

[DRAFT] SEMANTIC ANNOTATION OF  
URBAN SCENES:  
SKYLINE AND WINDOW DETECTION

**MSc Thesis**

written by

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## **Abstract**

We build an automatic system that adds semantics to a urban scene. A 3D model was extracted by combining the *FIT3D toolbox*[11] combined with a skyline detection algorithm. The skyline detector extracts straight line segments from the upper edges of an image. These are used to set the heights of the walls of the 3D model. Next, windows are extracted by two different methods. The first method searches for connected horizontal and vertical edges which come from the window frame. The second method works on rectified facades and consist of 1) the determination of the alignment of the windows and 2) the classification of the windows. The alignment and classification are based on the interpretation of the Histogram function of a Hough transform of the edge image. Both methods detect at least 99% of the windows.

# 1 Introduction

When we humans look at an urban scene we immediately can tell which part represents a building, a tree, a door, a window or a parked car. Even if the scene suffers from high occlusion (a tree occluding the largest part of a building) or extreme perspective distortion (a building seen from the corners of your eye) we perform this task with a very high accuracy. For a computer system however, this task is far from trivial.

Let us address the question that arises many times in Artificial Intelligence: Why are we humans so good in this task? What can we learn from ourselves and how can we apply this on a computer system?

The most important reason of our excellent visual perception is that we combine a series of depth cues [24] (which enables us to experience depth) with top down processing (which enables us to classify objects).

One of the most important depth cue is stereopsis. We use two eyes and look at the same scene from slightly different angles. This makes it possible to triangulate the distance to an object with a high degree of accuracy [24] [12].

Objects are classified using a widely supported theory in psychology: top down processing [4] If we want to perceive a window, we tap into the neurons that are activated according to our (generalized) description of a window. I.e. because windows are often rectangular shaped and the color stands out we tap into the neurons that perceive straight parallel lines, orthogonal corners and intense color changes. These visual processes are extremely informative if we want to build a computer system that acts accordingly.

This thesis is about our work of an automatic system that adds semantics to a urban scene inspired on the human brain. We use stereopsis to generate a 3D model of the building. This model is improved by detecting the building contour using edge features. The 3D model is used to rectify a facade which makes windows appear orthogonal. Next we detect horizontal and vertical edges that come from window frames. Furthermore we use density of edges to classify windows.

Before we explain our methods let us first share the variety of applications that use semantical interpretation of urban scenes.

## 1.1 Application examples

### 3D City models

Manual creation of 3D models is a time consuming and expensive procedure. Therefore semantic models are used for semi automatic 3D reconstruction/modelling. The semantic understanding is also used in 3D city models which are generated from aerial or satellite imagery. The (doors and) windows are mapped to the detected 3D model to increase the level of detail [16]. Some other applications can automatically extract a CAD-like model of the building surface.

### Historical buildings documentation and deformation analysis

In some fields of research, historical buildings are documented. The complex structures that are contained in the facades are recorded and reconstructed. Another field of research is the analysis of building deformation in areas containing old buildings [21]. Window detection provides information about the region of interest that could be tracked over time for an accurate deformation analysis.

### Interactive 3D models

There are some virtual training applications that are designed for emergency response requiring interaction with a 3D model. For the simulation to be realistic it is important to have a model that is of high visual quality and has sufficient semantic detail (i.e. contains windows). This is also the case for a fly-through visualization of a street with buildings. Other applications that require semantic 3D models are virtual tourism, visual impact analysis, driving simulation and military simulation systems.

### Augmented reality

Some mobile platforms apply augmented reality using facade and window detection to make an accurate overlay of the building. An example overlay is the same building but 200 years earlier. Semantical information is used to not only identify a respective building, but also find his exact location in the image. The accuracy and realistic level of the 3D model are vital for a successful simulation. And because the applications are mobile, very fast building understanding algorithms are required. Window detection plays an important role in these processes as the size and location of the windows supply an effective descriptor that can be used for robust and fast building identification. Furthermore it provides an accurate alignment of the overlay.

### Building recognition and urban planning

Building recognition is used in the field of urban planning where the semantic 3D models are used to provide important references to the city scenes from the street level. Building recognition is done by using large image datasets where the buildings are mostly described by local information descriptors. Some



Figure 1: Simulation environment

approaches try to describe the 3D building with laser range data. Some methods fuse the laser data with ground images. However, those generated 3D models are a mesh structure which do not make the facade structure explicit. For a more accurate disambiguation, other types of contextual information are desired. The semantical interpretation of the facade can provide this need. In this context, window detection can be used as a strong discriminator.

We can conclude that semantic interpretation plays an important role in the interpretation of urban scenes and is applied in a wide range of domains.

## 1.2 Thesis outline

The outline of this thesis is as follows:

We start with explaining basic computer vision techniques and the 3rd party software *FIT3D toolbox* in Chapter 2. These techniques are the driving force behind the algorithms used in both skyline detection and window detection. In Chapter 3 we explain a novel application of skyline detection: the detection of building contours in urban scenes. Next we use this result in Chapter 4 to extract a 3D model of a building. In Chapter 5 we start a new topic: window detection. We propose a window detection method that operates on an unrectified facade. The second method uses a rectified facade. We discuss and compare two window alignment methods and two classification methods. We conclude in Chapter 6 and we finish with additional results in the Appendices.

Many methods used in this thesis are independent from each other. Therefore we choose to discuss the results, discussion and future research for each method separately. Also the chapters are independent from each other. Therefore, a reader only interested in one particular topic may read only the associated chapter while skipping the other chapters.

## 2 Preliminaries on Computer Vision

In this chapter we discuss the basic computer vision techniques that are used for the skyline detection, and window detection. Furthermore we discuss 3rd party software, the *FIT3D toolbox* [11] which is used in 3D building extraction and facade rectification.

### 2.1 Hough transform

#### 2.1.1 Theory

A widely used method for extracting line segments is the Hough transform [10]. In the Hough transform, the main idea is to consider the characteristics of a straight line not as its image points  $(x_1, y_1)$ ,  $(x_2, y_2)$ , but in terms of the parameters of the straight line formula  $y = mx + b$ . i.e., the slope parameter  $m$  and the intercept parameter  $b$ .

The Hough transform transforms the line  $y = mx + b$  to a point  $(b, m)$  in parameter space. With this representation it is impossible to describe a vertical line as the slope  $m$  is infinite. Therefore it is better to use a different set of parameters, denoted  $r$  and  $\theta$ . These are the Polar Coordinates.

The parameter  $r$  represents the distance between the origin and the line and  $\theta$  is the angle of the vector orthogonal to the line. Using this parameterization, the equation of the line can be written as

$$y = \left( -\frac{\cos \theta}{\sin \theta} \right) x + \left( \frac{r}{\sin \theta} \right)$$

$$r = x \cos \theta + y \sin \theta$$

This means that a point in  $(x, y)$  space appears as a sinusoidal curve in the Hough parameter  $(r, \theta)$  space. Furthermore a line in  $(x, y)$  space appears as a point in  $(r, \theta)$  space. Let's see an example, the following image is transformed into the space  $(r, \theta)$ .

As you can see for every edge point in Figure 2 a curve is generated in  $(r, \theta)$  space in Figure 3(a). On eight positions (white dots) the number of intersecting sinusoidal curves is high. These position correspond to the eight separate straight line segments in Figure 2 .

This simplifies the problem of detecting straight lines in finding peaks in the Hough parameter  $(r, \theta)$  space.

#### 2.1.2 Implementation

The input of a Hough transform is a binary image. In our research it is the output of the skyline detector (3). In the case of window detection (5) it is the output of an edge image.

The Hough transform develops an accumulator array of a quantized parameter space  $(r, \theta)$ .

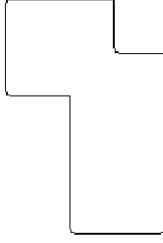


Figure 2: An input image, consisting of eight straight lines, for the Hough transform

It loops through the binary image and for each positive value it generates all possible lines, quantized  $(r, \theta)$  pairs, that intersect with this point. For each candidate it increases a vote in the accumulator array. Lines  $(r, \theta)$  that receive a large amount of votes i.e. the dots in Figure 3(a) are the found straight lines in the  $(x, y)$  space.

These positions are found by looking for local maxima in the accumulator array.

### 2.1.3 $\theta$ constrained Hough transform

The accumulator array consist of two dimensions  $r$  and  $\theta$ .  $\theta$  typically ranges from  $[-90..90]$  resulting in 180 unique bins. Note that a line with  $(r, \theta) = (t, j)$  can also be represent by the identical  $(-t, j - 90)$ , e.g.  $(4, 135) == (-4, 45)$ . This makes it possible to represent every line with the interval  $[-90..90]$ .

Sometimes we want to find lines that have a certain angle. For example the skyline of a building will appear about horizontal. If we want to detect windows we would like to detect edges in the horizontal and vertical directions. This can easily achieved by adjusting the  $\theta$  range. For example if one would detect lines in the horizontal direction of a photograph of a building taken by a user,  $\theta = [-10..0..10]$ . Although only  $\theta = 0$  presents an exact horizontal line we broaden the interval because the user hardly ever holds the camera exactly orthogonal.

### 2.1.4 MATLAB[15] parameters

We used a standard MATLAB[15] implementation of the Hough transform for straight lines. This implementation comes with some interesting parameters:

The *MinimumLength* parameter specifies the minimum length that a line must have to be valid. This is especially interesting if we want to detect a large straight skyline or if we want to discard lines that are to small to form for example a window.



(a)  $(r, \theta)$  values



(b)  $(r, \theta)$  accumulator array (quantized)

Figure 3: Hough transform

Furthermore it contains the parameter *FillGap* that specifies the distance between two line segments associated with the same  $(r, \theta)$  pair. When this inter line segment distance is less then the *FillGap* parameter, it merges the line segments into a single line segment. In our application this parameter is of particular interest when we want to merge lines that are interrupted by for example

an occluding tree or street lamp.

## 2.2 Coordinate systems

In this thesis three different coordinate reference systems are used. The first one is located at the image level and describes the location of the pixel in 2D. It is called the Image Coordinate Frame (ICF), in Figure 4 the ICF is spanned by  $(x_0, y_0)$ . The second is the Camera Coordinate Frame (CCF), the system is aligned with the camera: the origin is fixed at the the camera center (center of projection) and the CCF is rotated with a rotation vector that is equal to the camera's viewing direction. The coordinates are expressed in (XYZ).

The last system is the World Coordinate Frame (WCF) and it is used to describe the positions of the 3D model of the scene and the position of the cameras in the world in (ijk). An overview of the systems can be found in Table 1.

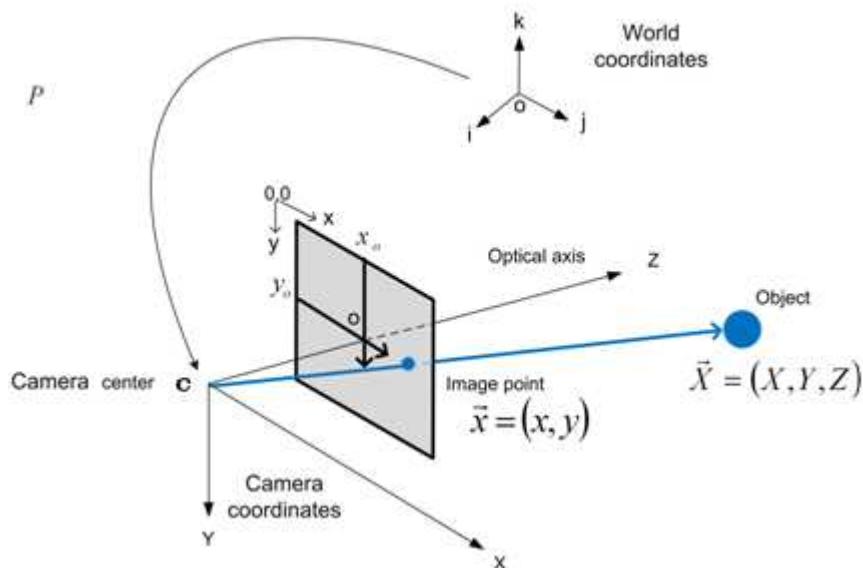


Figure 4: Coordinate systems

Table 1: Coordinate reference systems with their properties

Reference system name	abbreviation	dimensions	axis
Image Coordinate Frame	ICF	2D	x,y
Camera Coordinate Frame	CCF	3D	X,Y,Z
World Coordinate Frame	WCF	3D	i,j,k

## 2.3 Camera calibration

Camera calibration is done to determine the relationship between what appears on the image (or camera sensor) and where it is located in the 3D world. This involves calculating the camera's intrinsic and extrinsic parameters.

### Intrinsic parameters

The intrinsic parameters contain information about the internal parameters of the camera. These are focal length, pixel aspect ratio, and principal point. These parameters come together in a calibration matrix  $K$ . The Floriande dataset (originated from the Fit3D toolbox [11]) comes with a calibration matrix  $K$ . For the other datasets we calculated  $K$  with the Bouguet toolbox [5]. This method involves taking images of a checkerboard in different positions and orientations. An algorithm detects the grid on the chessboard and monitors its transformations under the different images. If enough images are given (at least 10) and the images contain enough variety in chessboard pose, the Bouguet toolbox can calculate the intrinsic parameters quite accurate. More details about this method can be found in [5].

### Extrinsic parameters

The extrinsic parameters present the center of the locations of the camera and the camera's rotations. These are unique for every view. In some systems these are recorded by measuring the cameras location and rotation at the scene. In other systems this is computed afterwards (from the images). We calculated the values also afterwards and used existing software for this: *FIT3D toolbox* [11], details of this process is explained next.

## 2.4 FIT3D toolbox ??

The *FIT3D toolbox* ?? is used for several aims in this thesis. It is used in the window detection module to rectify the facades. and the skyline detection used *FIT3D* to extract a 3D model.

In order to extract this 3D model a series of frames (originating from different views) is used to estimate the relation of the camera coordinates to the world coordinates, Next, the result is used to extract a point cloud of matching features. Finally this point cloud is converted to planes which correspond with the walls of the building.

Because the toolbox plays an assisting role we explain the steps briefly. Detailed knowledge about the methods can be found in ??.

### 2.4.1 Multiple views

*FIT3D* uses multiple views to gather information about the 3D structure of the building. The toolbox comes with a prepared dataset of 7 consecutive images (steady (zoom, lightning, etc.) parameters) of a scene. *FIT3D* doesn't

require the input images to be chronological however they need to have sufficient overlap.

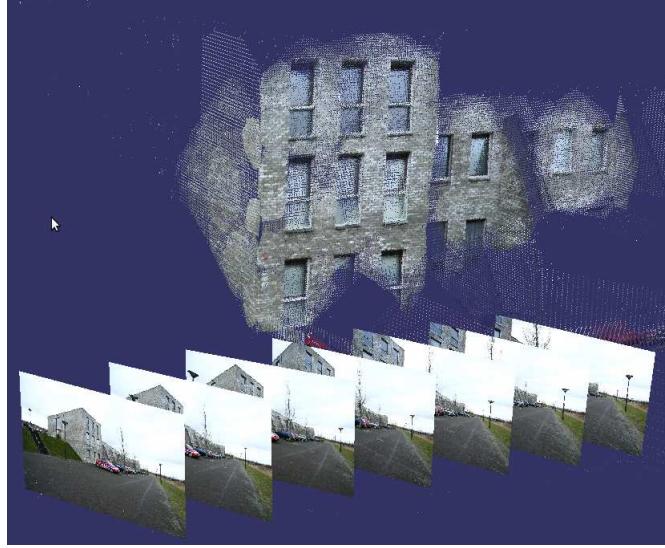


Figure 5: Example series of 7 consecutive frames, (dataset: *FIT3D toolbox*[11])

#### 2.4.2 Relating the camera coordinates to the world coordinates

The different views are used to estimate the relation of the camera frame coordinates to the world coordinates, (the extrinsic parameters). In other words the different positions of the camera centers (from the origin of the WCF to the camera center) and the camera's rotation are estimated. This is done by calculating the relative motion between the different views.

The frame to frame motion is calculated by extracting about 25k SIFT features of each frame. Next, SIFT descriptors are used to describe and match the features within the consecutive frames. Not all features will overlap or match in the frames therefore RANSAC[2] is used to robustly remove the outliers. After this an *8-point algorithm*[12] together with a voting mechanism is used to extract the relative camera motion.

The frames are matched one by one which returns an estimation of the camera motion. Because this estimation is not accurate enough, a 3-frame match is applied next. This result is more accurate but comes with a certain amount of re-projection error which is minimized using a numerical iterative method called *bundle adjustment*[25].

From every frame the camera motion is stored relative to the first frame. The motion is stored as a rotation and translation form (3x4)  $[R|t]$ . This is gathered for all 7 frames in a (7x3x4) projection matrix  $P$ .  $P$  can be used to translate camera coordinates of a specific view to 3D world coordinates and vice versa.

#### 2.4.3 3D point cloud extraction

The next step is to use this projection matrix  $P$  to obtain a set of 3D points, which correspond to the matching SIFT features of the different views. The set of 3D points is extracted using a *linear triangulation*[12] method.

The 3D point cloud of the building is illustrated in Figure 5. After obtaining the point cloud, a RANSAC based plane fitter [2] is used to accurately fit planes through the 3D points, see Figure 6.

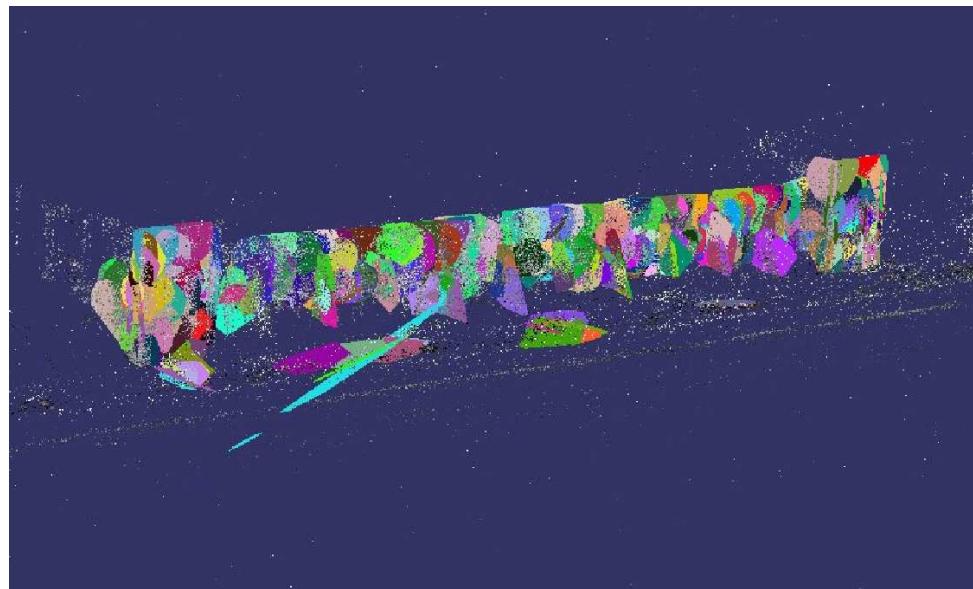


Figure 6: Fitted planes

In this thesis the plane fitting step is skipped and a new method is used to obtain the 3D model. This is explained in 4.

## 3 Skyline detection

### 3.1 Introduction

If we take a regular image on which both sky and environment are present, there is often a clear separation between them. This separation is called the skyline. The detection of this skyline has proven to be a very successful computer vision application in a wide range of domains ranging from object detection[8], guiding micro air vehicles[18], car localization, etc.

In this research skyline detection is applied on different views of a scene to estimate heights of facades of a 3D model. This is a novel application for skyline detection.

The organization of this chapter is as follows: first we give a summary of related work on skyline detection. Next we explain how we developed a new robust skyline detection algorithm. Then we present and discuss some results and, finally, conclusions are given.

### 3.2 Related work

Castano et al. [8] present a clear introduction of different skyline detection techniques.

#### Detection of dust devils and clouds on Mars

In [8], mars Exploration Rovers are used to detect clouds and dust devils on Mars. Their approach is to first segment the sky from the ground and then determine if there are clouds in this region. The sky is detected by an innovative algorithm that is similar to the one of Cozman et al. [9]. This time the variation in intensity is used to discriminate the sky from the ground. The algorithm uses a sliding window that slides from top to bottom. If looks for an location where the intensity variation is high. This location is classified as a skyline point. The sky is segmented by taking the area above these skyline points. Next, this segmented sky is used for the detection of clouds and dust devils.

This method looks like a very sophisticated one, as it is accurate and autonomous. However, in our research we have a stable scene with sharp edges at the building contour so this method would be an implementation overkill.

#### Horizon detection for Unmanned Air Vehicles

In the domain [18] of unmanned vehicles, scientists detect the horizon to stabilize and control the flight of Unmanned Air Vehicles.

S.M. Ettinger et all [18] use a horizon detector that takes advantage of the high altitude of the vehicle, in that way the horizon is approximated to be a straight line. This straight line separates the image into sky and ground. They use color

as a measure of appearance and generate two color distributions: one for the sky and one for the ground. They use the covariance and the eigen values of the distributions to guide a bisection search for the best separation. The line that best separates the two distributions is determined to be the skyline.

This work is not applicable for detecting a building contour as the straight line assumption doesn't apply. But it needs to be mentioned that some ideas for section ?? are inspired by this method.

### Planetary Rover localization

Cozman et al. [9] use skyline detection in planetary rovers to estimate their location. To recover the rover's position they match image structures with a given map of the landscape (hills, roads, etc). One of the matching image structures they use is the shape of the skyline. A ground truth skyline model  $m$  is obtained using a full 360 degree panorama of the scene. Next, a matching function is applied to the skyline observations and  $m$  to estimate the rovers location, see Figure 7.

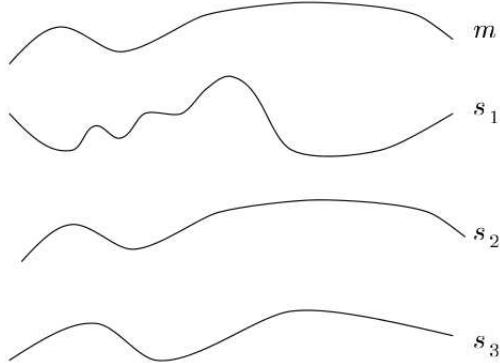


Figure 7: By matching map  $m$  to the observations  $s_1$ ,  $s_2$  and  $s_3$  the position of a planetary rover is estimated

The skyline is detected using the fact that at a large change in intensity occurs at skyline points. This is obviously because the color changes from sky to ground. For every column of the image a search is done for a high intensity change. The largest change is determined to be the skyline.

The advantage of their algorithm is the simplicity and effectiveness, this could make their algorithm suitable for this project. A big drawback is that they prefer speed over accuracy. To increase accuracy, the detector is part of an

interactive system where an operator refines the skyline. For our application the skyline detector must operate without any user interaction. This brings us to our research question.

### 3.3 Method

#### Research question

Can we build a skyline algorithm that operates without any user interaction, is simple, is fast, and yet accurate enough to provide a solid skyline that can be used to estimate wall heights?

##### 3.3.1 Situation and assumptions

As the Rover method [9] is simple and effective we used it as a basis and build a custom algorithm with higher accuracy on top of that.

#### Situation

Before we present the method, we define the situation and make some assumptions.

#### Definition: skyline in urban scene

*A skyline in an urban scene is a set of points of the size  $w$  (where  $w$  is the width of the image) where each point describes the location of the transition from the sky to an object (e.g. a building) which is connected to the earth.*

How are we going to detect this sky-building transition point?

In general, the color of the sky is very different from the color of the building. A color-based edge detector would be an intuitive decision as this produces edges on regions where intense color transitions appear. However, the sky and the building itself also contains color transitions (caused by for example clouds and windows). So how do we determine the right transition (edge)?

One of the solutions is to increase the threshold of the edge detector. In this way the detector will only return intense color transitions. Note that this will only pay off if the building-sky transition is the biggest transition in the image. Its easy to see that this is a tricky assumption as other objects may contain larger color transitions. Furthermore it would not be robust to a change in the lightning conditions, influenced heavily by the weather.

To solve this problem we draw an assumption that is based on the idea of [9]. Instead of using the sharpest edge we take the most upper sharp edge and classify this edge as the skyline.

### Top sharp edge assumption

*The first sharp edge (seen from top to bottom) in the image represents the skyline.*

Having defined the situation and assumptions we now explain our algorithm.

#### 3.3.2 Related algorithm

As our algorithm is based on a related algorithm presented in [9], this is in detail described first.

The algorithm uses three main steps first it applies a smoothing preprocessing step then it calculates the intensity gradient to find a big color transformation and finally it searches for the highest transformation.

Because the related algorithm searches for strong edges a preprocessing step is applied to remove all vague edges. The pre-processing consist of a sizable Gaussian smoothing window that is applied on the input image. The size of the window size is correlated to the amount of vague edges that are removed.

Next the smoothed image is sliced in  $\#w$  pixel columns. Each column represents the  $\#h$  intensity values of the image (where  $w$  and  $h$  are the width and height of the input image). These columns are transformed to their derivative, called the smoothed intensity gradient. The values of this transformed column are high when a big change in color happens (e.g. when an edge is detected) at that location on the image.

Next the system walks through the values of a column, starting from the top. When it detects a value with a gradient higher then a certain threshold it stores its y-position (the height) and continues to the next column. After the position in each column of the highest sharp edge is determined the algorithm is done. The result is a set of  $y$  coordinates of length  $w$ , that represent the skyline.

#### 3.3.3 Improved algorithm

Taking the smoothed intensity gradient is a computational cheap way to detect edges. It also has a big disadvantage because it is not robust to vague edges (they don't survive the threshold). It is not surprising that the algorithm in [9] was used in an interactive system where the user has to refine the result.

Our aim is to develop an autonomous skyline detector, the only user interaction that we allow is to set some parameters of the system. Furthermore the vague edges need to be detected if they are part of the skyline. We will now discuss the adaptations that we developed with respect to the related algorithm.

The column based approach of the related algorithm seems to be very useful and is therefore unchanged. To be robust to vague edges we explored and tested edge detecting methods that are different then the smoothed intensity gradient based method.

The output of the different edge detection techniques was studied on an empirical basis and the Canny edge detector [7] was a clear winner. This is probably because Canny is a more advanced edge detector:

It uses two thresholds, one to detect strong and one to detect weak edges. It starts with the strong threshold and when it finds an edge it calculates his direction. This direction is used to search for weak edges that are connected at one of the sides of the strong edge. In this way noisy weak edges are discarded because they are not connected to a strong edge. Furthermore it doesn't discard the vague edges that are desired. In Table 2 we list MATLAB[15]'s built-in edge detectors together with the method explanation. In the section 3.4.1 one can find the results of the different edge detection methods.

Table 2: Different edge detectors explained, Source: MATLAB[15] Documentation

Name	method
Sobel	The Sobel method finds edges using the Sobel approximation to the derivative. It returns edges at those points where the gradient of the image is maximum.
Prewitt	The Prewitt method finds edges using the Prewitt approximation to the derivative. It returns edges at those points where the gradient of the image is maximum.
Roberts	The Roberts method finds edges using the Roberts approximation to the derivative. It returns edges at those points where the gradient of the image is maximum.
zero-cross	The zero-cross method finds edges by looking for zero crossings after filtering the image with a filter that has to be specified.
Laplacian	The Laplacian of Gaussian method finds edges by looking for zero crossings after filtering the image with a Laplacian of Gaussian filter.
Canny	The Canny method finds edges by looking for local maxima of the gradient of the image. The gradient is calculated using the derivative of a Gaussian filter. The method uses two thresholds, to detect strong and weak edges, and includes the weak edges in the output only if they are connected to strong edges. This method is therefore less likely than the others to be fooled by noise, and more likely to detect true weak edges.

We classify Canny as the most robust edge detector, and use it for the skyline detection algorithm: the Canny edge detector outputs a binary image, therefore the column inlier threshold is set to 1, which means that it finds the first pixel that is white. This is, as in the related algorithm, done from top to bottom for every column in the image.

Because we know we are looking for sharp edges, we improved the algorithm by introducing two preprocessing steps. First the contrast of the image is increased, this makes sharp edges stand out more. Secondly the image undertakes an extra

Gaussian smoothing, this removes a large part of the noise.

The system now has several parameters which have to be set manually by the user:

- Contrast
- Window size of Gaussian smoothing
- Edge detector threshold

If the user introduces a new dataset these parameters need to be configured as the image quality and lightning condition are scene depended.

### 3.4 Results

#### 3.4.1 Edge detection

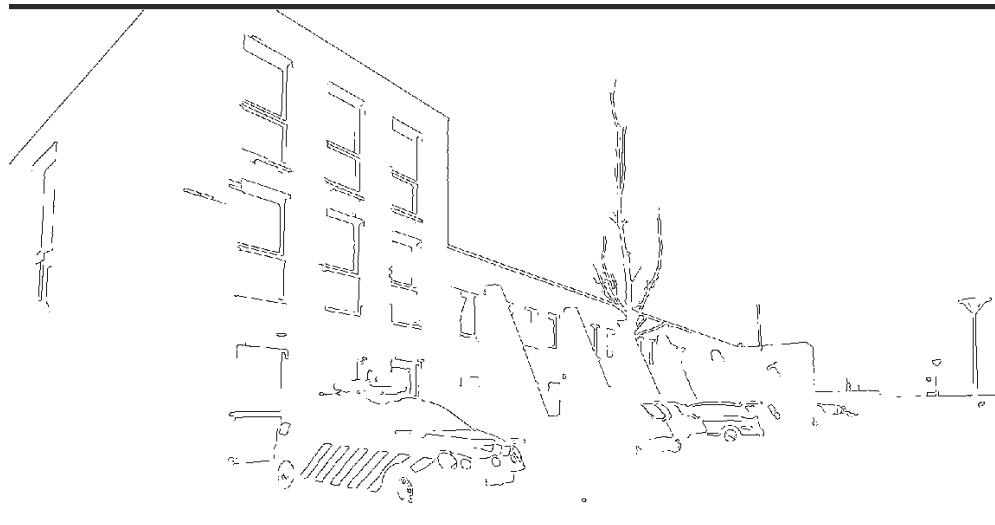


Figure 8: Edge detection results. Method: Canny

The edge detection results of the other methods can be found in the appendix (A.1).

### 3.4.2 Skyline detection

#### Datasets

The skyline detection algorithm was applied on three datasets.

Table 3: Dataset properties

Name	Resolution	Source	Location
Floriande	1728x1152px	FIT3D [11]	Unknown
Bram	3072x2304px	Author	Amsterdam, 'Postjesweg' west side
Folkert	3072x2304px	Author	Amsterdam, 'Postjesweg' east side



Figure 9: The output of the skyline detector on the *Floriande* dataset. The skyline elements are marked red.



Figure 10: The output of the skyline detector on the *Bram* dataset. The skyline elements are marked red.



Figure 11: The output of the skyline detector on the *Folkert* dataset: a scene which violates the top sharp edge assumption. The hanging streetlight causes the detection of a sharp edge above the building. This results in a damaged skyline.

### 3.5 Discussion

Consider Figure 9, the largest part of the building edge is detected. This is a good result, given the algorithm operates without any user interaction.

We assumed that the first sharp edge (seen from top to bottom) in the image represents the skyline. We showed in Figure 11 that the first sharp edge is not always the skyline. This holds for more scenes: e.g. Amsterdam contains a large amount of hanging street lights. Furthermore, other sharp edged objects that appear above the building, e.g. tree's or even an aircraft, will also produce a scene that violates the top sharp edge assumption. Therefore it would be nice to relax the or discard the first sharp edge assumption. This implies that we have to extend the column based approach which is done theoretically and described in Future research (3.7).

### 3.6 Conclusion

Let's answer our research question. *Can we build a skyline algorithm that operates without any user interaction, is simple, is fast, and yet accurate enough to provide a solid skyline that can be used to estimate wall heights?*

Beside some scene dependent parameters (like the threshold of the skyline) the system works without any user interaction. No manual refinement step is needed because the algorithm is robust and accurate enough to provide a base for the next module in the system. Furthermore the algorithm is simple and has a low complexity.

It is interesting to point out that the skyline detector is a stand alone method and it can be optimized individually without any knowledge of the other modules of this project.

Because the top sharp edge assumption closes the door for a large amount of scenes, an alternative is desired. We designed a concept that relaxes this assumption which is shared next.

## 3.7 Future research

### 3.7.1 Hypothesis based skyline detection

The first top sharp edge in Figure 11 is on a large area a hanging street light instead of the skyline. If we take a look at the edge image in Figure 12 we observe that the skyline in this area is the second or third sharp edge. Let's relax the first top sharp assumption to an assumption where the skyline is part of the first  $n$  sharp edges (seen from top) with for example  $n = 3$ . The scene in Figure 11 now agrees with this assumption.

The next challenge is to do detect the skyline properly on the entire image. The existing column based approach could be used to generate  $n$  hypotheses and we

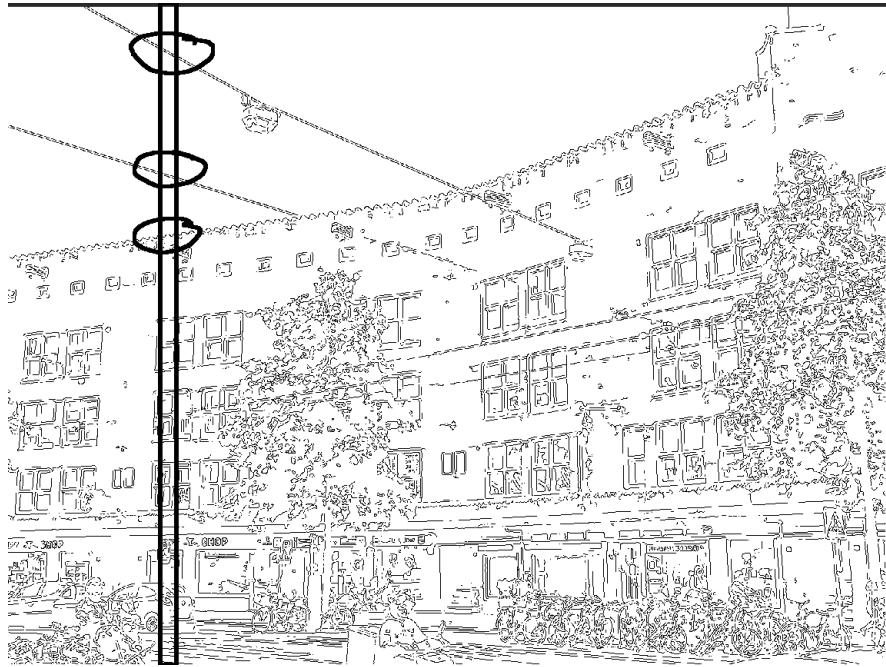


Figure 12: Three top sharp edges of the *Folkert* dataset are highlighted. For the highlighted column the skyline happens to be the 3rd top sharp edge.

can build an algorithm on top of that to classify which hypothesis is right (i.e. which edge presents the skyline).

The hypothesis classifier must gather additional information. We could discriminate the hypothesis for example by texture, color distributions or height variation. We discuss the last two.

#### **Color based skyline classification**

The buildings color differs from the sky color. Furthermore, as a function of the horizontal location (x-axis), the color in both sky and building only changes slowly.

One could extract the color distribution of the color in a certain area above and under the skyline, let's call these A and U.

A and U should 1) have a significant difference (local) and 2) they should not vary much from other positively classified skyline points (global).

The global color distribution could be calculated by taking the mean of the color distributions at previously detected skyline points. Both conditions (local and global) could have a weight which would be a parameter of the system.

Let's test this conceptual algorithm on the scene in Figure 11. We initialize the algorithm at an interesting location which is highlighted in the figure.

The first (top) highlighted sharp edge doesn't have a large local difference in color distribution above and under the skyline. The color above and under the position are mostly white. Because the first condition fails and the second condition can't be checked as no global color distribution is stored yet, the algorithm continues with the next edge.

For this edge the same holds. The third edge, however, succeeds because it has a large local color difference. Therefore the algorithm classifies it as a skyline point. Furthermore it stores his color distribution to compare following skyline points. Next the algorithm takes for example one x location to the right. It will again agree on the third edge on the same terms. This time it rejected the outliers (first and second edge) with additional because their color distributions differ too much from the color distribution of the previously detected skyline point.

The expected output of the skyline detector using hypothesis based on color is displayed in Figure 13).



Figure 13: The expected output of the skyline detector using hypothesis based on color

### **Height variation based skyline classification**

Let's zoom in to an image of the *Floriande* dataset, see Figure 14. We observe that many outlying skyline points are located at the tree. The algorithm based on the first  $n$  sharp edges wouldn't be robust because the tree produces a too large amount of edges. Therefore an alternative classification is desired.

The skyline points on the tree have a large height variation in common. This could be used to isolate this area from the skyline.

Once areas that have a large variation of height are discarded we could connect the positive classified skyline parts to fill the gap, see Figure 15.

Note that we used height variation instead of height difference for a reason. A large height difference with a neighboring skyline point is allowed because the building contour may contain large steps in height (e.g. at the left side of Figure 14 the skyline suddenly drops in height).

We showed some examples of simple classifiers. Note that there is no limitation to the approach of the classifier because it can be developed individually using the existing column based method as its hypothesis generator.



Figure 14: Zoomed image of the *Floriande* dataset. The height variation is large on the tree area.

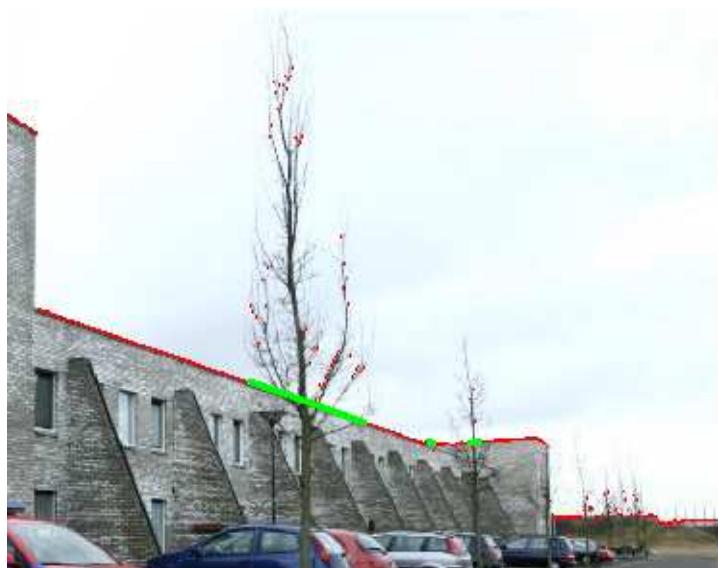


Figure 15: The green lines connects the positively classified skyline parts at isolated areas where the height variation is too high

## 4 Extracting the 3D building

### 4.1 Introduction

In the previous chapter we explained our skyline detection algorithm which extracted the skyline of a scene. The output is a set of 2D points which was collected for a sequence of images. The aim of this chapter is to use this set of points together with an aerial 2D model of the building and the 3D point cloud obtained by the *FIT3D toolbox[11]* (2.4) to generate a 3D model of the building.

#### Research question

Is it possible to use a set of (noisy) skyline points together with an aerial 2D model and a 3D point cloud obtained by *FIT3D toolbox[11]* to generate a 3D model of the building?

We present a stepwise solution.

First *Openstreetmap[1]* is used to obtain a 2D top view of the outline of the building. The line segments of the 2D model represent the walls of the building. Next the 3D point cloud obtained by the *FIT3D toolbox[11]* is used to align this 2D model in the scene. After this, the set of points returned by the skyline detector is transferred to a set of lines. Then each line segment is assigned to a part (wall) of the aligned 2D model. Next the line segments are projected to vertical planes spanned by the 2D model. The result is used to estimate the height values of the walls of the 2D model. The 2D model is transformed according to this height values to a 3D model. We will now elaborate on each step.

### 4.2 Method

#### 4.2.1 Extracting the 2D model

The basis of the generated 3D model is a map containing the 2D outline polygon of the building originated from *Openstreetmap[1]* (Figure 16) which is a freely accessible 2D map generated by users all over the world. It contains information about streets, building contours, building functions, museums, etc. We are interested in the building contours therefore we take a snapshot of a particular area and extract this building contour. This is a set of ordered points where each point corresponds to a corner of the building. Next we link these points to line segments which represent (the top view of) the walls of the building.

#### 4.2.2 Aligning the 2D model

We want to align the 2D model extracted from *Openstreetmap[1]* in the scene. This means we want to position the 2D model in the world coordinate using a translation, rotation and scaling.



Figure 16: Openstreetmap[1] with annotated buildings

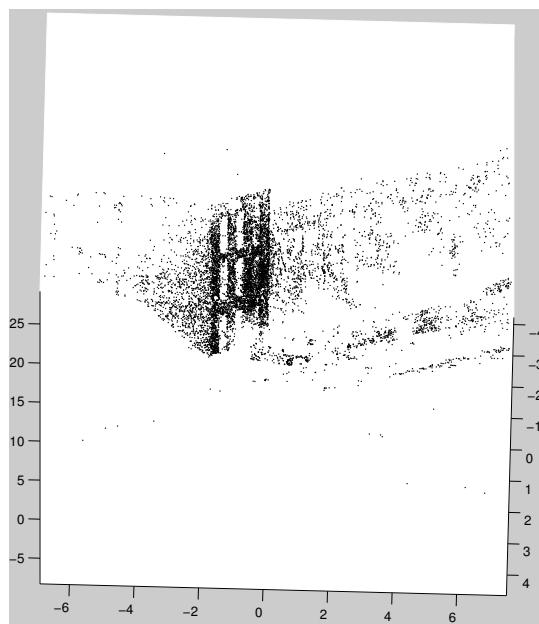


Figure 17: 3D point cloud of the walls of the building

From *FIT3D*[11] we have the 3D point cloud of the building in world coordinates

(Figure 17). The first challenge is to obtain a top view of the 3D point cloud. How can we determine the direction of the top view? We want to project in the direction that is most parallel to the walls and orthogonal to the 2D model.

### Gravity aligned walls assumption

*The walls of the building are aligned with the gravity direction which is orthogonal to the 2D model from Openstreetmap[1].* This means we assume the images taken upright: the camera's *roll* = 0 (Figure 30).

Now we have defined the wall direction, we obtain the top view of the 3D point cloud by discarding the y-dimension of the points. Note that this is equivalent to a projection to the x,z plane. The result is a set of 2D points that represent the top view of the 3D point cloud (Figure 19).

We determine the walls by fitting line segments in the point cloud. We annotated these line segments manually. (If the system needs to operate automatically, RANSAC can be used to fit lines in this point cloud.)

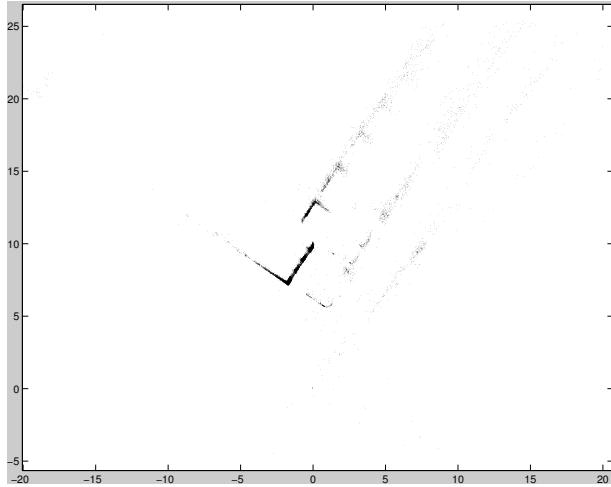


Figure 18: The projected 3D point cloud of the walls of the building

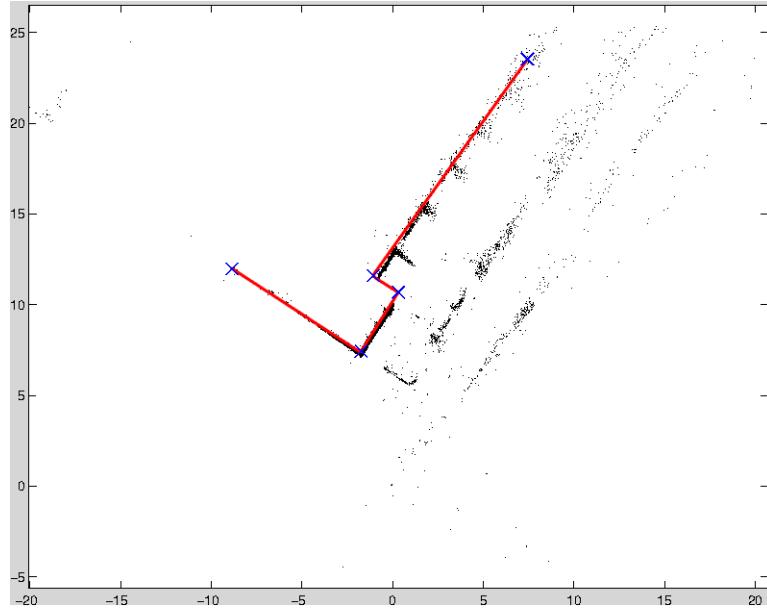


Figure 19: The top view building walls represented the fitted line segments, M1

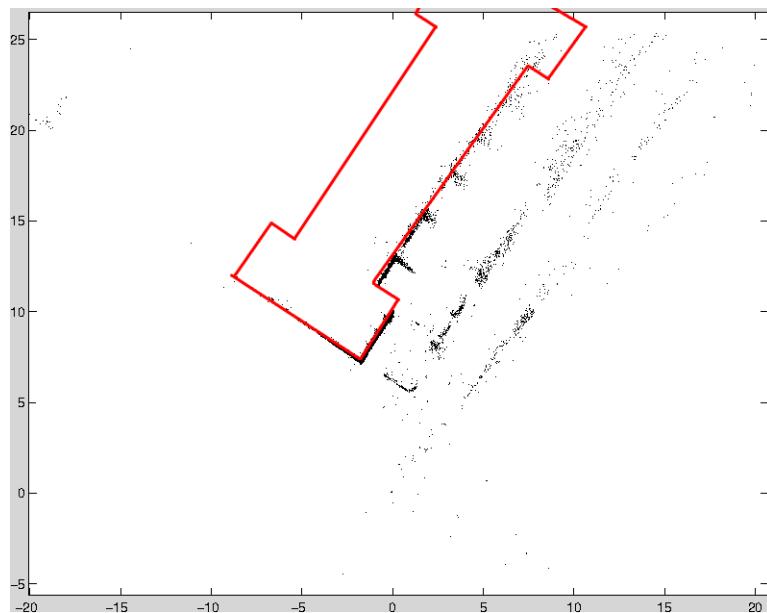


Figure 20: M2, the 2D model extracted from *Openstreetmap*[1] aligned with the point cloud

The next step is to align the 2D *Openstreetmap*[1] model  $M_1$  with these line segments of the projected point cloud  $M_2$  in the world coordinate frame. First the endpoints of the line segments, which correspond to the wall corners, are extracted in both models. Note that the walls of  $M_2$  that are located at the back of the building are often missing because they are occluded by the front walls. We only consider the corners that are present in both models. Next the correspondences between these corners are annotated manually. This is used to generate a set of linear equations which are solved in closed form [12]. The result is a matrix  $A$  which represents the rotation, translation and scaling that is needed for a coordinate of  $M_1$  to be transformed to  $M_2$  in the world coordinate frame. Finally  $A$  is applied on all corner points of  $M_1$  which results in an aligned 2D model (Figure 20).

#### 4.2.3 Transferring the aligned 2D model to 3D

Because the 2D model is based on aerial images it contains no information regarding the height of each wall. In the next section we explain how we obtain the precise height values.

For the sake of presentation we use an average building height to generate a rough estimate of the 3D model. The 3D model is generated by taking 2D model and extend it in the orthogonal direction. An example of the 3D model can be seen in Figure 21.

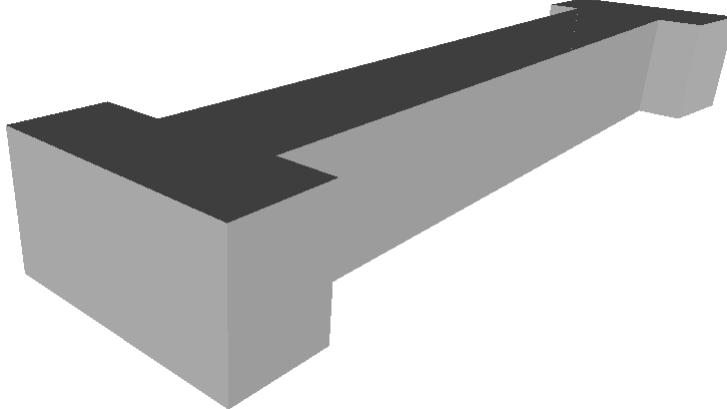


Figure 21: An example of a basic 3D model, generated by extending a basis (2D) model from *Openstreetmap*[1] to an average building height

#### 4.2.4 Extracting line segments

Because we want to estimate the height of the building walls of the 3D model we need to know how high the walls in the 2D images are. To estimate this we first determine which part of the skyline is part of the building contour. Straight lines in the skyline area are likely to come from the building contour. If we have a method that extracts straight line segments from the skyline, we can use these lines segments to estimate the height of the walls of the 3D model. In this section we explain how we extract these straight line segments.

#### Assumptions

Many urban areas contain buildings with a flat roof. Therefore the contour of the building is always formed by a set of straight line segments. Furthermore the building contour is often aligned with the topside of a building wall. If we assume a flat roof we can find the height of the building walls without having to concern for (complex) roof types.

#### Flat roof assumption

*We assume each building has a flat roof, implicating that the building contour is aligned with the topside of a building wall. The building walls may have different heights but the roof should be flat.*

#### Hough transform

As was discussed in chapter 2, a widely used method for extracting line segments is the Hough transform [10]. We regard this as a suitable method because it is used a lot for this kind of problems. This is probably because it is unique in its low complexity (compared to other methods like *RANSAC*, who often use an iterative approach). For a detailed explanation of the Hough transform can be found in section 2.1.

The input of the Hough transform that is build in in *MATLAB[15]* is a binary image. This is in our case the output of the skyline detector (chapter 3).

If a pixel is classified as a skyline pixel (a pixel that lies on the skyline according the skyline detector), the Hough transform increases a vote value for every valid line  $(r, \theta)$  pair that crosses this particular pixel. Lines  $(r, \theta)$  pairs that receive a large amount of votes contain a large amount of skyline pixels.

Because the algorithm detects straight lines containing only skyline pixels it returns only the straight parts of the skyline. As these straight skyline parts come from the building contour we found exactly what we were looking for.

Results of the Hough transform on the output of the skyline detector are displayed and evaluated in the Result section (4.3).

#### 4.2.5 Project the skyline to the 3D model

The Hough transform of the previous section returned a set of 2D line segments which likely present parts of the building contour. As we want to estimate the building wall heights we need to determine the wall of the building that is most likely responsible for that line segment. We can solve this problem by projecting the line segments to a specific part of the 3D model. This is done in three steps, first the camera is calibrated, next we project the line segments to the building and finally we determine the specific building part that is associated with a line segment.

To project the line segments to the 3D model we need to know the camera's position and rotation when it took the photo (extrinsic parameters). Furthermore we need to know in what way this camera transformed the image (e.g. lens distortion) (intrinsic parameters). This process is referred to as Camera Calibration and is explained in (2.3)

#### From image point (2D) to possible points in scene (3D)

What can we do if we computed the camera calibration parameters? The line segment that was returned by the Hough transform consists of two endpoints  $v$  and  $w$ . These endpoints are in 2D but are recorded in a 3D scene and therefore present a 3D point in space. We don't know which point this is as for example we don't know the distance from the 3D point to the camera that took the picture. However, because we calibrated the camera (2.3) we can reduce these possible points in 3D space to a line. Next we explain how we calculate this for one 2D image point (for example a line segment endpoint).

We know:

- $\vec{x} = (x, y)$ , the image point (in the camera coordinates (XYZ))
- $\vec{x}_h = (x, y, 1)'$ , the homogeneous coordinate of the image point
- $\vec{c}$  and  $R$ , the camera's extrinsic parameters (the camera's center and rotation in world coordinates (ijk))
- $K$ , the camera's intrinsic parameters
- $P$ , the projection from camera coordinates (XYZ) to world coordinates (ijk). It contains the extrinsic parameters (the camera's center  $\vec{c}$  and rotation  $R$ ) and is applied to transfer the camera image points  $\vec{x}$  (XYZ) to world coordinates (ijk)

The two coordinates that span the line of possible points in 3D space are calculated as follows:

- $\vec{c}$ , the location of the center of the camera in world coordinates (ijk)
- $\vec{x}_{ijk} = PK'\vec{x}_h$ , the image point expressed in world coordinates (ijk)

This is illustrated in Figure 22.

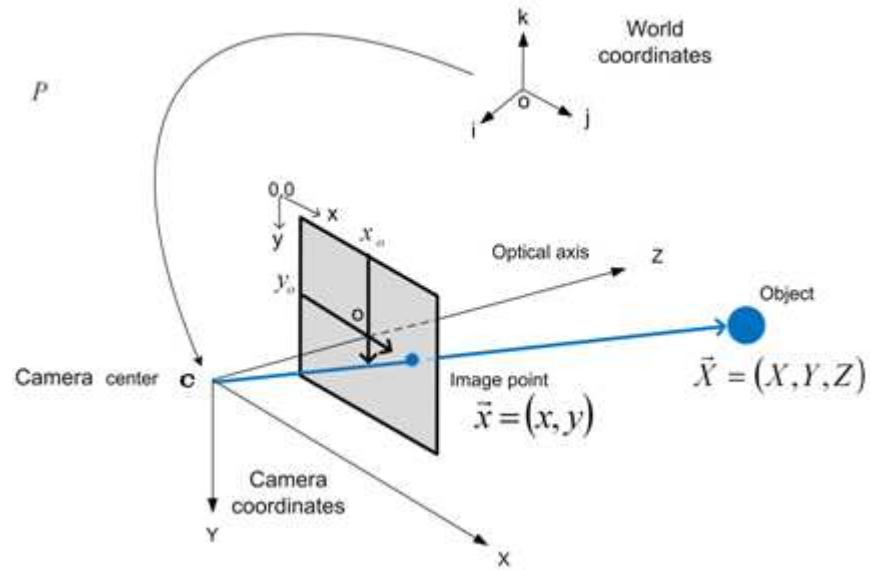


Figure 22: The blue line spanned by the camera center  $\vec{c}$  and the image point  $\vec{x}$  transferred to world coordinates represent the possible 3D points in space.  $\vec{X}$  is a random possible point on the line.

Using the two required coordinates we set up an equation of the line of possible points in 3D.

$$l = \vec{c} + (\vec{x}_{ijk} - \vec{c})t, t \in \mathbb{R}$$

for example if  $t = 100$  then the point in the real world lies at 100 times the distance from the camera center to its retina. In Figure ??  $t$  is about 4 (for point M).

Above calculations are done for all the line segment's endpoints. This results in a line of possible points in 3D space for each endpoint. We can use this to find the correspondence between a lines and the walls which is explained next.

#### 4.2.6 Associating line segments with building walls

##### Building wall appearance assumption:

*We assume that every straight line segment of the skyline represent (a part of) the upper side of a specific wall of the building.* Unfortunately we don't know which line is associated with which building wall. In this section we determine this association.

First we prepare the 3D model. Next we project the line segments to all planes of the 3D building by taking their endpoints and using the technique of the previous section (4.2.5) Finally we determine the most likely plane based on the largest line-wall overlap.

##### Walls to planes

The 3D building model consists of different walls. A wall is described by two ground points, a height, and a direction. The height is based on an average building height, the direction is always the y-direction (see *Gravity aligned walls assumption*).

First we transform the walls into (infinite) planes. This is done for two reasons: first this transformation is required to calculate the intersection properly. Second, because the 3D model is an estimate, the walls maybe just to small which could result in a missing intersection.

##### Intersect with all walls

Now we have the building walls transformed to planes we take the endpoints of the lines and project them to all the planes of the building.

Each 2D endpoint has a line of possible 3D points which we calculated in the previous section. This was the line spanned by the camera center and the image point in world coordinates. This line is intersected with all planes of the building walls. Every 2D endpoint is now associated with multiple intersections resulting in  $2 \times l \times w$  points in 3D (grouped by the line segments), 2 means #endpoints of the line,  $l$  is the number of lines and  $w$  is the number of walls.

We now calculated every possible projection to (/intersection with) every plane. How do we determine which plane represents the most likely wall? Recall that the wall is a subset of the plane. We only calculated the projection to the planes spanned by the walls hence we don't know which line lies on the wall and which falls outside the wall. To solve this problem let's zoom in to the situation: If we project  $l$  to the plane spanned by a wall  $W$  we get a line  $l_{proj_W}$  in  $\mathbb{R}^3$ . If we assume  $l$  to come from the contour of wall  $W$ , then  $l_{proj_W}$  should have a large overlap with this wall  $W$ . Let's call this the line-wall overlap value,  $lwo$ . Note that the projection of  $l$  with the other walls should have a small or zero  $lwo$  value, see Figure 10a and 10b.

#### **Largest line-wall overlap assumption:**

*A line segment is associated with the wall with the largest projection overlap.*  
Having defined the assumptions, the situation and the idea behind the line-wall association, we can now explain the line-wall matching algorithm.

A line segment is projected to all walls and the amount of line-wall overlap,  $lwo$  is calculated. The wall with the largest overlap with the specific line segment is classified as the most likely wall for that line segment. Next the line segments are projected to their most likely wall and the algorithm outputs this set of lines in  $\mathbb{R}^3$ .

This line-wall overlap is calculated in different steps. Before we explain the steps we discuss the different types of overlap. Next we explain how the algorithm determines the *overlap type*. Finally we calculate the overlap amount and normalize this value.

$l_{proj_W}$  can overlap  $W$  in four different ways, this is illustrated in Figure 10. The wall  $W$  is spanned by  $abcd$ , and  $l_{proj_W}$  is spanned by  $vw$ .

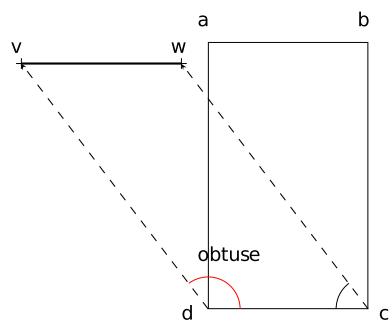


Figure 10a

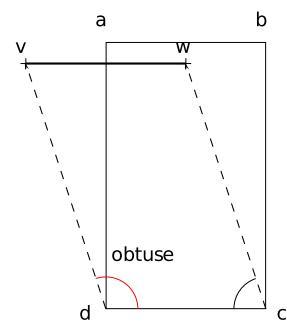


Figure 10b

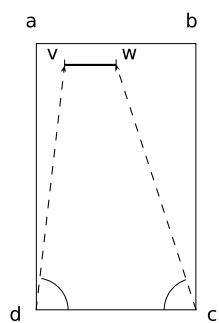


Figure 10c

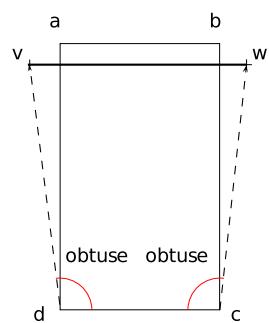


Figure 10d

The type of overlap is defined by exposing the endpoints of the line segments to an *in polygon* test, where the polygon represents a wall of the building (e.g. *abcd* in Figure 10).

Table 4 represents the types of overlap with the corresponding number of points that pass the *in polygon* test and their possible line-wall overlap value.

Table 4: Types of overlap with corresponding number of points in polygon

Type of line-wall overlap	Points in polygon	Line-wall overlap	Figure
No overlap	0	0	10a
Partial overlap	1	[0..1]	10b
Full overlap (included)	2	1	10c
Full overlap (overextended)	0	1	10d

### No overlap

If the point in polygon test returns 0, the line-wall overlap calculation is skipped and 0 is returned. The remaining overlap types, partial and full, are treated individually:

### Partial overlap

Let's first consider the partial overlap type (Figure 10b), the *in polygon* test returned 1, that means that one of the line segments endpoint lies inside and one lies outside the wall.

To determine the amount of line-wall overlap, the part of the line segment that overlaps the wall is calculated. The length of this part is measured and stored as its *lwo* value.

The trimmed line has two coordinates: 1) the point that passed the *in polygon* test and 2) the intersection of the line segment with one of the vertical wall sides (*da* or *cb* from Figure 10b).

We assume the walls to be of infinite height, therefore the partial overlapping line segment always intersects one of the vertical wall sides.

To determine which of the two vertical wall sides is crossed, we determine on which side the point that doesn't lie in the polygon (*v*) is on. This is done by an angle comparison.

First, two groups of two vectors are defined: *dv, dc* and *cw, cd* (see Figure 10b). We measure the angles between the vectors and call them  $\angle d$ , and  $\angle c$ . Because one of the line segment endpoints lies outside the wall  $\angle d$  or  $\angle c$  is obtuse, in this case  $\angle d$  is obtuse. (Note that this holds because the walls are orthogonal to the basis which we assumed in the *Gravity aligned walls assumption*

To be more precise:

- If  $\angle d$  is obtuse, the left vertical wall side  $da$ , is crossed.
- If  $\angle c$  is obtuse, the right vertical wall side  $cb$ , is crossed.

The angles are acute or obtuse if the dot product of the vectors involved are respectively positive or negative. The advantage of this method is that it is simple and has low computational costs.

#### *Line-wall overlap calculation*

The amount of line-wall overlap is calculated by cutting of the point where  $l$  intersects the determined vertical wall side ( $da$  or  $cb$ ) and measuring its remaining length.

#### **Full or no overlap**

Now let's consider the overlap types where the *in polygon* test returned 0. As you can see in Figure 10a and 10d this resulted in either full or no overlap. Again we analyze the vector angles to determine the remaining overlap-type. If only one of the angles is obtuse with no points in the polygon, like in Figure 10a, the whole line segment lies outside the wall: an overlap value of zero is returned.

Otherwise, if both angles  $\angle d$  and  $\angle c$  are obtuse or acute (Figure 10d), both endpoints lie on a different side of the wall, and they cross the wall somewhere in between. Full overlap is concluded here.

The amount of overlap is now calculated by measuring the length of the line segment which is cut down by his intersections with  $da$  and  $cb$ . In this case this is the same as line  $dc$ , but its easy to see that this is not the case when  $vw$  is not parallel to  $dc$ .

#### **Line-wall overlap normalization**

Finally the line-wall overlap is normalized by the line segments length:

$$lwo' = \frac{lwo}{|l|} \quad (1)$$

Where  $lwo'$  is the normalized line-wall overlap,  $lwo$  is the length of the trimmed line segment, and  $|l|$  is the total length of the line.

The intuition behind this is that line segments that are likely to present a wall not only have a large overlap but also have a small part that has no overlap, the missing overlap should have a negative effect. By calculating the relative overlap  $\frac{lwo}{|l|}$ , both amounts of overlap and -missing overlap are taken into account.

Normalizing the line-wall overlap on the line length implies that the length of the line does not have influence anymore. This can be seen as a disadvantage because small (noisy) line segments with 100% overlap will outperform large robust lines with little overlap. This problem is solved by discarding all line segments smaller than a *MinimumLength* value. This is done in an early stage at the Hough transform module.

Next the normalized line-wall overlap is used to search for the correct line-wall association. This is achieved by associating a line segment with the wall that has the largest line-wall overlap.

To summarize, the overlap type is determined by calculating the numbers of in polygon points and evaluating two dot products. Next the line segment is cut off depending on the overlap type and the line is normalized. The wall where the line segment scores the maximum *two'* value is associated with this line segment's most likely wall.

#### 4.2.7 Improving the 3D model by wall height estimation

In the previous section we associated the line segments with their most likely wall. In this section this information is used to estimate the heights of the walls of the 3D model.

Every different view of the building produced a collection of lines that are associated with a certain wall. For example if we consider 4 views and for wall  $W$  the views have respectively 2,4,4,1 lines that are associated with  $W$ , we have a total of 11 line segments for wall  $W$ .

Next we re-project the line segment from the different views on their associated walls. The re-projection is done as explained in (??) by intersecting both endpoints of the line segment to the plane that is spanned by the associated wall.

Next the average height of the projected line segments is calculated for each wall. This is done by taking collecting and averaging the y-value of the 3D intersection points of the corresponding wall. These averages are then used as the new heights of the walls of the building. Note that this is only permitted in presence of the *flat roof assumption*.

The new individual heights are applied to the 3D model by adjusting the height of the existing upper corner points of the walls. We copy the bottom left and right corner points and add the estimated height from the previous section to its y-value. The y-value is the direction of the gravity which is obtained through the *Gravity aligned walls assumption*.

### 4.3 Results



Figure 23: Three best ranked lines of the Hough transform on the skyline detector match the building walls

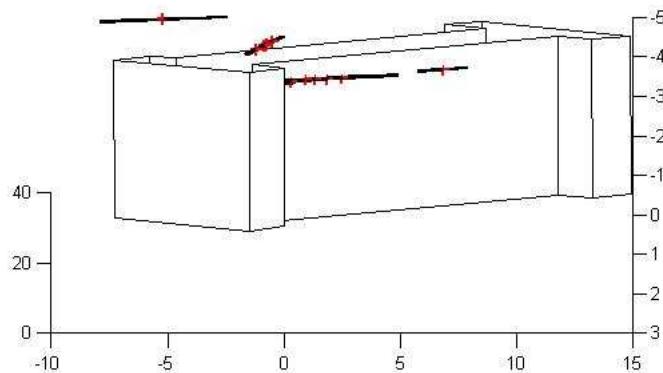


Figure 24: Houghlines projected on the most likely wall



Figure 25: The walls of the building differ in height

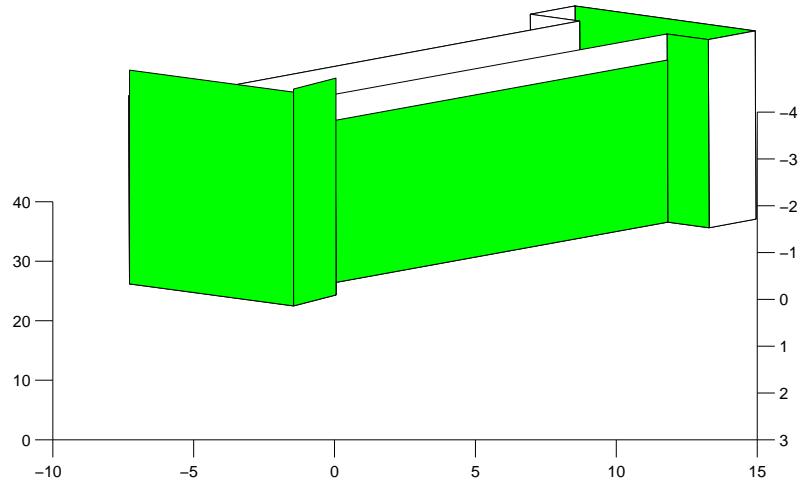


Figure 26: Improved 3D model

Figure 23 shows the top 3 longest Houghlines of a single view. The endpoints are denoted with a black and blue cross. All three line segments lie on the building contour. The left line segment covers only a part of the building wall.

The middle line segment covers the full wall contour. The left and middle line segment are connected. The right line segment covers the wall until the occluding tree.

Figure 24 displays the line segments (collected from Figure 23 and 6 other views) projected onto their associated walls. For a clear illustration we selected just three walls and plotted their associated lines. For each view a different red cross is drawn at the average middle. The red crosses illustrate the calculated average height.

Figure 26 displays the updated 3D model. The corner points of the walls are adjusted according the calculated wall heights. The green plane displays the modified wall. The left and middle wall are extended whereas the right wall is shortened.

#### 4.4 Discussion

As can be seen in Figure 23, the top three Houghlines correspond to the three most prominent building walls.

What also can be seen is that the left line segment doesn't cover the whole building wall. This is caused by the use of strict parameters in the Hough transform (like a small line thickness parameter). If some ascending skyline pixels fall just outside the Houghlines, a gap is created and the line segment is cut down at that point. This is however not a big problem because the lines are long enough to produce a good wall height estimate. Furthermore there are 5 other lines (originated from different views) that support the estimate for this wall.

The different red crosses in Figure 24 which illustrate the average height per view agree in height. This means the camera calibration, edge detection and Houghline extraction were accurately processed.

Although the building appears to have similar building heights the middle part of the building has a lower height, see Figure ???. This is supported by the updated 3D model in Figure 26.

#### 4.5 Conclusion

Let's answer our research question.

##### Research question

Is it possible to use a set of (noisy) skyline points together with an aerial 2D model and a 3D point cloud obtained by *FIT3D toolbox*[11] to generate a 3D model of the building?

Yes this is possible, we showed that a Houghline transform is a useful method to discard skyline outliers and find prominent structure in the contour of a building with a flat roof. We introduced a method to extract a 2D model of a building from *Openstreetmap*[1] and aligned it to the scene using the *FIT3D toolbox*[11]. Next, we extracted the skyline and transformed this to Houghlines which we paired up with their associated walls. This was used to produce new wall heights which were propagated to the 3D model. Existing and novel AI computer vision techniques were powerfully combined resulting in a reasonable 3D model based on only a few 2D images.

## 4.6 Future research

### 4.6.1 Gravity aligned walls assumption

In this project we assumed the walls to align with the gravity. This means the camera must be up right: his parameter *roll* must be exactly zero when capturing the images. In practical use this is not true. We demonstrate this by plotting the 3D point cloud with the 3D model in Figure . Although this assumption let us focus on the important issues it would be nice to incorporate gravity estimation in future research. Costin Ionita wrote a part of his master thesis about gravity estimation in [13].

### 4.6.2 Double wall height influence

Sometimes two line segments appear on the same single wall. This means that they have a double influence on the average wall height, which is unjustified. A simple solution would be to add a normalization pre-process step, so each view has only one wall height vote per wall. A more decent solution would be to merge the two (or more) line segments to a single line segment. Lines that are close and parallel could be merged and averaged. Lines that lie in each others direction could be merged by increasing the Hough transforms *FillGap* parameter. E.g. for the right wall of the building in Figure 24 the *FillGap* parameter needs to be at least as big as the occluding tree.

### 4.6.3 Complexity

In this thesis little is discussed about the computational costs. Because the computations are done efficiently (e.g. using matrix multiplications in MATLAB[15]) and off line, the calculation are done in reasonable time. However, if we want to make the application real time, the next speedup would be useful.

To determine the best line-wall association the line segments are now projected to every wall and for every wall the amount of line-wall overlap is calculated. This is computational very expensive and looks a bit like an overkill.

It would be a significant speedup to reduce the set of walls to only the walls that contain the middle point of the line segments. To be more concrete the

middle point needs to be calculated by averaging the line segments endpoints, this middle point is used in the *in polygon* test for every wall. Next the line-wall association algorithm only treats the walls that pass this test. The downside of this method is that it makes the system less accurate because it will result in more false negatives. A line segment that overlaps the wall with only 1/3 could be an important candidate for the height estimation but because the speedup method it is discarded. What can be concluded is that there is a trade off in the accurateness of the height estimation and the computational costs.

#### 4.6.4 Alternative roofs

We assumed a flat roof, this doesn't mean that our methods are unusable if we discard this assumption. E.g. without adaptations the existing methods could be used to determine the (maximum) building height. If we discard the flat roof assumption the building is allowed to have any shape. In this situation it should also be possible to extract a full 3D model. We will now consider other roof types and discuss what adaptations the system should require to handle these. In Figure 27, 6 different roof shapes are displayed.

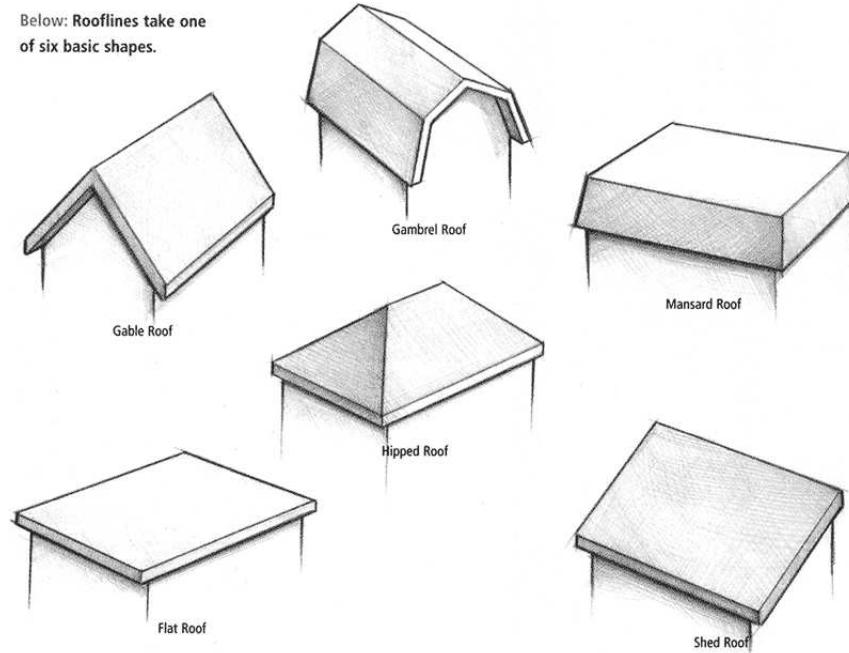


Figure 27: Different types of roofs

Consider the *Gable Roof*, it is a roof consisting of two planes which are not parallel with the facade of the building. This makes the problem of extracting

the 3D model more complex, but not impossible.

Because we assume that the roof images are taken from the ground, the skyline detector will always detect the top of the building. In case of a flat roof this is also the top of the building walls. In case of an alternative roof, this will be just the top of the building. The building walls however could lie a lot lower, therefore something else needs to be developed to find the wall heights. It would be useful to develop a method that can detect the shape of the roof estimate the wall heights and finally generate an entire 3D model.

A idea about this is now proposed:

The 3D model of a building with a non-flat roof type will consist of a cuboid with a custom roof on top of it. First we would generate the custom roof using the shape of the skyline. Next we would determine the height of the cuboid. Finally we connect both parts and have a full 3D model.

The skyline detector discussed in chapter 3 could be used to extract the contour of the roof. Next we would extract a basic 3D model (discussed in chapter 4) which is used to transform the roof contour to a frontal view. Houghline extraction could be used to extract straight lines which correspond to the base of the primitive planes of the roof. For example the Gable roof will return two straight lines connected in the middle. Next we extend the lines to planes. We would extract a point cloud of the side wall using the *FIT3D toolbox*/11/ to determine the alignment of the planes.

Next, a shape is cut out of the plane according to the side view of the building contour. For example the Hipped roof (Figure ??) would imply we have to cut out a trapezium shape whereas most other roofs require a rectangular shape. Note the power of combining the frontal and side view to determine the roof planes. Let us consider the Gable roof, we extract two lines and extend them to skew rectangular surfaces which are connected in the middle.

Next the height of the cuboid needs to be determined. This could be done by detecting the roof-wall separation on the side view of the building. This can be done by detecting horizontal lines using the Hough transform. To discard outliers we would only search between the ground plane and the top of the roof. The location of the top of the roof could be determined by the highest skyline point that is present in both frontal and side view. The ground plane could be estimated using Costins ?? method. The roof color often differs from the wall color which produce strong edges. Also some building contain a gutter connected to the roof. The gutter will also produce a long strong edge. These strong edges can be used to find the cubic height and the lower bound location of the roof. Finally we connect the roof and the cuboid to obtain a full 3D model.

## 5 Window detection

### 5.1 Introduction

In this chapter we deal with an important aspect of semantic urban scene interpretation: window detection. From the introduction we learned that window detection can play an important role in a variety of domains: semi automatic 3D reconstruction/modelling of city models, documenting historical buildings, analysis of old building deformation, augmented reality, building recognition, etc.

This chapter deals with our developed methods of window detection and it is organized as follows:

We start with related work and put our work in context. Next we describe our first window detection approach that is invariant to viewing direction. After this we present a facade rectification method. Next the rectification result is used for our second method that assumes orthogonal and aligned windows. Finally we show and discuss our results.

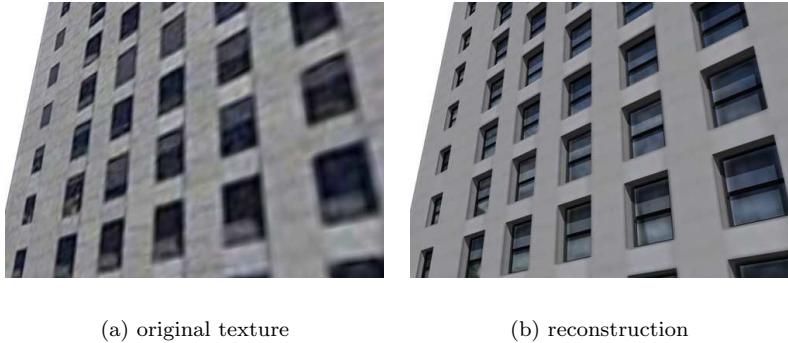
### 5.2 Window detection: state of art

A large amount of research is done on semantical interpretation of urban scenes. First we briefly discuss the research that is done on window detection using approaches that differ from our approach. After this, we discuss state of art window detection that lays at the basis of our approach in detail.

#### 5.2.1 Alternative approaches on window detection

Muller et al. [17] detect regularity and symmetry in the building. The symmetry is detected in the vertical (floors) and horizontal (window rows) direction. They use shape grammars to divide the building wall in tiles, windows, doors etc. The results are used to derive a 3D model of high 3D visual quality. Although they achieved some interesting results, their method has some disadvantages. As their method is fully based on detecting symmetry, they have to assume repeating and aligned windows: this constrains the variety of scenes the system can handle. Furthermore they match template window objects which they predefine. This constraints the variety of window types that could be matched. At last they use expensive algorithms that make it impossible for the system to run in real time.

Using a thermal camera, Sirmacek [22] detects heat leakage on building walls as an indicator for doors or windows. Windows are detected with L-shaped features as a set of *steerable filters*. The windows are grouped using *perceptual organization rules*: they search and group intersecting L-shapes to close a window shape. A shape is determined closed if it can separate an inside region from



(a) original texture

(b) reconstruction

Figure 28: Results of Muller et al.

the outside, i.e. determine if it is a window.

Ali et al. [3] describe the windows with *Haar* like features, the features are combined using a cascading classifier. The cascading classifier (which acts like a decision tree) is learned using the *Ada boost* algorithm. They also use window detection to determine the region of the facade.

Although this method is used a lot in computer vision, it is not the most promising approach to window detection because it has to be supervised. This means that it requires a large dataset in which every window must be accurately annotated. As the cascader uses a fixed swiping window it is sensitive to scale: all window sizes must be equal and a size range must be given to the system. Furthermore the system is always over fitted to the learning data , making it hard to generalize (detect windows that are not included in the dataset). A more general descriptor of the window that is size invariant is desirable.

To investigate this, we developed two methods of which one method does not require repeating windows nor aligned windows. One of the main targets of our research is to have small requirements on the input data. First our system doesn't need a large annotated dataset. Furthermore we took the images with a mobile phone and decided to extract the windows from the image space only, this makes us independent of additional expensive data like heat or laser range images. It doesn't mean the previous work on window detection using laser or heat images isn't of good use. Instead we learned a lot from the previous research as they have to match the laser or heat data to the real image space. This matching process involves a description (semantical annotation) of the facade. Let's explain a method of that kind and discuss other approaches that are more similar to our approach.

### 5.2.2 Similar approaches

Pu and Vosselman [19] combine laser range images with ground images to reconstruct facade details. They solve inconsistency between laser and image data and improve the alignment of a 3D model with a matching algorithm. In one of the matching strategies they compare the edges of a 3D model to extracted Hough lines of both ground and laser range images. They match the lines by comparing the angle, location and length differences. These criteria are also used in our approach.

They also detect windows and use them to provide a significant better alignment of the 3D model. As windows have a high reflection, they form hole like shapes in the laser range images. These holes are directly used to extract the windows. Unfortunately due to bad laser range data, the results were far from accurate.

The work of Pu and Vosselman [19] provides a useful practical application of window detection. It amplifies the need for a robust window detection technique that is independent of laser range data.

Recky et al. [20] developed a window detector that is build on the primary work of Lee and Nevatia [14] (which is discussed next). In order to make clear orthogonal projections they rectify the facade. To determine the alignment of the windows the edges are projected into their orthogonal direction. For example the horizontal edges are projected in the vertical direction to establish the vertical division of the windows.

A function is developed that counts the amount of projected edges on each lo-



Figure 29: Projection profiles of Lee and Nevatia’s work

cation. This is the *Projection profile*, see Figure 29. A threshold is applied on the projection profile to indicate the window boundaries that are used for the

window alignment.

In the next step they use color to disambiguate the window areas from non-window areas. To be more precise, they convert the image to CIE-Lab color space and use k-means to classify the windows. Although this method is robust, both color transformation and k-means clustering are very computational expensive. Furthermore the classification based on color is sensitive to change in illumination conditions.

As in the work of Recky et al. [20], Lee et al. [14] perform orthogonal edge projection to find the window alignment. As different shapes of windows can exist in the same column/row, they only use the window alignment as a hypothesis. Then, using this hypothesis, they perform a refinement for each window independently. Although this comes with accurate results, the iterative refinement is a computational expensive procedure. As we want to run our system in real time this method is not suitable for our application.

### 5.2.3 Our work in context

The state of art window alignment procedure in [20] and [14] is very robust. Therefore we have decided to use this method as a basis and improved the alignment algorithm. Furthermore we have build a different window classification method.

Our improvement on the alignment procedure is as follows. In the previous work [20] and [14] a single projection profile for each direction is used. We improved this process by fusing two (more advanced) projection profiles for each direction. E.g. for the determination of the horizontal division of the windows we fuse both horizontal and vertical projection profiles.

Furthermore we have build two alternative window classification procedures which are based on a higher level of shape interpretation of these projection profiles. As the classification is based on the projection profiles (edge information) we don't require expensive color transformations and we only apply (rectification) transformations on line segment endpoints. This makes our algorithm invariant to change in illumination and perform in real-time.

## 5.3 Method I: Connected corner approach

### 5.3.1 Situation and assumptions

A window consists of a complex structure involving a lot of connected horizontal and vertical lines, we use this property to detect the windows. We introduce the concept *connected corner*, this is a corner that is connected to a horizontal and vertical line. The search for these connected corners is based on edge information. The connected corners give a good indication of the position of

the windows. In this approach the viewing direction is not required to be frontal. The windows could be arbitrarily located and they don't need to be aligned to each other neither to the X and Y axis of the image. As such the windows are detected individually.

### 5.3.2 Edge detection and Houghline extraction

Edge detection is done using the Canny edge detector motivated earlier in section (3.3.3). From the edge images two groups of Hough lines are extracted. The groups fall in the two window directions horizontal and vertical. This is done by controlling the allowed angles,  $\theta$  bin ranges, in the Hough transform. The horizontal group has a range of  $\theta = [-30..0..30]$  degrees, where  $\theta = 0$  presents a horizontal line. The vertical group has a range of  $\theta = [80..90..100]$  degrees. We use these ranges because 1) the user hardly ever holds the camera exactly orthogonal. 2) we work with unrectified facades, meaning we deal with perspective distortion. To be more concrete, if the user takes a photo (Figure 30) with a certain Yaw  $\bar{\theta}$ , the horizontal lines become skew. The range of the vertical group is smaller than the horizontal group as the user often takes photos with a low pitch value and a high yaw.

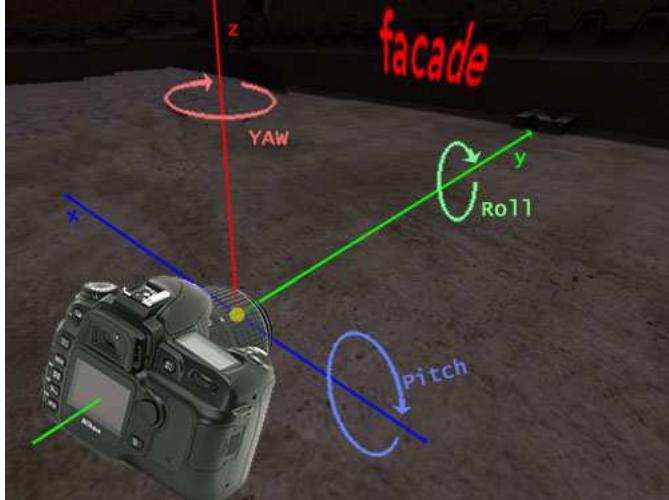


Figure 30: Pitch roll and yaw of the camera

The results of the edge detection and the Hough transform of two images can be seen in Figure 32 and 33.

### 5.3.3 Connected corners extraction

A window often consists of several sub windows enclosed in rectangular window frames. As the color of the window frames differ from the glass, the amount of horizontal and vertical edges is large at these locations. As the horizontal

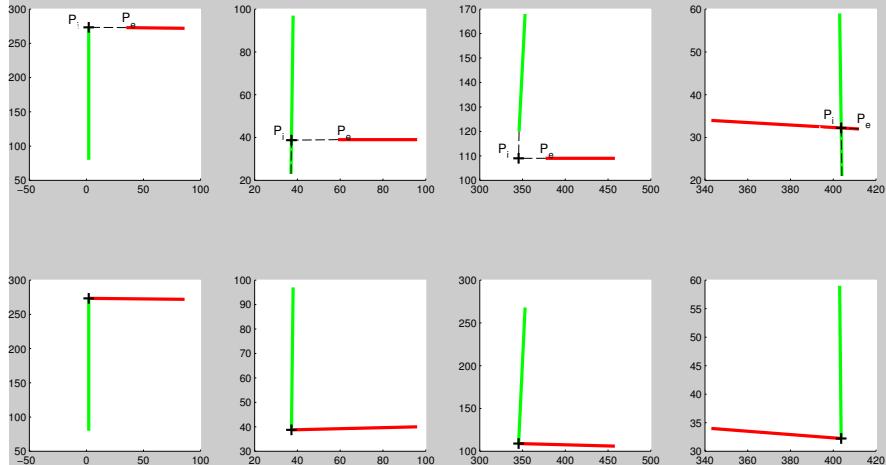


Figure 31: First row: different type of connected corner candidates. Second row: the result the clean connected corner

and vertical edges come from rectangular window frames they often share a corner of the window. We developed an approach where we pair up these horizontal and vertical lines to determine *connected corners* that indicate a window.

Often a connected corner contains a small gap or an extension which we tolerate, these cases are illustrated in Figure 31 in the top row. A horizontal gap, a vertical and horizontal gap and a vertical elongation. The cleaned up corners are given in the bottom row. When the horizontal and vertical lines intersect, the gap distance is  $D = 0$ . When the lines do not intersect, the distance  $D$  between the intersection point  $P_i$  and the endpoint  $P_e$  of the line is measured  $D = \|P_i - P_e\|$ , this is illustrated as dotted lines in Figure 31. Next,  $D$  is compared to a *maximum intersection distance* threshold  $midT$ . And if  $D \leq midT$ , the intersection is close enough to form a connected corner.

After two Hough lines are classified as a connected corner, they are extended or trimmed, depending on the situation. The results are shown in the second row in Figure 31. In Figure 31(I) the horizontal line is extended. Figure 31(II) shows that the vertical line is trimmed. In Figure 31(III) both lines are extended. At last, Figure 31(IV) shows how both lines are trimmed.

#### 5.3.4 Window area extraction

To retrieve the actual windows, each connected corner is mirrored along its diagonal through the endpoints. The connected corner now contains four sides which form a quadrangle window area. All quadrangles are filled and displayed in Figure 35, this result is discussed in section 5.3.5.

### **5.3.5 Results**

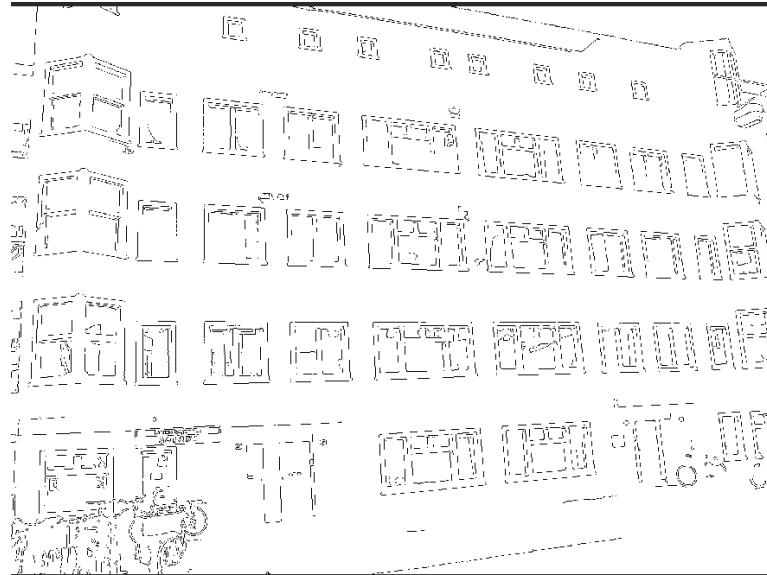


Figure 32: Edge detection

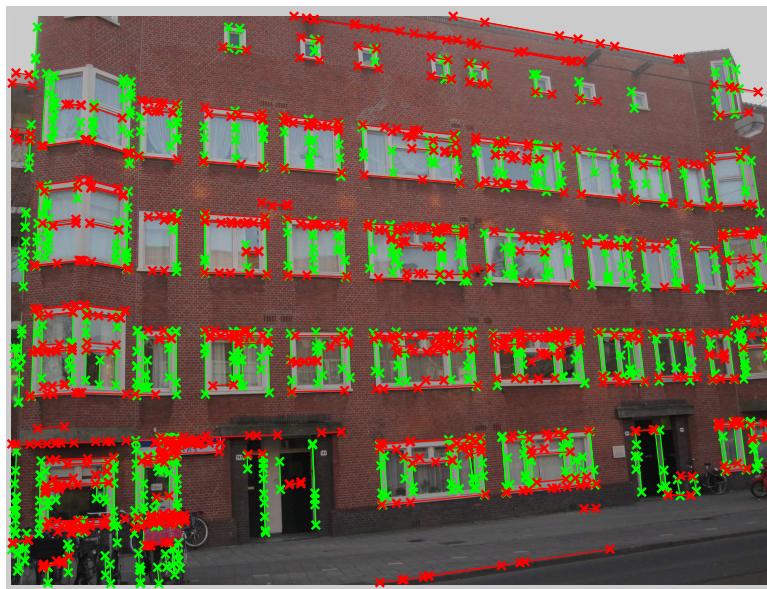


Figure 33: Result of  $\theta$  constrained Hough transform



Figure 34: Found connected corners

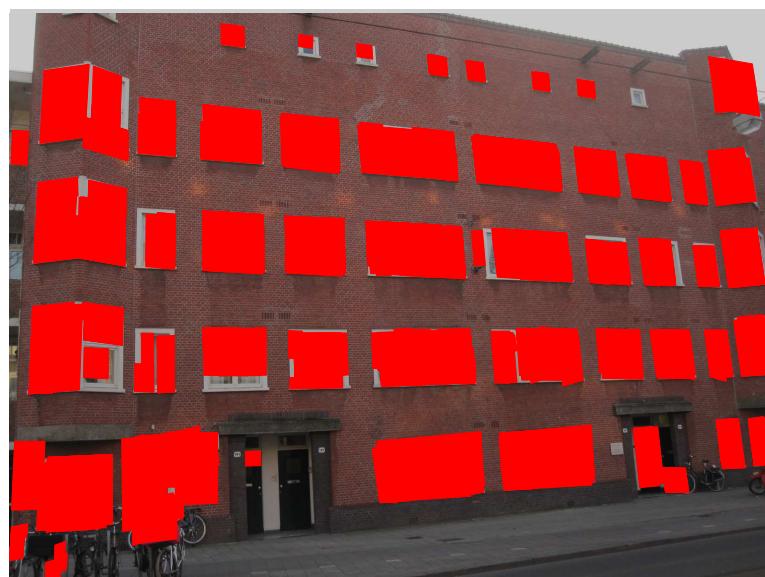


Figure 35: Window regions

Figure 35 displays the result of the connected corner approach on an unrectified scene. It contains 110 windows of which are 109 detected, this is 99%. Furthermore there are some false positive areas, this is about 3 %. Sometimes a window is not detected, for example the window on the right top isn't detected, this is because its smaller than the minimum window width.

### 5.3.6 Future research

We only developed L-shaped connected corners. In future research we could connect more parts of the window. E.g. to form U shaped connected corners or even complete rectangular shapes. The latter is difficult because the edges are often incomplete due to for example occlusion.

Furthermore the next step in this study would be an analysis of the substructure of the windows. The big window that contains sub windows could be found by calculating the convex hull of the red areas in Figure 35. The sub windows could be found by grouping connected corners that correspond to the same sub window.

This could be done by clustering the connected corners at their location. It would be useful to assume the number of sub windows as this can be used to determine the maximum inter-cluster distance. We could also incorporate not only the center of the connected corner as a parameter of the cluster space but also the length and position of the connected corners' horizontal and vertical line parts. The inter cluster distance and the number of grouped connected corners could form a good source for the certainty of the sub window.

## 5.4 Facade rectification

### 5.4.1 Introduction

In order to apply our second method of window detection (5.6), we need the windows on the facade to be orthogonal and aligned. Therefore we rectify the facade, this can be achieved in a manual or in an automatic way.

The manual rectification method uses point to point correspondences. This requires annotation of the corner points of the facade that are mapped with the corners of a rectangle. This mapping is used to calculate a transformation matrix. The downside of this method is that it is not very accurate as it doesn't take the width and height ratio of the facade into account. It also does not take the camera lens distortion into account. Another downside is that it requires (manual) annotation of the corner points. As we want our rectification method to be accurate and fully automatic this method is not suitable.

The second method involves the extraction of a 3D plane of the facade. This method is more complex but gives more accurate results. Extracting a 3D plane from a series of images is a comprehensive process and a large amount of research is done in this area. As we want to focus on the annotational part of facade interpretation, we used existing software to assist our rectification.

I. Esteban's *FIT3D toolbox* [11] comes with an add-on which extracts a 3D model from a series of frames. This add-on involves a process that calculates the motion between a series of frames in order to extract a point cloud of matching features. This point cloud is used to extract a plane for every unique wall. More details of this process are explained in (2.4).

#### 5.4.2 3D plane based rectification

The next challenge is to use the extracted 3D plane in order to rectify the facade. It would be straight forward to rectify the full image. However this is computational very expensive as each pixel needs to be projected. To keep the computational cost to a minimum we project only the necessary data. Since we are using Hough lines we project only the coordinates of the endpoints of the found Hough lines. This is allowed because the projective transformation we apply is an affine transformation which preserves the straightness of the lines [6]. Note that this means we apply the edge detection and Houghline extraction on the unrectified image.

If  $h$  is the number of Hough lines, the number of projections is  $2h$ . When we rectify the full image the number of projection is  $w \times h$ , where  $w, h$  are the width and height of the image. To give an indication, for the *Anne1* dataset this means we apply 600 projections instead of 1572864: a factor of almost 3k faster.

The Houghline endpoints are projected to the 3D plane we extracted in the same way as we explained in chapter 3. We send rays from the camera center through the Hough line endpoints and calculated the intersection with the 3D plane. The result is a 3D point cloud where each point is labeled to its corresponding Houghline.

The next step is to transform the facade (and therefore the Hough lines) to a frontal view. Instead of transforming the facade we rotate and translate the camera. This means the heading (z-axis) of the camera needs to be equivalent to the normal of the facade plane. We determine the rotation matrix  $R$  by calculating the angle between the camera's heading and the normal of the facade. This process involves calculating 1) the orthogonal rotation vector  $\vec{n}$  and 2) the angle  $\theta$ , see Figure 36.

Next,  $R$  is applied to the 3D point cloud resulting in a set of rectified 3D points that are grouped to their Hough lines.

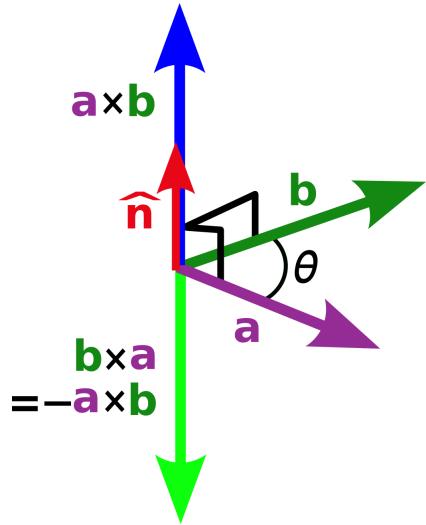


Figure 36:  $\vec{a}$  is the camera's heading and  $\vec{b}$  is the normal of the facade plane,  $\vec{n}$  and  $\theta$  are used to generate rotation matrix A [23]

#### 5.4.3 Results

We show the result of two datasets, Anne1 and Dirk. Note that we also rectified the image pixels itself, this is only for the purpose of displaying the projected Hough lines in context.



Figure 37: Dataset: Anne1, Original, (unrectified) image

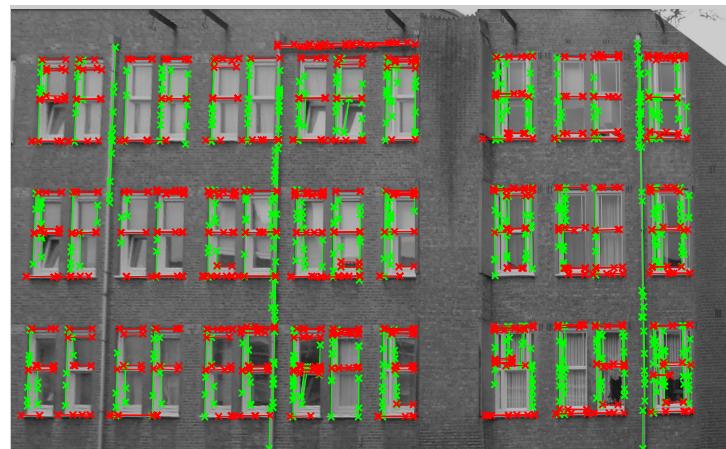


Figure 38: Dataset: Anne1, (Projected) Hough lines on rectified image



Figure 39: Dataset: Dirk, Original, (unrectified) image,

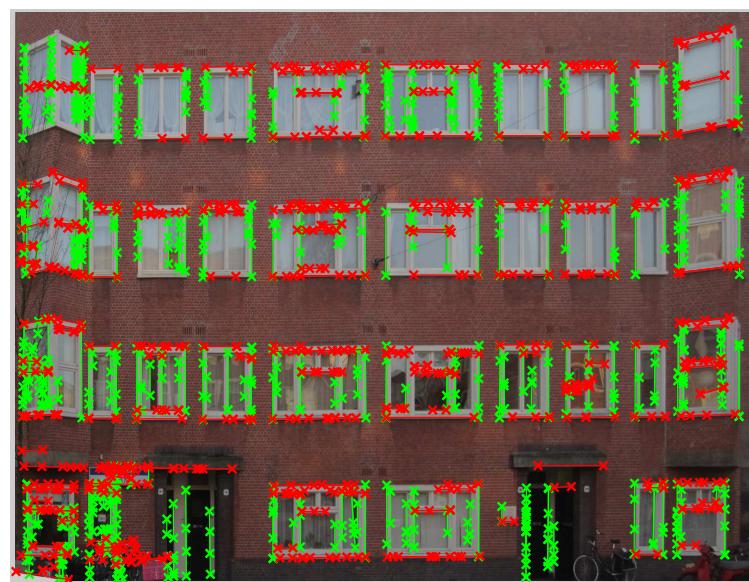


Figure 40: Dataset: Dirk, (Projected) Hough lines on rectified image

## 5.5 Datasets

To avoid over fitting we used multiple datasets that contain different urban scenes. Furthermore every dataset has a challenge/handicap. We used three datasets that are recorded in the suburban area 'de Baarsjes' of Amsterdam. All images have an original resolution of 3072x2304 pixels and are down scaled (using cubic interpolation) to 1280x1024 pixels.

### 5.5.1 Anne1

The challenge of this dataset is that it suffers from rectification errors. This makes the window alignment a challenging task as it assumes the windows to be aligned with the x-axis and y-axis of the image. The rectification error can be seen as the skew window alignment (and skew drainpipe) on the left of the image. Furthermore the yaw value of the camera (horizontal viewing angle) was (relative to the other datasets) high, making parts of the windows occluded. The height of the windows on the right side of the image is 698 pixels, at the left side this is 320 pixels: a resolution of more than 2 times smaller which makes it hard to detect the left windows. Trilinear interpolation is used to minimize this loss. To reduce the number of handicaps (and to focus on the rectification and occlusion error) we cut off the bottom of the image which included cars, unaligned doors and windows.



Figure 41: Dataset: Anne1, Rectified image

### 5.5.2 Anne2

This dataset contains images of the same scene as Anne1. It has zero rectification error: the windows are perfectly aligned, although the resolution on the left is as in the Anne1 dataset, two times smaller. The challenges of this dataset are the occlusion artefacts and the bottom area of the image (cars, unaligned doors and windows).



Figure 42: Dataset: Anne2

### 5.5.3 Dirk

The Dirk dataset represents an everyday scene as it contains light spots on the facade, bicycles and an occluding tree. It contains zero rectification error but the windows are partially aligned. The windows are very close to each other (making it hard to detect non-window areas between them), furthermore they differ in shape, size and in type. The yaw of the camera is relatively low, implicating little or no occlusion artefacts.



Figure 43: Dataset: Dirk

## 5.6 Method II: Histogram based approach

### 5.6.1 Introduction

In the previous section we saw that from a series of images, a 3D model of a building can be extracted. Furthermore we saw that using this 3D model the scene could be converted to a frontal view of a building, where a building wall appears orthogonal. This frontal view enables us to assume orthogonality and alignment of the windows. We exploit these properties to build a robust window detector as follows: first we rectify the image as described in the previous section. Then the alignment of the windows is determined. This is based on a histogram of the Hough lines. We use this alignment to divide the image in window and not window regions. Finally these regions are classified and combined which gives us the windows. We present a regular and alternative window alignment method followed by two different kind of window classifications.

#### Situation and assumptions

To be more precise in our assumptions, we assume the windows have orthogonal sides. Furthermore we assume that the windows are aligned. This means that a row of windows share the same height and  $y$  position. For a column of windows the width and  $x$  position has to be equal. Note that this doesn't mean that all windows have the same size.

### 5.6.2 Extracting the window alignment

#### Regular window alignment

We introduce the concept alignment line. We define this as a horizontal or vertical line that aligns multiple windows. In Figure 44 we show the alignment lines as two groups, horizontal (red) and vertical (green) alignment lines. The combination of both groups give a grid of blocks that we classify as window or non-window areas.

How do we determine these alignment lines? We make use of the fact that among a horizontal alignment line a lot of horizontal Hough lines are present, see Figure 38. For the vertical alignment lines the number of vertical Hough lines is high, see the green lines.

We begin by extracting the pixel coordinates of Hough transformed line segments. We store them in two groups: horizontal and vertical. We discard the dimension that is least informative by projecting the coordinates to the axis that is orthogonal to its group. This means that for each horizontal Houghline the coordinates on the line are projected to the X axis and for each vertical Houghline the coordinates are projected to the Y axis. We have now transformed the data in two groups of 1 dimensional coordinates which represent the projected position of the Hough lines.

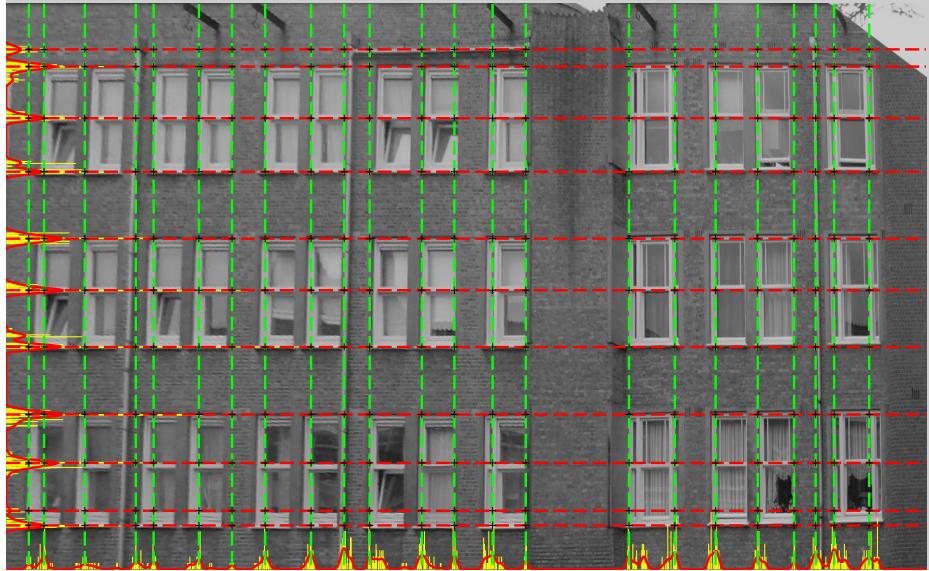


Figure 44: Dataset: Anne1, Regular window alignment (parallel projection): Based on a smoothed histogram (red line) that displays the amount of overlapping Hough lines, for the column division the horizontal Hough lines are counted (at each  $y$  position), for the row division the vertical Hough lines are counted (at each  $x$  position)

Next we calculate two histograms  $H(\text{horizontal})$  and  $V(\text{vertical})$ , containing respectively  $w$  and  $h$  bins, where  $w \times h$  is the dimension of the image. The histograms are presented as small yellow bars in Figure 44.

The peaks are located at the positions where an increased number of Hough lines start or end. These are the interesting positions as they are highly correlated to the alignment lines of the windows.

It is easy to see that the number of peaks is far more then the desired number of alignment lines. Therefore we smooth the values using a moving average filter. The result, red lines in Figure 44 , is a smooth *projection profile* which contains the right number of peaks. The peaks are located at the average positions of the window edges.

Next step is to calculate the peak areas and after this the peak positions. Before we find the peak positions we extract the peak *areas* by thresholding the function. To make the threshold invariant to the values, we set the threshold to  $0.5 \cdot \max \text{Peak}$ . This value works for most datasets but is a parameter that can be changed. Next we create a binary list of peaks  $P$ ,  $P$  returns 1 for positions that are contained in a peak, i.e. are above the threshold, and 0 otherwise. We detect the peak areas by searching for the positions where  $P = 1$  (where the function passes the threshold line). If we loop through the values of  $P$

we detect a peak-start on position  $s$  if  $P(s-1), P(s) = 0, 1$  and a peak-end on  $e$  if  $P(e-1), P(e) = 1, 0$ . I.e. if  $P = 0011000011100$ , then two peaks are present. The first peak covers positions (3, 4), the second peak covers (9, 10, 11).

Having segmented the peak areas, the next step is to extract the peak positions. Each peak area has only one peak and since we used an average smoothing filter, the shape of the peaks are often concave. Therefore we extract the peaks by locating the max of each peak area. These locations are used to draw the window alignment lines, they can be seen as dotted red lines and dotted green lines in Figure 44.

### Alternative window alignment

As you can see in Figure 45 a few window alignment lines are not found and a few lines are found at wrong locations. The right side of the window frame of the first 4 columns of windows is not found. This means we have to find another way to detect the window alignment on these positions.

For the vertical alignment we only took vertical lines into account. In this method we examine the projection profile of the *horizontal* Hough lines projected on the X axis,  $X_h$ , Figure 46. On the positions of the desired vertical alignment lines there appears to be a big decrease or increase of  $X_h$  at the window frame. This is because on these positions a window (containing a large amount of horizontal lines) starts or end.

We detect these big decreases or increases by creating a new pseudo peak profile  $D$  that takes the absolute of the derivative of  $X_h$ , Figure 46.

$$D = \text{abs}(X'_h)$$

Next we extract the locations of the peaks as the previous method.

### Fusing the window alignment methods

We have presented two window alignment methods, next we fuse the methods to gain a robust window alignment. The target is to have as few as possible false positives while detecting all alignment locations.

If a window alignment position is found by both methods, the peaks are often located very close to each other, see Figure 47. If this is the case we want to fuse the results by grouping the peaks. Most of the times the peaks indicate the same window alignment but have some disparity. This is often the case when horizontal lines stop at the *inside* of a window frame while the vertical edges are located at the *outer* side of the window frame (this is supported by the fact that the disparity is often the size of the window frame part). Yet, in other cases close peaks indicate different windows that are just happen to be located closely. To apply a proper grouping of the peaks the challenge is to distinguish

these two cases.

First we decrease the total number of found window alignment locations by increasing the individual thresholds (from  $0.3 * \text{max peak}$  to  $0.3 * \text{max peak}$ ). Note that this has a positive side effect that the peaks that are found are more certain. After this we group the peaks as follows:

First we calculate the average of the maximum window frame part and the minimum window distance and call this the maximum peak group distance  $G$ . Next we compare all peaks and if the distance between two peaks is lower than  $G$ , we discard the peak with the least evidence (lowest peak). The result, a set of unique peaks, can be seen in Figure 53.

The advanced peak grouping is only required for the vertical alignment of the windows: the horizontal inter window distance is often big enough to not be mistaken by a window frame part.

## Results

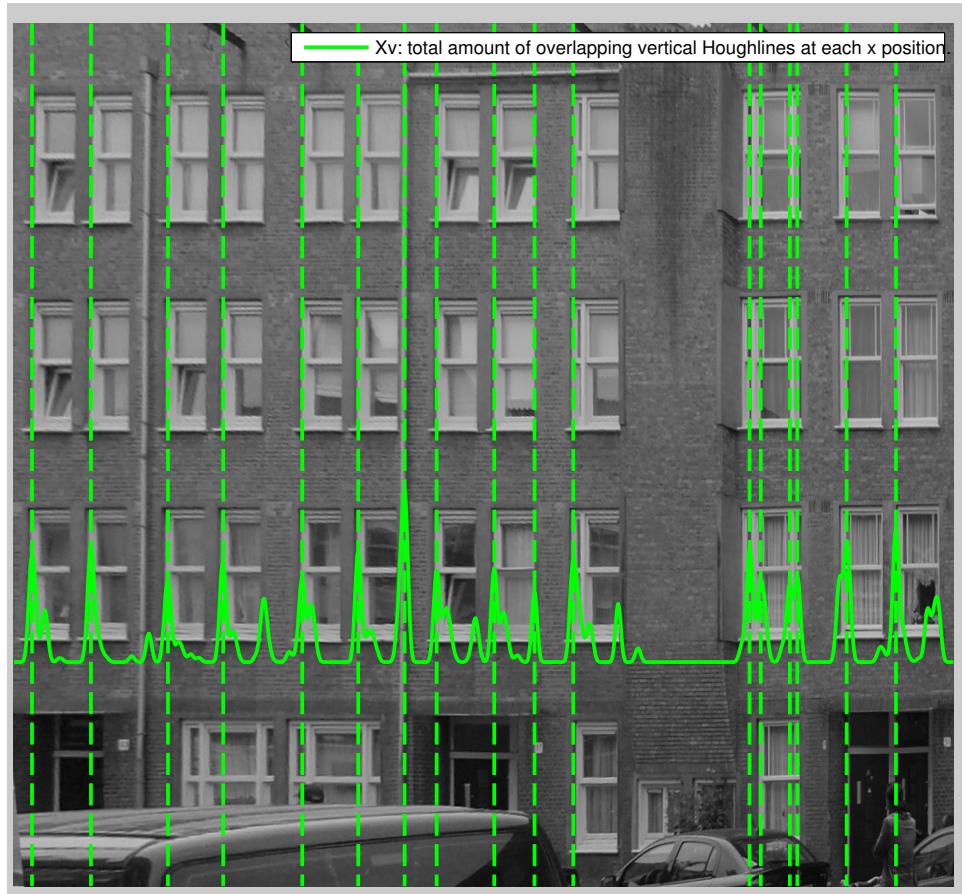


Figure 45: Dataset: Anne2, Regular window alignment: based on a histogram that displays amount of overlapping vertical Hough lines at each  $x$  position



Figure 46: Dataset: Anne2, Alternative window alignment (orthogonal projection): Based on the shape of the smoothed histogram function. For the column division, the number of *horizontal* Hough lines is counted (Note that this is the orthogonal opposite of the regular window alignment method). Peaks (that represent a big decrease or increase of the histogram function) are used for the alignment.

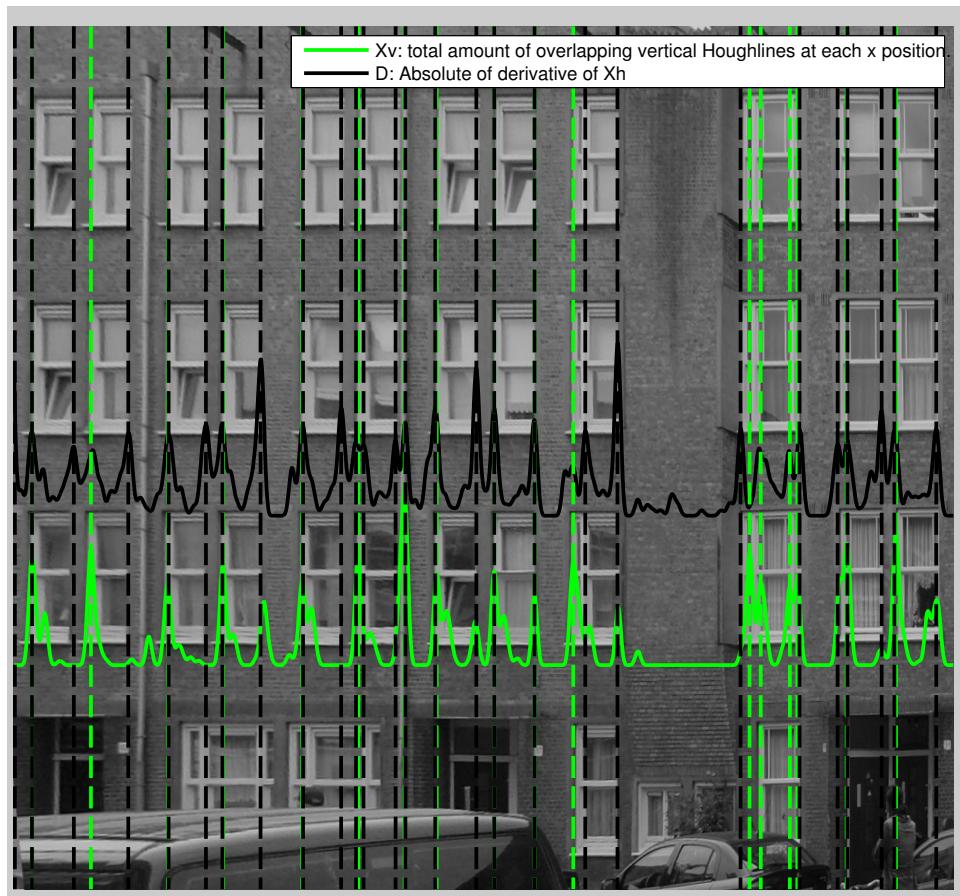


Figure 47: Dataset: Anne2, Regular and alternative window alignment combined

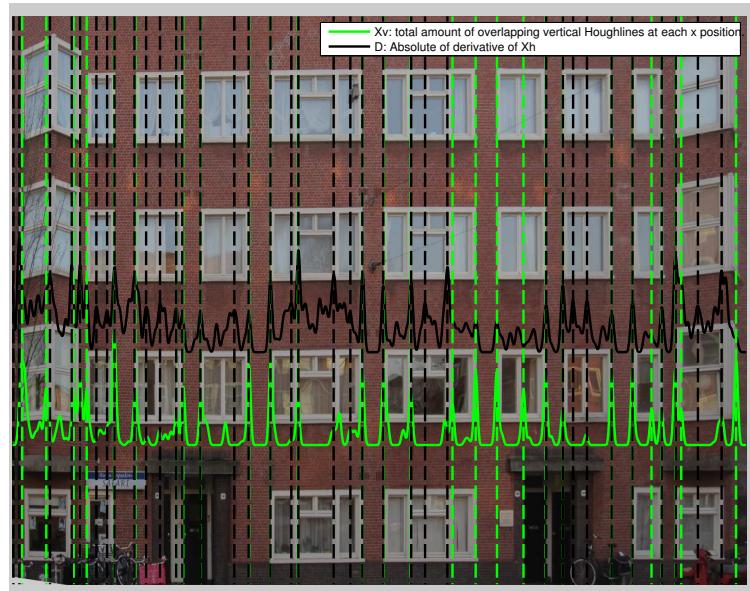


Figure 48: Dataset: Dirk, Regular and alternative window alignment combined

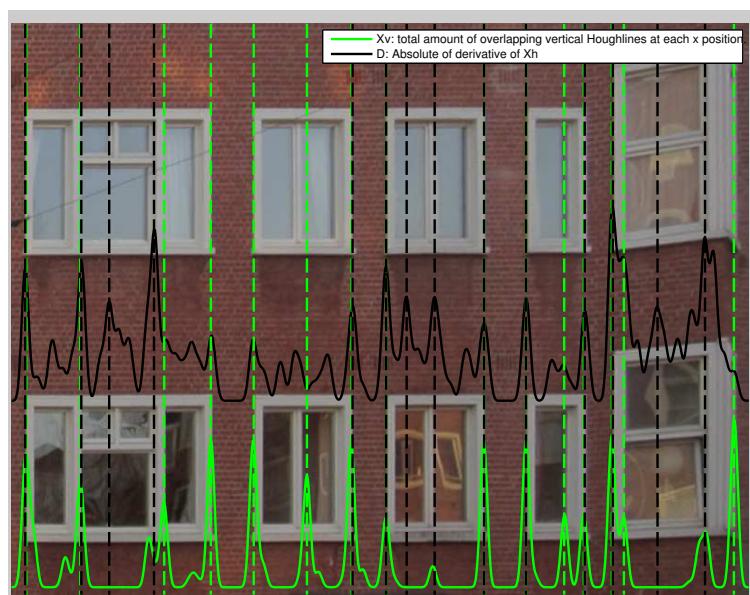


Figure 49: Dataset: Dirk, Regular and alternative window alignment combined, close-up

## **Discussion**

The results are promising, as for both datasets 100 % of the alignment lines are positioned either at the boundary of a window area or inside a window area.

### **Discussion:Many alignment lines**

In Figure 48, too many alignment lines are detected and not every alignment line is placed correctly. This is mainly because the windows are partially aligned: the two front doors contain many vertical edges that are not aligned with the upper windows, therefore a double alignment is found (doors and windows). Another cause of this artefact is that the bicycles on the left (see Figure 66) cause a large amount of found Hough lines which implies a (false) alignment line. Although the causes are clear, these additional window alignment lines cause that lie inside a window area cause no problem because adjacent window areas are grouped by the classification module.

Fortunately no alignment lines are found at non-window areas.

### **Discussion:Fusing the methods**

If we evaluate the independent window detection results on the Anne2 dataset we see (Figure 46, 45) that in both datasets neither the regular window alignment method nor the improved window alignment method detect 100% of the window alignment lines. The effect of fusing the methods is high as after fusing, 100% of the window alignment is found on both datasets: each window alignment line is detected by at least one method. This is basically explained by the fact that both methods are based on a different Houghline direction. We now discuss the interesting cases, where only one method succeeds in detecting the window alignment.

If we take a look at the regular window alignment in Figure 45 we see that for the first 4 window columns the right side of the window is not detected. This is because the original (unrectified) image (Figure 37) is not a frontal image. This makes building wall extensions (middle of Figure 37) or drainpipes occlude parts of the windows. In this case the windows are countersunked into the wall, making the building wall itself occluding the right window frame (Figure 45). The color of the reflection of the window is very similar to the bricks and because the windows and walls are not separated by the window frame, the edge detector doesn't find a strong edge. This means that on all positions where the window frame is missing, no vertical Hough lines will be detected and (as the regular window alignment is based on the amount of vertical Hough lines) no window alignment will be found. This artefact can be studied in 1) the edge image Figure 64 (few or no edges are present), and 2) at the low height of the peaks at these positions (Figure 45).

However, the alternative window alignment does find a window alignment on these positions. This is because the method is based on the opposite Houghline

direction: for the vertical window alignment the horizontal Houghline direction is taken into account. This occlusion artefact has no effect on the horizontal Hough lines, which makes the alternative window alignment method a strong alternative for the alignment of (partially) occluded windows.

In general, the alternative window alignment performs better than the regular window alignment method. This is because this method takes the horizontal window frame parts into account which is a priori stronger as there are more horizontal window parts than vertical window parts present. E.g. in Figure 38 every window has (as it has two vertical sub windows) 3 horizontal window frame parts but only 2 vertical window parts. Furthermore the method is more robust because it relies on a higher level of histogram interpretation (by using the derivative). However, in a few cases the alternative window alignment method is outperformed by the regular window alignment. For example, in Figure 49, the left side of the second window column is not detected. This is because this window type has no horizontal subdivisions. Only the top and bottom of the window frame produce an edge, therefore the derivative of the amount of Hough lines will return a small peak on this position (which is too small to survive the threshold). The threshold is a priori hard to survive because it has a high value as it is determined by taking a fraction of the maximum peak which is located at the windows that do have horizontal subdivisions (for example the most left or most right window column).

### **Future research**

#### **Future research:Determine window alignment of different window types**

A solution of the missing window alignment lines on a scene with different window types (Figure 49) would be to decrease the threshold if multiple window types are found. One could design a measure of variety of the window types. This could be done by taking the variation of the derivative of the amount of Hough lines. This amount of variation will determine the amount of decrease in threshold. Let's explain this by two examples: If there is just a few variation the maximum peak is very representative for a window so the threshold could be for example  $0.7 * \text{max peak}$ . However if there is a large variation is found (which means multiple window types are present), the threshold should be lowered to  $0.3 * \text{max peak}$  to detect the hard window types (with few horizontal divisions). Another method would be to cluster the amount of Hough lines in  $n+1$  values where  $n$  is the number of window types (the 1 is for the non-window area). Areas that transcend from a window area cluster to a non-window area cluster (or vice versa) are determined as the window alignment locations. For both methods the challenge is again to detect the window alignment with unknown window types but keep the number of false positives (e.g. a drain pipe) zero. It is also possible to discard the false positives by an additional (e.g. local refinement) method.

### **Future research:Peak grouping**

We fused the result of the horizontal and vertical Hough lines and discarded peaks that were close. A more accurate result would be achieved if close peaks were averaged, the height of the peak could be used as a weight. We used a manual maximum peak group distance ( $G$ ), this value could also be automatically derived from the image by for example taking a percentage of the window, or by detecting the size of the window frame parts.

It is challenging to handle multiple close peaks, e.g. if 4 peaks are close, then peak 1 could indicate the same window as peak 2 but indicate a different window than peak 4. The location of the close peaks: inside, at the border, or outside the window could add important evidence, some methods of the window classification could be used to detect these values.

### **Future research:Window alignment refinement**

To get more accurate result or to handle scenes with poor window alignment a refinement procedure could be applied. As mentioned in the related work, Lee et al [14] applied window refinement. Although this comes with accurate results, the iterative refinement is a computational expensive procedure. It would be nice to have a dynamic system that is aware of this accuracy and computational time trade off. A system that only refines the results when the resources are available. For example if a car is driving and uses window detection for building recognition the refinement is disabled. But if the car is lowering speed the refinement procedure could be activated. Resulting in accurate building recognition which opens the door for augmented reality.

Both window refinement and window alignment steps could use some additional evidence which could be provided by feature based methods. For example a *multi scale Harris corner detector* could help an accurate alignment or refinement of the windows.

#### **5.6.3 Basic window classification (based on line amount)**

The image is now divided in a new grid of blocks based on these alignment. The next challenge is to classify the blocks as window and non-window areas: the window classification, we developed two different methods for this.

Instead of classifying each block independently, we classify full rows and columns of blocks as window or non-window areas. This approach results in an accurate classification as it combines a full blockrow and blockcolumn as evidence for a singular window.

The method exploits the fact that the windows are assumed to be aligned. A blockrow that contains windows will have a high amount of vertical Hough lines, Figure 38 (green). For the blockcolumns the number of horizontal Hough lines (red) is high at window areas. We use this property to classify the blockrows/blockcolumns.

For each blockrow the overlap of all vertical Hough lines are summed up. (Remark that with this method we take both the length of the Hough lines and amount of Hough lines implicitly into account.)

To prevent the effect that the size of the blockrow influences the outcome, this total value is normalized by the size of the blockrow.

$$\forall Ri \in \{1..numRows\} : R_i = \frac{HoughlinePxCount}{R_i^{width} \cdot R_i^{height}}$$

Leaving us with  $\|R\|$  (number of blockrows) scalar values that give a rank of a blockrow begin a window area or not. This is also done for each blockcolumn (using the normalized horizontal amount of Hough lines pixels) which leaves us with  $C$ .

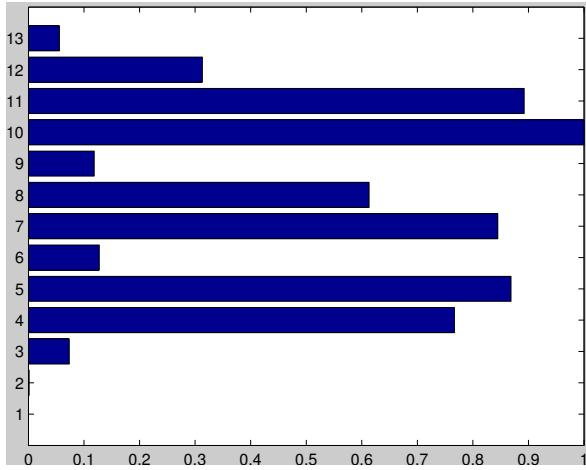


Figure 50: Classification values for window block rows representing the normalized vertical Houghline pixel count of ( $R$ )

If we examine the distribution of  $R$  and  $C$ , we see two clusters appear: one with high values (the blockrows/blockcolumns that contain windows) and one with low values (non-window blockrows/blockcolumns). For a specific example we displayed the values of  $R$  in Figure 50. Its easy to see that the high values, blockrow 4,5,7,8,10 and 11, correspond to the six window blockrows in Figure ??.

How do we determine which value is classified as high? A straight forward approach would be to apply a threshold, for example 0.5 would work fine. However, as the variation of the values depend on (unknown) properties like the number of windows, window types etc., the threshold maybe classify insufficient in another scene. Hence working with the threshold wouldn't be robust.

Instead we use the fact that a blockrow is either filled with windows or not, hence there should always be two clusters. We use  $k$ -means clustering (with

$k = 2$ ) as the classification procedure. This results in a set of Rows and Columns that are classified as window and non-window areas.

The next step is to determine the actual windows  $W$ . A block  $w \in W$  that is crossed by  $R_j$  and  $C_k$  is classified as a window iff  $k\text{-means}$  classified both  $R_j$  and  $C_k$  as window areas. These are displayed in Figure ?? as green rectangles. The last step is to group a set of windows that belong to each other. This is done by grouping adjacent positively classified blocks. These are displayed as red rectangles in Figure ??.

As the figure gives a binary representation of the windows it is not possible to see how certain a block is classified. To get insight about this we developed a measure of certainty function.

$$P(R_i) = \frac{R_i}{\max(R)}$$

$$P(C_i) = \frac{C_i}{\max(C)}$$

$$C(w) = \frac{P(w^{R_i}) + P(w^{C_i})}{2}$$

As you can see  $C$  is normalized, this is to ensure the value of the maximum certainty is exactly 1. The results can now be relatively interpreted, e.g. if the rectangle's  $P = 0.5$  then the system knows for 50 % sure it is a window, compared to its best window ( $P = 1$ ). And, as the normalization implies this, there is at least one window with  $P = 1$ .

The visualization of the measure of certainty is shown in Figure 51, the whiter the area the higher the measure of certainty.

## Results

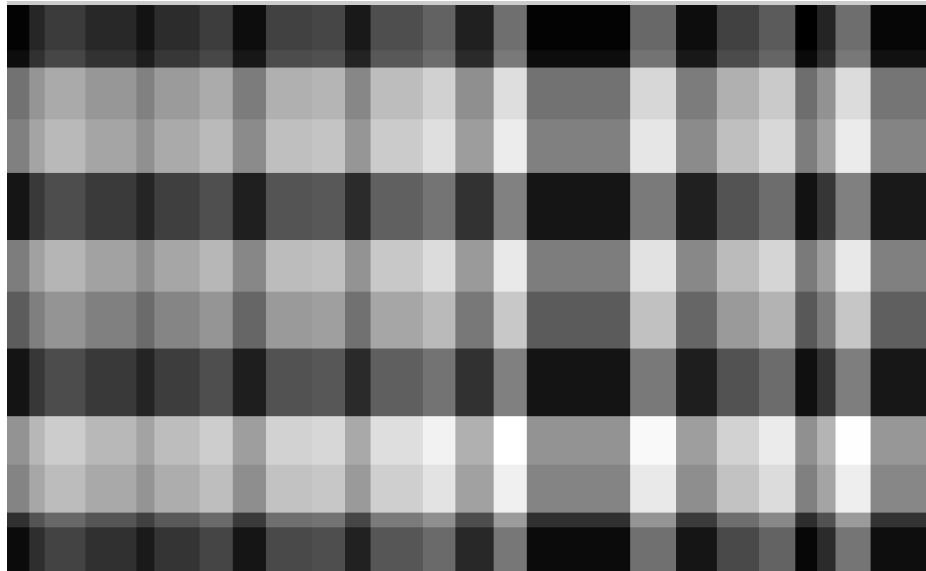


Figure 51: Dataset: Anne1, Basic window classification method:Measure of certainty, the whiter the area the higher the measure of certainty.

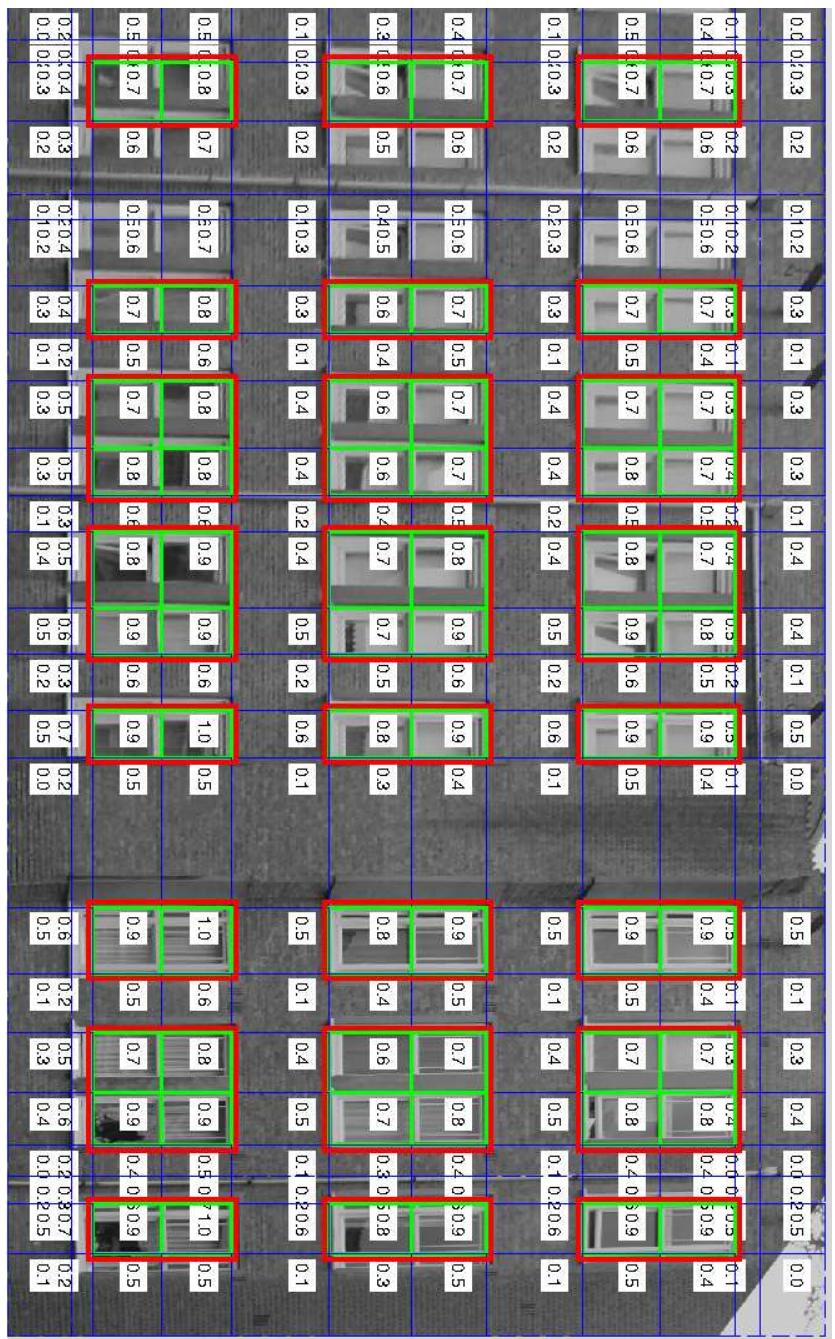


Figure 52: Dataset: Anne1, Basic window classification method: The extracted windows, red:the grouping

The bright rows and columns in Figure 51, indicate window blockrows and blockcolumns, whereas the dark rows and columns indicate non-window areas. The stripe patterns support that the classification process exist of individual row and column classification. The area of window positions is particularly white, as it intersects a bright (positively classified) row and column. One can compare this result to the windows in the original image (Figure 41).

### Discussion

The outcome of this method is non-deterministic, as it depends on to the random initialization of the cluster centers. This means that our results could be correct by coincidence. To exclude this artefact, we ran the cluster algorithm 10 times on all datasets. Unfortunately for the Dirk dataset, 2 of 10 times it resulted in a bad result. This result can be found in Appendix Figures 69, 70, 71 and 72. This result can be explained as follows. The Dirk dataset has window types in the middle of that contain a horizontal subdivision while the others don't. The windows in the middle will cause k-means to drag the cluster center to a value that is too high making windows classified as non-window areas.

### Future research

A solution to the bad luck on the initialization of the cluster centers is to increase the number of cluster centers to  $n+1$ , where  $n$  is the number of window types (the 1 is for the non-window area).

#### 5.6.4 Improved window classification (based on shape of the histogram function)

If we take a look at Figure 53 we see that  $X_h$  (the amount of horizontal Hough lines) has two shapes that repeat: At the location where a window is present  $X_h$  is concave whereas at non-window areas  $X_h$  is convex. This is because a window contains framed sub windows that create a large amount of edges. The number of edges is large at the center of the window. Whereas the number of edges at positions that lie between the windows (the non-window areas) is small. The concave and convex shape of  $X_h$  also supports that these values increase towards the window center and decrease towards non-window area centers. This artefact is used for our second window classifier.

This shape type of  $X_h$  is detected as follows: We took a similar approach as in improved window alignment (). First we examine the derivative of  $X_h$ , blue line in Figure 53. Next we investigate the positions where  $D = X'_h$  changes from sign, these are the peaks or valleys of  $X_h$ .  $X_h$  is concave at the sign changes from positive to negative (+,-) and  $X_h$  is convex if the sign changes (-,+).

We expect one sign change per block, however it is possible that multiple sign changes occur. In this case we smooth  $X_h$  again and repeat the algorithm until

for each block a maximum of one sign change is found.

Now we have detected the shape type (concave or convex), we can directly classify the blockrows and blockcolumns as window areas and non-window areas. The windows are determined as the previous classifier by combining the (positively classified) blockrows and blockcolumns.

For the purpose of clear illustration, only blockcolumns are drawn. The method for the blockrows is almost the same: the projection profiles are projected to the Y-axis.

## Results

### Results:Anne dataset

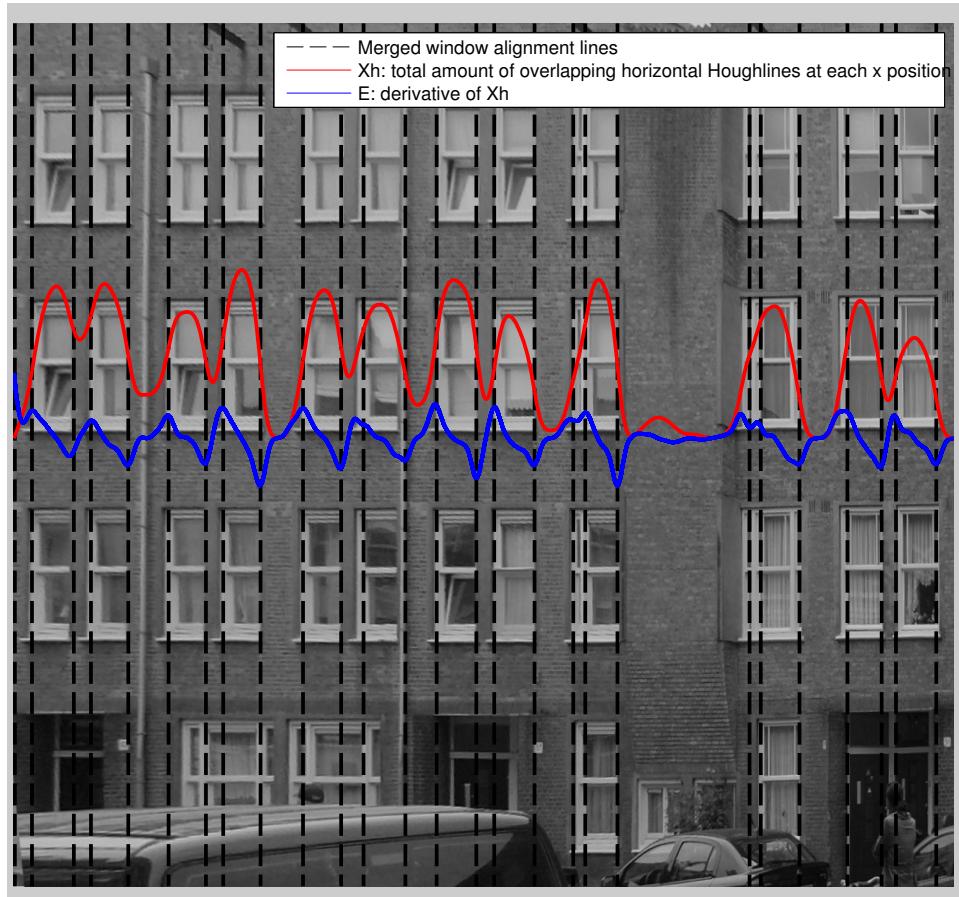


Figure 53: Dataset: Anne2, Improved window classification method: The red line shows concave shapes at window locations and convex shapes at non-window locations

Although the scene contains a lot occlusion artefacts and suffers resolution loss, especially on the left side of the image, the results for the Anne2 dataset, a 100% detection rate and a 100% true positive rate. This means that all windows are detected and that all areas that are classified as windows are indeed window areas.

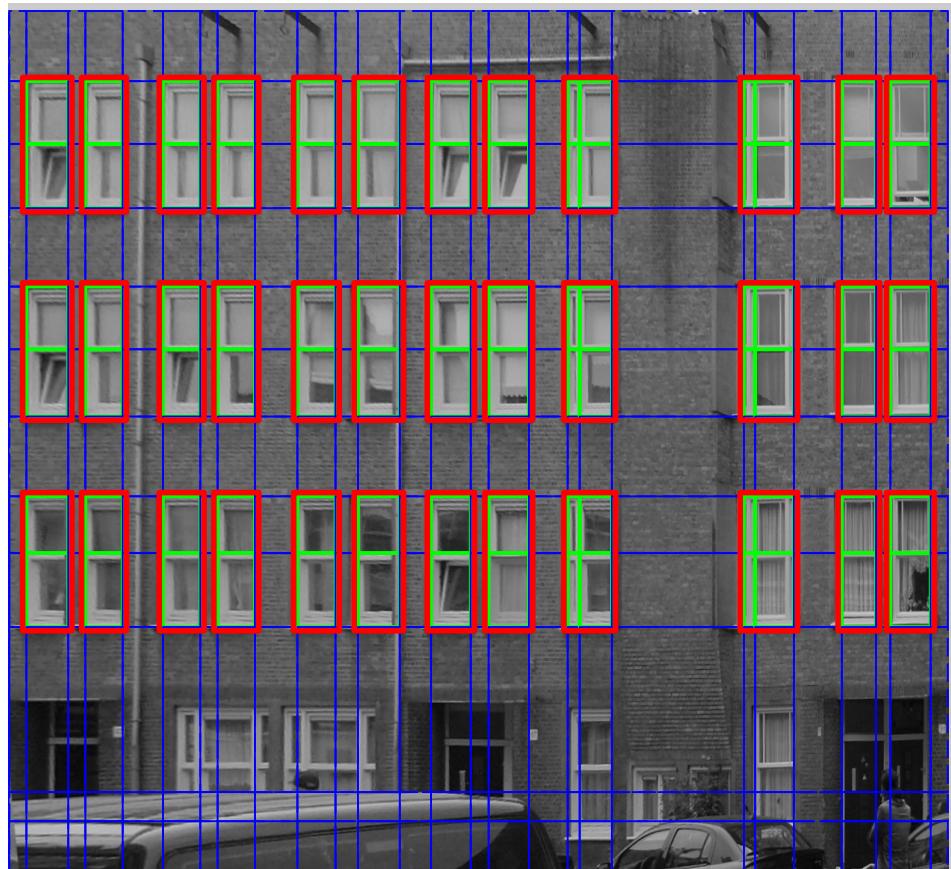


Figure 54: Dataset: Anne2, Improved window classification method: The extracted windows, red:the grouping

Table 5: Improved window classification results on Anne2 and Dirk dataset

Type	Anne2 dataset (Fig 54)	Dirk dataset (Fig 57)
Detection rate	100 %	100 %
True positive rate	100 %	87 %
False positive rate	0 %	11 %
False negative rate	0 %	9 %

### Results: Dirk dataset



Figure 55: Dataset: Dirk, Rectified image of a realistic scene which is realistic as it contains light spots, bicycles. Note that the windows are partially aligned and the differ in size and type

The results on the Dirk dataset are also promising given we are dealing with a scene which violates the aligned window assumption and also contains different window types. All windows that are present are detected (100 % Detection rate). 88 % of the detected windows are actually window areas. 12 % from the classified windows are not window areas: these are the doors at the lowest row. 9 % of the areas that are classified as non-window areas should be window areas, this is caused by the unaligned parts of the windows in the first and last column.

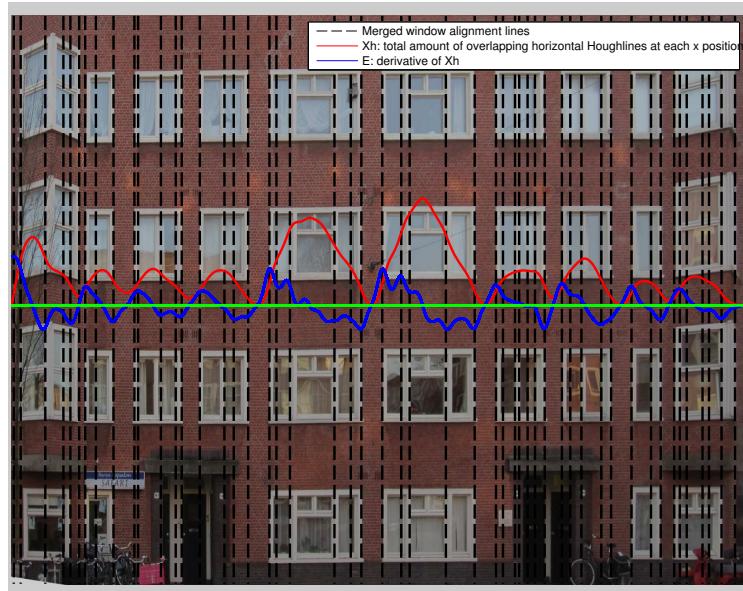


Figure 56: Dataset: Dirk, Improved window classification method: The red line shows concave shapes at window locations and convex shapes at non-window locations

Table 6: Grouping results on Anne2 and Dirk dataset

Type	Anne2 dataset (Fig 54)	Dirk dataset (Fig 57)
Grouped correct	100 %	90%
Grouped incorrect	0 %	10%

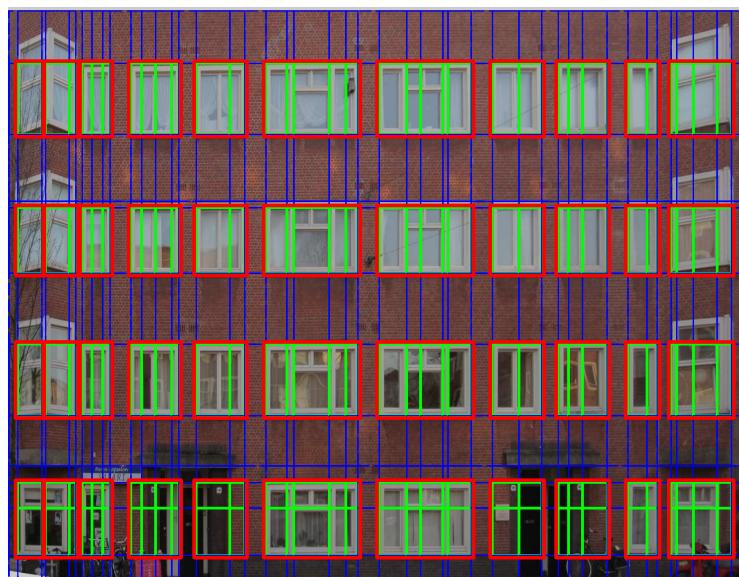


Figure 57: Dataset: Dirk, Improved window classification method: The extracted windows, red:the grouping

We discussed in the section about window alignment that the classification module would handle the redundant window alignment lines. This can be seen in Figure 57 where the classification took advantage of the fact that all alignment lines are located at a boundary of a window or in a window. The peak fusing module discarded many close alignment lines and the residual redundant alignment lines create small green adjacent sub windows which were grouped to clear red big windows.

This grouping result is promising as 90% of the grouping went well. This is a quite good result given the scene contains a large variety in window shape, window size and window type. This result is mostly due an almost perfect window alignment and classification (as the grouping only groups adjacent positively classified sub windows). The first two window rows in Figure 57 however are classified as two groups but this should be one. Normally the peak merging step would handle this problem, but with this dataset we could not use a large *maximum peak distance* value because the windows in the image (especially the first and last columns) are very close. More on this in *Future research on window classification (5.6.4)*.

### **Future research**

#### **Future work:Extensive evaluation methods**

As the classification worked very well it would be interesting to find out on which point it will fail? This could be investigated by using low quality images (which are taken for example with a cell phone), furthermore we could down-scale the images and/or add Gaussian noise to the data.

The results of the classification module depend heavily on the result of the window alignment. It would be nice feature research to make an independent evaluation of the classification modules. This could be done with a random window alignment generator. Some evaluation should be developed and it would help if the windows are annotated.

#### **Future work:Grouping error minimization**

Although the grouping module gave promising results it can be optimized. The grouping module now groups adjacent positively classified window areas. Some window in Figure areas are false negatively classified, see the left side of Figure 57. This is caused by a small area between the windows that is classified as a non-window area. This could be solved by adding a minimum size constraint of an area to be treated as a non-window area. In this way small negatively classified areas cannot interrupt the adjacent windows.

### **Performance measure for extreme viewing angles**

It would be nice to investigate the effect of the occlusion and to examine the robustness of the window detector under extreme viewing angles. For example the viewing angle could be plotted against the percentage of correct detected windows.

## **5.7 Conclusion**

We discussed two novel methods of window detection. The first method is used for scenes where no calibrated input data is available. Despite of the lack of this data it performed really well as it detected 99% of the windows. However the labeling of the windows could be more decent. This is achieved in our second method which uses a calibrated scene. It is based on Histograms of Houghlines and came with a 100% detection rate of the windows. We now discuss the method independent conclusions.

### **5.7.1 Connected corner approach**

As can be concluded from our results, the connected corner method is suitable for, and robust to, scenes with a variation in window sizes and types. This makes the connected corner approach suitable for a wide range of window scenes where no or few prior information about the windows is known.

Furthermore, the system has small requirements on the input data. It is independent of calibrated input data and 3D information about the building and no image rectification is required.

### **5.7.2 Method II: histogram based approach**

#### **Histogram based window alignment**

We conclude that interpreting the amount of Hough lines is a strong approach towards determination of the window alignment: the results in this work and in previous work are very promising.

We proposed two window detection methods and can conclude that the alternative approach performs better because it is based on a horizontal window division and because it interprets the derivative of the histogram function.

#### **Occlusion**

We showed that window alignment becomes a challenging task if the windows are partially occluded (due to for example a non frontal viewing angle). One of the main solutions we proposed is to use multiple window detection approaches. To have a 100% detection rate one need to be certain that if one approach fails

at least one other approach must succeed. We proposed the strong combination of two methods where the first method filled the gap of the second method and the other way around. For example we took care of the window parts that suffer vertical occlusion by a method that detects horizontal window parts. We can conclude that a method that fills the gap of the occluded alignment locations must generally rely on Hough lines that lie in the orthogonal direction of the occlusion.

### **Relative thresholding fails at differing window types**

Furthermore we discussed the implication of the use of different window types in the same scene. We can conclude that applying a threshold that is relative to a maximum peak doesn't work well on window types that differ. (in for example horizontal subdivisions). This is caused by the relative high maximum peak which is determined by the window with many sub windows which produce a large amount of edges. The window types with few subdivision don't survive this threshold and missing alignment lines is the result (Figure 49). This means that if we want to stick with the relative thresholding method, we have to assume a certain equality of the window types. Otherwise an alternative thresholding method should be developed (e.g. a threshold that is altered depending on the window type).

### **Window classification**

We discussed two different window classification methods.

#### **Certainty based window classification**

The certainty based window classification works quite good on the dataset we used. However, it requires a very well alignment of the windows which is a disadvantage. As it is based on the number and length of the found Hough lines, the errors in the window alignment will propagate to the classification. This makes this classification method inappropriate for a system where one cannot fully rely on the window alignment.

This conclusion amplified the need for a robust classification method that is less dependent to window alignment errors.

#### **Histogram based window classification**

The certainty based window classification only took the number of Houghlines in an certain block into account. In this approach we used the fact that the number of edges, caused by framed sub windows, increases towards the center of the window. We interpreted the Histogram function on a derivative level: and searches for a strong increase or decrease in the number of Houghlines.

The method appear to be very robust because it classified 100% of the windows correct. This is mainly because the increase and decrease pattern is very consistent: it holds for all window and non-window areas in all datasets. It is

also robust because the increase and decrease we detect is a relative measure. In contrast to methods that use absolute measures, this method is robust to a variation of window types and lightning conditions.

We can conclude that this method, based on the shape of the histogram function, outperformed the certainty based window classification.

## 6 Conclusion

In this thesis we annotated urban scenes using skyline detection and window detection.

We proposed a skyline detection algorithm that is simple has a low complexity and works without any user interaction. Under the assumption that the skyline is the upper edge, the method works well. A set of upper edges should be seen as potential hypothesis which are evaluated using additional features like color and height variation.

Furthermore we proposed two window detection methods that both detect at least 99% of the windows. We can conclude that for uncalibrated scenes the connected corner approach performed best as it is robust to variation in window type and viewing angle. For calibrated scenes we can conclude that interpreting the amount of Hough lines is a strong approach towards determination of the window alignment. We concluded proposed several alignment methods and can conclude that they perform best if we combine them. Furthermore we developed two classification method. One uses the derivative of the Houghlines Histogram function, this method outperformed our other method which was more basic.

In this project we retrieved important semantics of an urban scene: a full 3D construction of the building and the extraction of his windows. Although this is very little in comparison to what humans perceive, we made a valuable start towards human-like interpretation of urban scenes.

The applications grow in the number of correct derived semantics. With just the extracted 3D model and the extracted windows we can now recognize buildings, build 3D city models, monitor building deformation and add augmented reality to scenes. Even more application would rise if we add more semantics like house numbers, doors, trees, cars or even (your stolen?) bicycle. The skyline is the limit.

## A Appendices

### A.1 Edge detection results

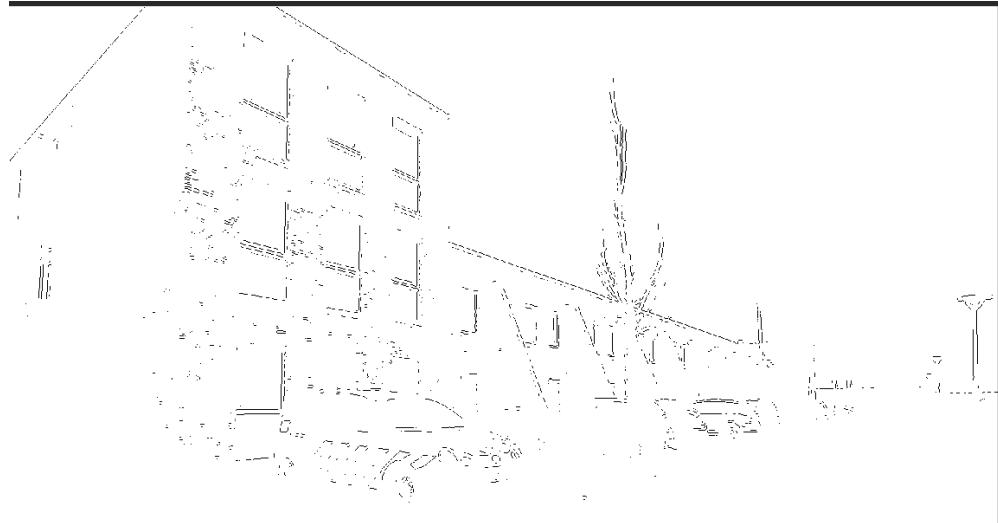


Figure 58: Edge detection results. Method: Laplacian of Gaussian

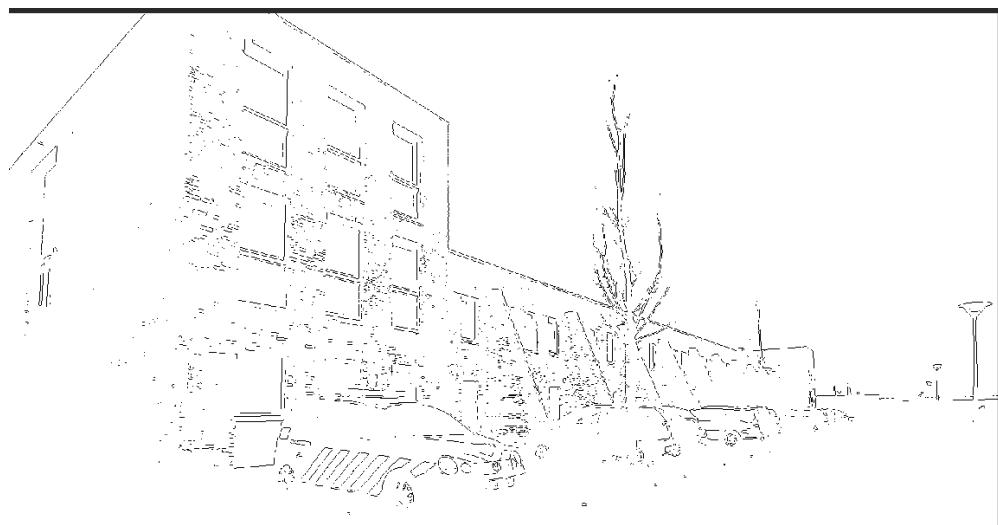


Figure 59: Edge detection results. Method: Prewitt

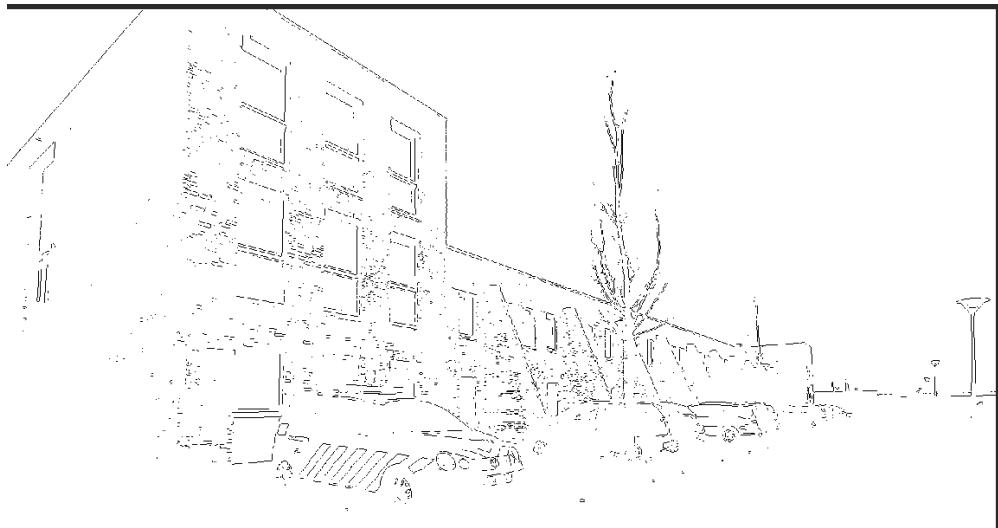


Figure 60: Edge detection results. Method: Roberts

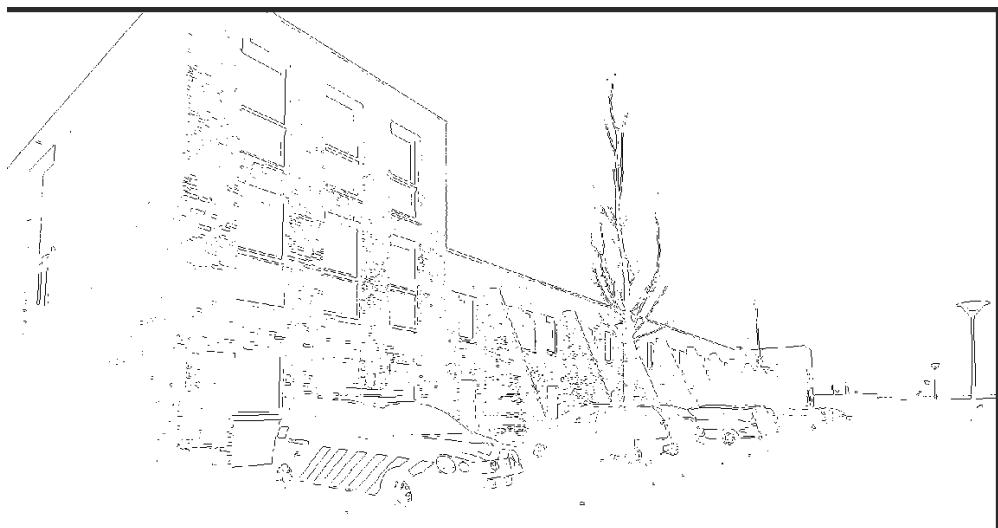


Figure 61: Edge detection results. Method: Sobel

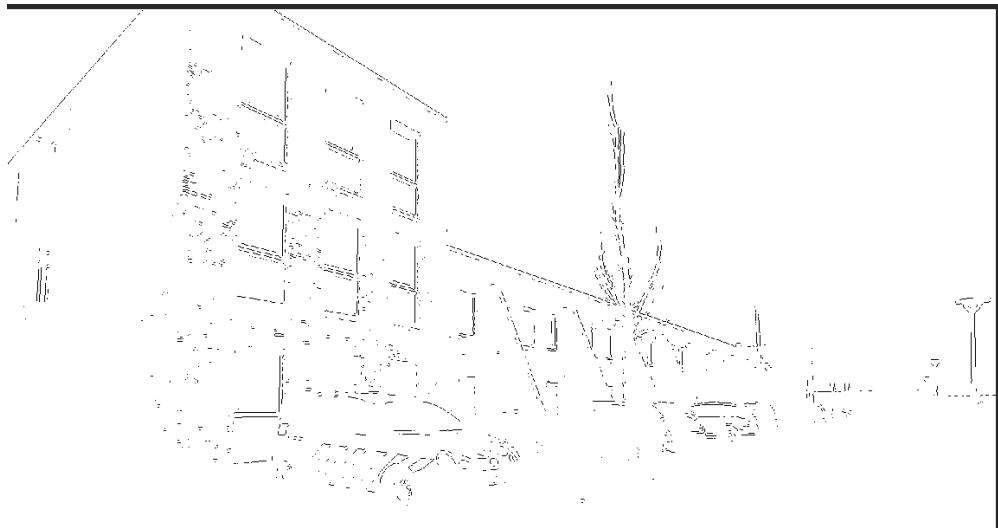


Figure 62: Edge detection results. Method: Zerocross

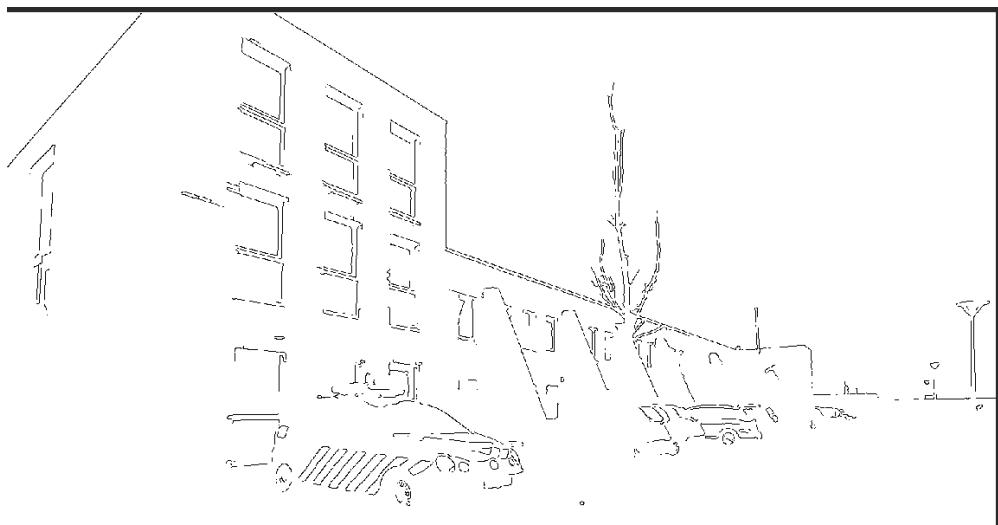


Figure 63: Edge detection results. Method: Canny

## A.2 Detailed window detection images



Figure 64: Dataset: Anne1, Result edge detection

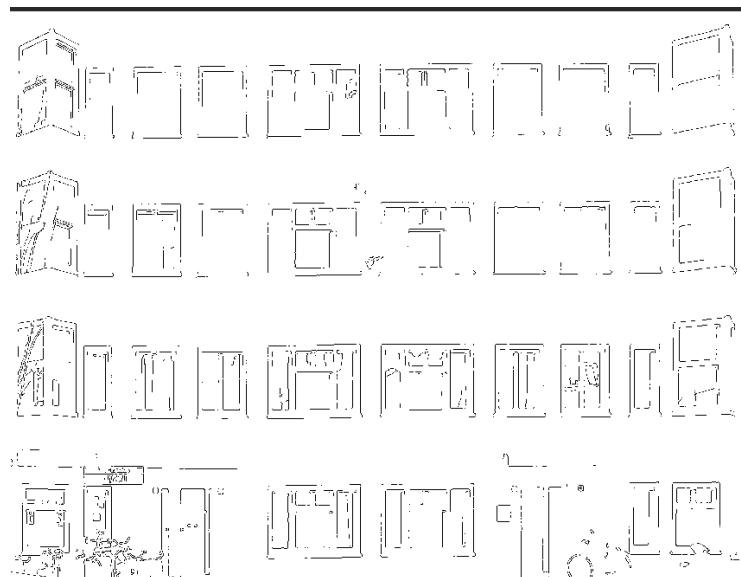


Figure 65: Dataset Dirk, Edge detection result

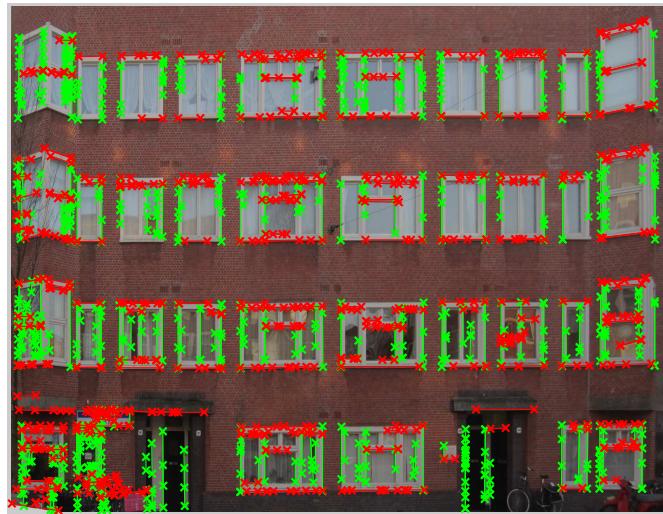


Figure 66:  $\theta$ -constrained Hough transform

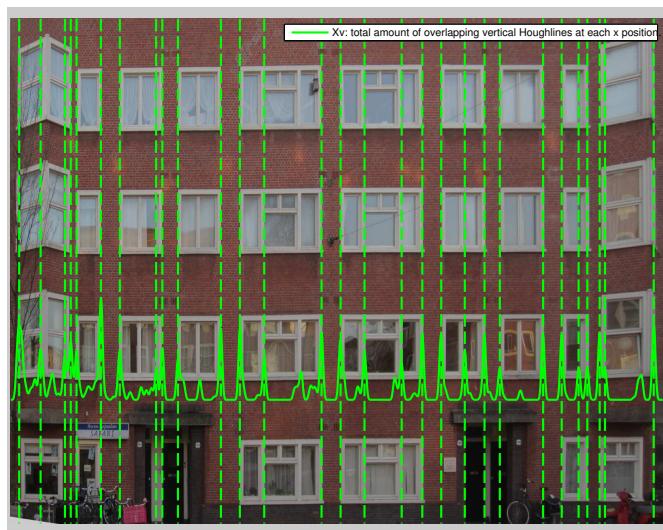


Figure 67: Dataset: Dirk, Regular window alignment: Based on a histogram that displays amount of overlapping vertical Houghlines at each  $x$  position

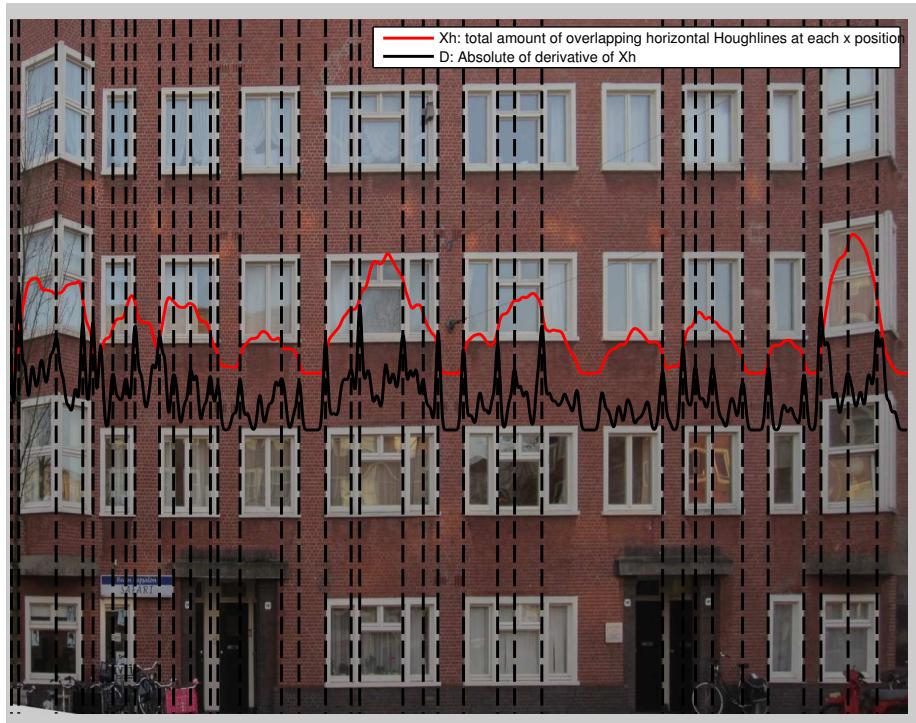


Figure 68: Dataset: Dirk, Alternative window alignment (orthogonal projection): Based on the shape of the smoothed histogram function. For the column division, the number of *horizontal* Houghlines is counted. Peaks (that represent a big decrease or increase of the histogram function) are used for the alignment.

### A.2.1 K-means bad luck

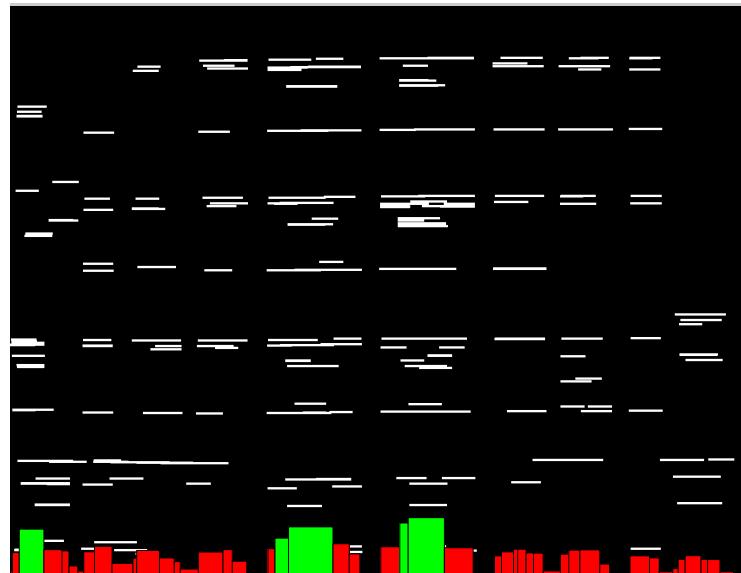


Figure 69: Dataset: Dirk, Horizontal Houghlines

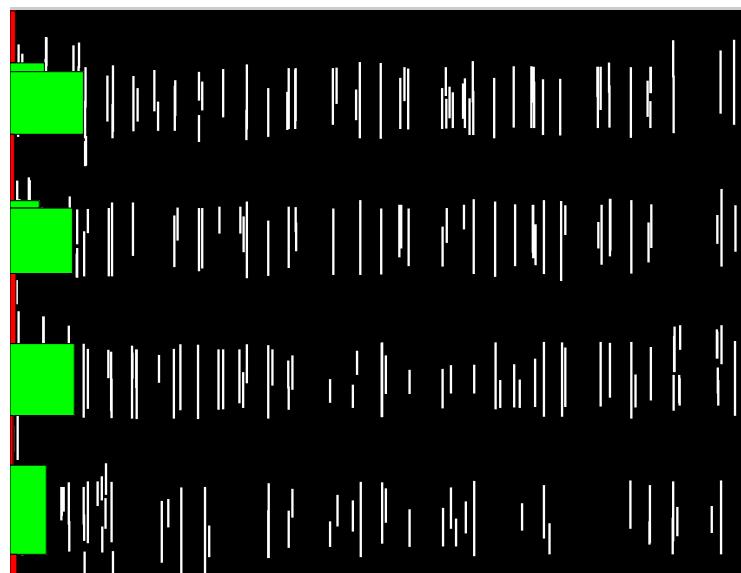


Figure 70: Dataset: Dirk, Vertical Houghlines

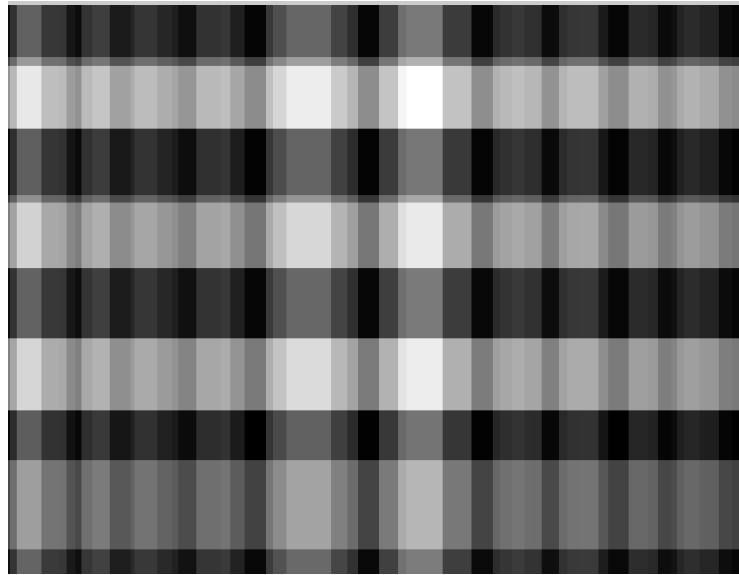


Figure 71: Dataset: Dirk, Basic window classification method:Measure of certainty, the whiter the area the higher the measure of certainty. The values of the window areas in the middle are relative large, this is due the horizontal sub windows.

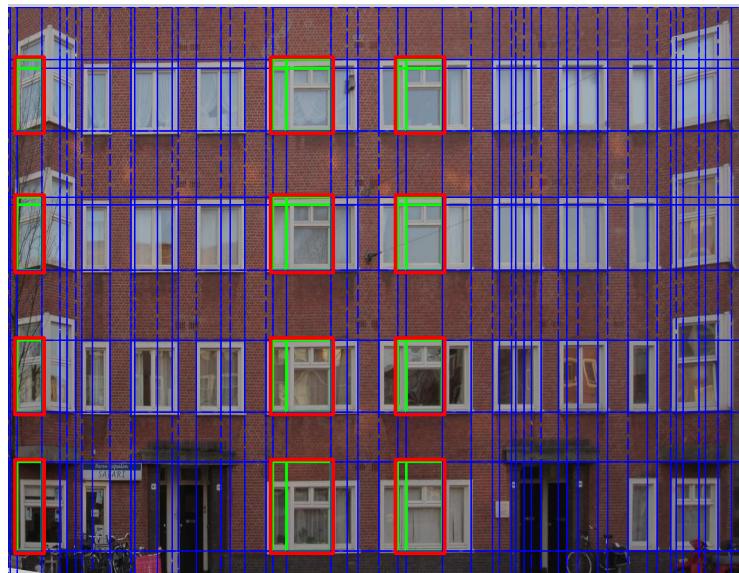


Figure 72: Dataset: Dirk, Extracted windows

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