint has been made to filter the data that all the wall points which above the roof area within 0.2 meters of horizontal distance will be removed. With the threshold of 0.2 meter, the threshold is big enough to remove majority of the wall points above the roof area but not too big to delete irrelevant nearby wall points. Result of this step is shown in Figure 32.



Figure 32 Result of structure based filtering

4.3 Analysis of roof outline extraction

4.3.1 Result of ordering and filtering

This research is using a position and density based algorithm to extract the outline of the roof. Compared to well-known Alpha shape which is using a disk with certain radius rolling around the dataset, they could generate almost the same result and this algorithm is simpler in implementation. Both of the methods suffer from incompletion at the concave corner.

After segmenting the data, the ordering algorithm is iterated through all the segments. According to the experiment and knowledge from architecture, the radius of searching order number jump has been set at 1 meter which could remove small trivial in dataset as well as retain some small concave structure of the building. Some small trivial objects caused by incorrect classification and extraction algorithms have been eliminated. The result is presented in Figure 33. The small figure on the right corner is the roof outlines before the ordering filtering. It is obvious that some of the small trivial parts have been removed and the roof outlines is more regular.



Figure 33 Result of ordering and filtering by order number

4.3.2 Result of roof refinement

Each segment of roof outline points from last step was delineated by Least Square method and adjusted by dominant directions of each building. The roof refinement is based on three rules which connect nearby lines by their order number defined in the previous chapter (see Figure 34). The cyan lines indicate the delineated roof outlines, and the blue points imply for the roof points. Most of the roof outlines fit the edges of roofs well, but there are some round corner of the building may lead zigzag patterns which have been shown in red circles are caused the constraint that each building only has two perpendicular dominant directions.





4.4 Analysis of complete footprint with roof outline

Owing to the assumption that the small hole on the roof may could be some trivial and removed, the wall has relevant to that hole should also be deleted. The left walls will find corresponding lines and complete missing lines according to the roof lines. Then to refine all the lines to force them connect with only two perpendicular lines. The final step is to remove the potential balconies which were defined as for the lines have two short perpendicular lines connect with it with same the direction, the selected line and two gap lines within a certain distance and the selected line is shorter than two gap lines. All the five lines will be deleted. Then calculate a new line based on the gap lines. After former processes, the final footprints of the study area have been generated. The generated footprint is shown in black lines in Figure 35, and the digital cadastral map is shown in grey polygons. For most parts, the footprint works well, but there are some places which don't fit. The main reason for them is the incorrect classification of the point clouds. They have been incorrectly classified into other classes but not meet the condition of roof recovery step because they are too small or have some noise nearby to fit a semi-horizontal plane. Even with lots of algorithm or approaches to remove or recover the data, the error propagation is inevitable.



Figure 35 Final result of footprint generation

4.5 Analysis of using the ground points

In the beginning of the research, the assumption of using ground points to help in footprint generation has been made. But after a series of experiments, this assumption will not work so well because of the transparent of the LIDAR. It may go through the glasses of building and shoot into the building. This may lead to some strange pattern on the ground which is shown in Figure 36. There are some grounds points in the building which it not supposed are there. So, the footprint generated in the former steps will not be adjusted by ground points until there is a good way to separate whether the points are into the building or not.



Figure 36 The strange pattern caused by transparent or multi-path problem The red points indicate the position of walls. The blue points imply the ground points.

4.6 Quality assessment

For compare to digital cadastral map which generated by roof outlines in ARCGIS, the outlines have been transformed to shape file (see Figure 37).



Figure 37 Comparison of digital cadastral map and transformed footprint shape file The black lines indicate the footprint generated by this thesis. The grey polygons imply the footprint which generated by roof outlines from other method.

The accuracy analysis calculates the completeness, correctness and quality. TP indicate the True positive which is the delineated area is inside the roof point area; FP indicates the false positive is the area which belongs to the delineated area but not a part of the roof point area. FN indicates the false negative which is the roof point area which outside delineated area inside.

$$Completeness = \frac{TP}{TP + FN}$$
$$Correctness = \frac{TP}{TP + FP}$$
$$Quality = \frac{TP}{TP + FN + FP}$$

The result of accuracy analysis has been illustrated in Table 2.

Table 2 Accuracy analysis of study area

data name	completeness	correctness	quality	
study area	97%	96%	93%	

The Figure 38 shows the completeness and correctness of all the 42 buildings. The grey line indicates the correctness and the black line implies the completeness.



Figure 38 The accuracy analysis of all the buildings in the study area Black line indicates the completeness and grey line indicate the correctness.

The figure indicates that the completeness is more stable than correctness. The minimum value of completeness is higher than 92% and for an average of 97%. The minimum value of correctness is 59% and for an average of 96%. According to the assumption which has made at beginning, the correctness should give a high value because the vertical structure should give a smaller footprint than roof outlines, so that the correctness should larger than completeness if the footprint is correct. For most of the buildings, the correctness is higher than completeness. But there are some exceptions. According to the reasons which lead to the mistake, they have been classified to 4 classes. First reason is the small pieces of incorrectly classified segments which are not meeting the conditions of roof recovery step. This could lead some part of footprint missing or some small buildings disappear on the footprint. Second reason is the small pieces of roofs which have different height with other big pieces of roofs and without wall points under them have been removed by the balcony remove filtering. The third reason is the buildings which don't follow the constraint that each building only has two dominant directions or the two dominant directions are not perpendicular to each other. The fourth reason is there may be some mistakes in the digital cadastral map. In the following chapter, each class of mistake will be analyzed.

The sample of first class of mistake is shown in Figure 39. (a) and (b) have the completeness which is 95% and 93%. The reason for this is that one of the roofs with different height with others has been incorrectly classified to wall data which are a part of footprint but not big enough to recovery which has been shown in green circle. For the rest part of those building, the algorithm works well. For (c) is the digital cadastral map and (d) is the classified points cloud. The small buildings in the red circle indicate the incorrect classified buildings as other classes and not big enough to recover.





(b)



(d)

Figure 39 Samples of first class of mistake

(a) and (b) indicate for the building which has some part of roof with different height has incorrectly classified to wall class. (c) is the digital cadastral map and (d) is the classified point clouds. The red circles in (c) imply the small incorrect classified buildings which are not big enough to be recovered.

The sample of second class of mistake is shown in Figure 40. The blue lines indicate for the footprint generated by this research and yellow polygon imply for the building on digital cadastral map. The green circle indicates where the second class of mistake happens. The small piece of roof has not enough points below 1 meter of it to keep it as roof. As the result, this small piece of roof has been incorrectly removed. The completeness of the building is 94% which lead by the mix of both first and second class of mistake. The correctness of the building is 97%.



Figure 40 Sample of second class of mistake

In (a), the blue lines indicate the footprint which is generated by this research; the yellow polygon implies the outline of building of digital cadastral map. The green circle shows the second class of mistake. (b) is the point cloud of the sample building, the green circle shows the low roof which has few points below it.

The sample of third class of mistake is shown in Figure 41. The blue lines indicate for the footprint generated by this research and yellow polygon imply for the building on digital cadastral map. The building in (a) has two dominant directions, but they are not perpendicular to each other. So this will leads the zigzag pattern on its footprint. With the effect of not perpendicular dominant direction, the completeness of this building is 97% and the correctness is 93%. The building in (b) has more than two dominant directions. But they have been forced to the dominant directions which defined by the longest wall of the building. As the result, it has been generated a very strange pattern at the bend part of the building. The completeness is 92% and the correctness is quite low is 77%. This is one of the nadirs of Figure 38.



Figure 41 Sample of third class of mistake

The blue line shows the footprints generated from this research; the yellow polygons show the buildings on digital cadastral map. (a) indicate the building which its two dominant directions don't perpendicular with each other. (b) imply the building which has more than two dominant directions.

The sample of fourth class of mistake is shown in Figure 42. In (a) the blue lines indicate for the

footprint generated by this research; the yellow polygons imply for the building on digital cadastral map. (b) shows the aerial survey images. It is clear to be seen that there is a roof between the buildings which could be also implied by the trunk missing for the trees. According to the images, the conclusion could be made that for this building the footprint generated by this algorithm is right and the building outlines in the digital cadastral maps is wrong.



Figure 42 Sample of fourth class of mistake

The blue lines in (a) show the footprint generated in this research; the yellow polygons indicate

the buildings in digital cadastral map. (b) is the image which captured by aerial survey. After analysis four kinds of mistakes, the outliers in Figure 38 could be marked with mistake class and images which are shown in Figure 43. This figure indicates three of the four of outlines with



Figure 43 The mistake class for low accuracy buildings.

If some of the obvious fourth kind of mistake in the digital cadastral map were removed. The

accuracy analysis diagram should be Figure 44. And both of the correctness and quality have increased for 2% and shown in Table 3. But according to the assumption of two perpendicular dominant directions made at the beginning of this research, class 3 mistakes are hard to eliminate.



Figure 44 The accuracy analysis of buildings except third kind of mistake in the study area Black line indicates the completeness and grey line indicate the correctness.

Table 3 Accuracy analysis after remove the third kind of mistake which leads by incorrect of digital cadastral map

8F			
data name completen		correctness	quality
study area	97%	98%	95%

According to the assumption in the beginning of the research, the footprint has been generated by vertical structures which should not be bigger than the digital cadastral map if both of them are right. From Figure 45, three buildings have been selected and shown the detail of edges. It is obvious that the footprint lines which are shown in yellow are within yellow roof points and the green grid shows 1 meter for each mark. For some roof outlines even 0.5 meters larger than wall footprints. This may indicate that for some buildings, the generated footprints are smaller than the roof outlines.



Figure 45 Relationship of delineated footprint and roof point

According to the false negative features which are generated by using digital cadastral map to erase generated footprint, it is obvious to see that they are all at the boundary of the buildings (see Figure 46). For a clear view, those features have been enlarged. Furthermore, the areas of completeness feature are 2399, as the areas of correctness features are only 1438 if some obvious forth class of mistake has been eliminated and among which there are nearly 400 areas are leads by the buildings which have more than two dominant directions. This may imply that the generated footprint have a smaller size than the digital cadastral map which generated by the roofs of buildings.



Figure 46 False negative features of the whole area.

Those images and statistics of lower completeness than correctness of this research prove the footprint generated by vertical structures should be smaller and logically more accurate than the normal map.

4.7 Summary

In this chapter, the algorithm has been tested on a group of buildings in the study area. For each step, the parameters have been tested according to knowledge and experiment; the algorithms have been analyzed and shown in figure. The quality of final footprint is 95% if some of the class 4 mistakes have been removed which indicate for the incorrect part of digital cadastral map. There are three main problems lead to the incorrect of footprints. First reason is the small pieces of incorrectly classified segments which are not meeting the conditions of roof recovery step. This could lead some part of footprint missing or some small buildings disappear on the footprint. Second reason is the small pieces of roofs which have different height with other big pieces of roofs and without wall points under them have been removed by the balcony remove filtering. The third reason is the buildings which don't follow the constraint that each building only has two dominant directions or the two dominant directions are not perpendicular to each other. Those three reasons may lead to the rest 5% of mistake in the footprint generation.

And according to the lower completeness than correctness, the comparison of generated footprint with laser points clouds and the confrontation of generated footprint with digital cadastral map. The conclusion could be made that the footprint generated by this research could

give a result which is not bigger than the digital cadastral map which generated by roofs. The size is depending on the roof structure of the buildings. In another word, the footprint generated by this algorithm is more logical than digital cadastral map which generated by the roof.

5 Conclusion and recommendations

5.1 Conclusions

To generate an accurate footprint of buildings by their vertical structure, a conceptual framework and a series of algorithms has been proposed. The framework contains pre-processing, vertical wall extraction, roof outline extraction and complete footprint using roof outlines. Finally, the result footprint has been analyzed and the difference for footprint with digital cadastral map has been given. Several conclusions can be drawn based on the analysis of the result.

- 2D and 3D connected component algorithm could cluster the nearby points belong to the same object. By using this method combine with a size and structure based filter, the small classified incorrect objects such as trees, street furniture or walls could be removed from dataset.
- Roof recovery step could recover some incorrectly classified roof data back. It could increase the accuracy of footprints
- Data cropping is a necessary step to remove some incorrect classified points and balconies which out of the roof area. So that the wall extraction step could have a better input data.
- There are some walls which should not appear on the footprint because they are the walls of multiple layer roof structure which has been mentioned in former chapter. They may not have any help in footprint generation but also leads to some trivial in the refinement step and increase the logical complex of refinement algorithm.
- After the outlines of the roof have been extracted, give the right order to them is essential to remove some small trivial in data caused by incorrectly classified concaves.
- According to the assumption and data test, the walls will be removed if their roofs which have been removed in the roof outline extraction phase. This could further refine the footprints.
- Using delineated roof outlines to complete vertical wall lines is necessary. Because even this
 research uses a richer dataset than traditional ones, there are still many gaps of wall lines.
 According to the research assumption that if there are no wall lines in a certain area, the
 roof lines will be used as footprint.
- The assumption that using ground points of help increase the accuracy of footprint may not be used because they are not stable enough for all the buildings which could lead a low accuracy for some buildings.
- The result analyses also prove the assumption which has been taken out in this research that the footprint generated by wall could have a logically higher accuracy than the ones generated by roofs.
- This research could identify some buildings which are incorrectly outlined in the municipality

within small samples.

5.2 Recommendations

The result of this research proves it accomplishes the research objectives. As the limitation of knowledge and time, there are still a lot of improvement could be done in further works and listed as follows:

- Some reference data could help in classification the points. Images captured during the acquiring of laser points are recommended for a higher accuracy result.
- The study area only covers a part of the overall dataset with limited of building type. If the algorithm could apply for the entire city or even larger, the accuracy analysis could give a more meaningful result.
- The result of classification of points could affect the result of footprints in a huge extent. Even the dataset has been well classified and some of the incorrect classified points have been recovered; the errors still remain for some points. For a better output of footprint, a more accurate classification method with more classes is recommended.
- Because of the shape and height similarity of some small roofs and balconies, it is difficult to distinguish them from each other perfectly. A more accurate algorithm to recognize them is necessary for further research.
- Each building could have multiple dominate directions instead of only two dominant directions defined in this research and two dominant directions of building could not perpendicular with each other.
- The calculation of dominate directions could be a length weight one but not force all the lines to two domination directions, but only take the similar ones. So that the stable and accurate could be higher.
- The threshold of ordered filter could be further improved by some parameters of building to best fit most of the buildings.
- An algorithm for judging whether the ground points could be used is important if the ground points are going to be used to increase the accuracy of generated footprint.

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