Usage of drones in the event of incidents on the rail - measuring efficient and accurate

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Challenge the future

USAGE OF DRONES IN THE EVENT OF INCIDENTS ON THE RAIL - MEASURING EFFICIENT AND ACCURATE

by

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Geoscience and Remote Sensing
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Contents

1 INTRODUCTION

1.1. PROBLEM STATEMENT

There are many incidents on the railtracks. From signal failure to train crashes. This research focuses mainly on the major incidents. At the time of an accident on the track, the rail link is unavailable for a long time. First, the forensic investigation must take place before it can be cleaned, repairs can take place and the railway can be released again. Currently, the full forensic investigation is done manually.Because everything must be measured manually on the spot , it is a time consuming and costly process. Every hour that the track is unavailable causes reduced revenue for ProRail, more cost of redirection, decreasing punctuality and reduced customer satisfaction, beyond the cost of manual research. The question is whether the lead time and costs can be reduced while improving the quality as much as possible.

1.2. RESEARCH QUESTION

Can the time and cost of measuring train incidents by ProRail be reduced by using 3D photogrammetry with drones while improving the quality of a train crash?

The research question will be answered on the basis of a number of subquestions:

- Which requirements must be met at least for ProRail?
- What and how should we measure?
- How should the data be processed into a 3D model?
- How can the accuracy be tested?
- How can ProRail benefit?

1.3. RESEARCH DESIGN

Firstly, there is an introductory section on the establishment of this research. Here the different shareholders and their roles will be discussed. Then there is a bit about the method of measuring with a drone and 3D photogrammetry. Then this technique will be put into practice on the situation as relevant to this research. In addition, the above subquestions will be taken into account, and they will also be handled separately. Subsequently, the main question can be answered and a recommendation can be made to ProRail.

Two people have made an important contribution to this research. Sam Koch has mainly engaged in the organizational part of the research, such as contacting and planning meetings and demos. In addition, Sam Koch has contributed to the preparation of the requirements.
Robert Voûte played an important role in the research. Robert Voûte is a teacher at the Faculty of Architecture at Delft University of Technology. In addition, Robert has the role of "Vice President Consulting" within CGI. Combining these two functions has led to a scientific research for business.

2

Organizational

2.1. Parties involved

CGI is a regular ProRail business partner and was thus involved in discussing the possibilities to determine and evaluate meaningful use cases for drones at ProRail. There were five useful cases out of which the use of drones for making 3D models of incidents on the track seemed the most useful.
After joining the conscious department at ProRail, it has soon been decided to join students. After some experiments on building a model house we concluded that a professional drone but also an experienced drone company would be required for the recovery (especially in terms of regulations) we came into contact with Eyefly. This could be a test with our specifications. Thus, a collaboration between CGI (customer and process knowledge) and as an ICT company capable of modeling the data chain, developed TU Delft students with knowledge of photogrammetry and geodesy and a drill specialist (Eyefly) for working with drones and initial processing.

In addition, experience has been gained at GeoDelta, a company that makes itself photogrammetry software, and attended a conference at Cranfield University. At Cranfield University, specialists from all sorts of subjects have been told to share their experiences with the use of drones.

2.2. Requirements

The approach, for handling the measurement of an incident on the track, in this study is entirely new to ProRail. The only requirement ProRail puts in this research is to create added value over the current method. This can be done through a reduction in research time or by adding quality. For this reason, additional requirements have been added that may be of added value, namely:

1. Overview of the situation in 3D
   The location where an incident has occurred can be unclear. Many different parts can be spread across the area. In order to get a clear overview of this situation, a 3D model can be used. In a 3D model, the situation can be viewed from all sides. It can be zoomed in on a detail or just a distance to the whole view.

2. Perform backwards measurements
   When an accident occurs, business is considered to be considered in advance. However, no extra information can be obtained after removing an incident. The method to be investigated should enable remote sensing to be measured in the 3D model. When measuring a 3D model, two things are important. First of all, the accuracy must be correct. The requirement set is that a relative accuracy of 1 centimeter must be achieved. Furthermore, it is important that the model is metrically correct.

3. Geo reference
   In a spatial perspective, it may be helpful to know the location of an incident. By measuring the coordinates of ground checkpoints, a model can get a geo-reference, a location in the real world.

4. Add handmade photos
   Details are important in an investigation. These details may appear on locations that can not be photographed by drones. In such cases, it should be possible to make photos with a single camera and add them to the 3D model, thus improving the accuracy of the model in these places.

5. Time
   Depending on the extent of an incident on the track, it takes several hours to complete the measurements around the incident, even before all other work to repair the situation can take place. The period that the track is not used will cost ProRail a lot of money. Therefore, the method to be tested must be completed at least in the same duration and preferably shorter.

6. Applicability
   The new solution that is being devised must work regardless of bad or even sunny weather conditions or hard winds. Also obstacles that are in the vicinity of the track should not cause any problems. An additional possibility is the use of thermal infrared images in the research.

7. Security
   If security around the location of an incident would be compromised by the deployment of drones, this should have a negative effect on the possibilities of this procedure.

3

METHODOLOGY

3.1. PHOTOGRAMMETRY

Photogrammetry is the technique that makes it possible to create 3D models from 2D photos. So, where photography is exactly the opposite, namely making a 2D image of a 3D reality, photogrammetry attempts to bring back this 3rd component by using multiple 2D photos. The depth lost at the time of taking a picture can be retrieved by comparing multiple photos from different points of view, just as the eyes do. Unfortunately, this process is not flawless, but the use of many pictures can significantly improve the accuracy.

The fundamentals of photogrammetry are originally in the triangulation theory. This principle teaches that if an unknown point can be observed from at least two known locations, and the distances and angles of these locations are known, the location of the unknown point based on this data can be determined. This results in a few important criteria for photogrammetry, which make it possible to apply this technique but also play a part in the accuracy of the result.

3.1.1. IMAGE ACQUISITION

The way in which the images are obtained is of great importance to the final 3D model that can be created. First of all, a distinction can be made between analogue and digital images. In recent years digital photography has played an important role in the possibilities of photogrammetry, and analogue images are becoming less and less used.

One of the first ways in which photogrammetry was used was the so-called stereoscopy (stereo image acquisition). This (analog) technique uses mainly aerial photographs of a landscape. Two images with sufficient overlap, at least 75%, are then used to regenerate the depth of the landscape. Overlap exists both in the forward and the lateral direction, see figure 3.1.

Since the introduction of digital photography, it has become possible to make this relatively simple way of photogrammetry by computers. This also included the ability to use more than two pictures to determine 3D points (multi-image acquisition). This made the technique a lot more accurate, but it also made it possible to create real 3D models.

What matters to all forms of photogrammetry is that there is enough overlap between photos. The size of the overlap differs by situation. In general, a forward overlap of 75% - 85% is retained and 60% to 70% lateral overlap. Certainly in the case of multi-image acquisition, this will prove to be difficult again. The larger the overlap between the pictures, the more points are found that are visible on more than three (needed for the three components of a location). These points can then be used as so-called "keypoints", then calibrate the model, but also the location and camera parameters of the pictures. This self-calibration is also called bundle triangulation.

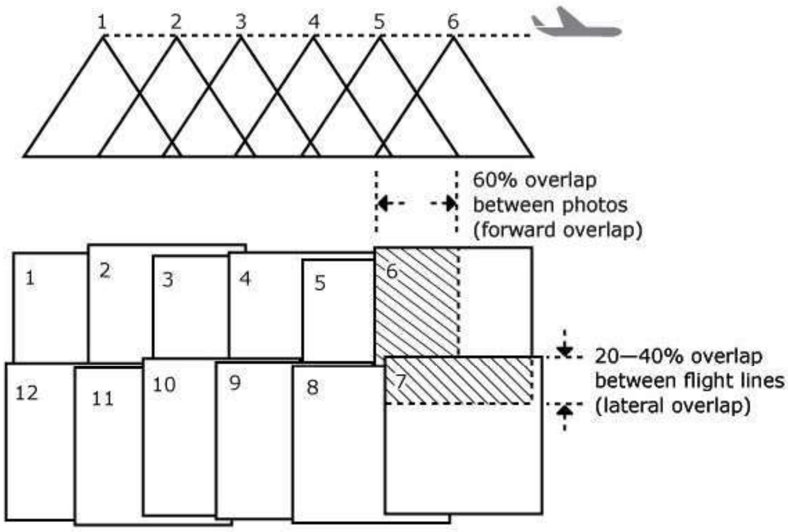


Figure 3.1: Forward overlap and lateral overlap between images. [1]

3.1.2. LOCATION

As mentioned, the location where the photos are taken plays a major role in the triangulation process. The drone determines by means of pseudo range measurements its location. The current location is provided when a recording is made. Disturbances, such as atmospheric or reflections of the signal, between the satellite and the drone, can not accurately determine the location. The locations of the recordings can only be taken as a starting point and must be refined to serve as a reference in the model [2]. This is where bundle of triangulation makes its entry.

Bundle triangulation is a method for simultaneous calibration of an undefined number of photos taken at different locations. It uses the initial values for the location of the photos (but also, for example, camera properties) to estimate the model. In this estimated model, a few keypoints can then be determined, in Chapter 3.2, we will investigate these key points more thoroughly. Then, these initial keypoints can be used to apply bundle block adjustment. This means that the mutual distances and angles of the found key points are used to match this "block" to points as best as possible in all pictures, see figure 3.2. With the help of geometric minimization, the location of the photos and thus the location of the keypoints is corrected [2].
By incorporating all initial values into the model, a so-called over-determined system is created. This means that there are more comparisons (available data) than unknowns, which in principle is good. A shortage of photos causes less available data that can make the system underdeveloped. By combining the over-determined system into a numerical model that can be calculated by computers, one can achieve a very accurate model.

The object coordinate system created by this form of multi-image photogrammetry has no reference to the real world. By adding reference points and / or scale factors, the model can be improved. The use of so-called Ground Control Points follows in more detail in chapter 3.3.
The arbitrary location of the found keypoints (and the rest of the model) can be converted to a desired coordinate system based on this data. Important to keep in mind is that the inaccuracy of the GCPs will translate into the inaccuracy of the model. At least in absolute area. The model will be able to achieve approximately the same absolute accuracy around the GCPs as from this such reference point, but will be further removed from these GCPs becoming less accurate. In relative terms, for example, determining a distance between two points, this inaccuracy does not affect. This depends purely on the soundness of the calculated photogrammetric model.

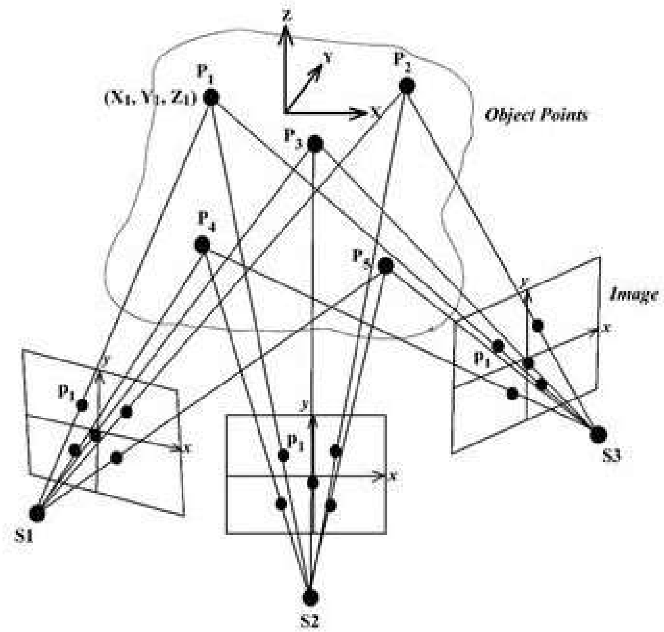


Figure 3.2: The visibility of objects seen from different images. [3]

3.1.3. CAMERA FEATURES

Camera specifications are important for the accuracy of this technique. In particular, the focal length determines the scaling of the model. However, other parameters, such as distortion and exposure, play a major role.

First of all, an additional note about the location mentioned above. Of course, the camera's location is extremely important, but at least as important is the orientation of this camera. The orientation of the camera determines the field of view of what can be seen in the picture. This field of view is essential to determine which photos can be compared to match matching points.
After finding the exact location of each photo, then 3 additional angles will be added to each photo that indicates in which exact direction the picture was taken.

The focal length of the camera is the distance between the lens in the camera and the sensor on which the image is sharply projected. The lens formula teaches us that this distance is important for the ratio of how the distances actually translate into the distances in the picture.

[1 / f = 1 / b + 1 / v]

If the focal length and distance of the lens to the sensor are known, the distance from the camera to the object on which it is focused can be determined. Since this is an image distortion of often a few millimeters (in camera), which relates to a target distance of often several meters, focal length inaccuracies have major implications for determining the exact locations.
Due to external conditions, such as temperature or humidity, the lens in a camera can already change shape. This is usually no problem for taking pictures, but it is a problem for photogrammetry if it is to be measured based on these pictures. Therefore, a camera is calibrated very accurately prior to measurement. That is, the focal length and image distance are determined very accurately. Another way to prevent inaccuracies is to use software that makes it possible to determine the focal lengths used later, more in chapter 3.2.
Not only for the distance between the camera and the object, focal length is important, but especially for later measurement in the model. The scaling factor that can be determined between the image and object spacing is required to convert distances measured on different images to actual distances, figure 3.3.

Consistent with the focal length is the distortion, or image distortion, which causes almost any camera lens.

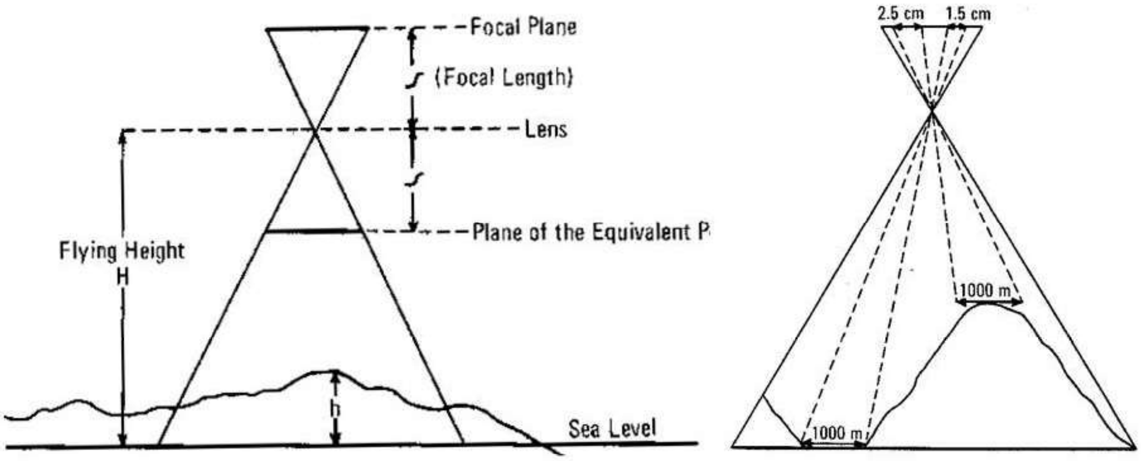


Figure 3.3: Relation between focal length and flying height. [4]

Distortion implies that the image projected by a camera is always slightly distorted towards the sides of the photo. A positive distortion means that the image in the middle is increased, as with a magnifying glass. In the case of negative distortion, it becomes smaller to the middle. A good example of positive distortion is, for example, a fisheye lens. Many drones are equipped with cameras with fisheye lenses, as soon as these images are used for photogrammetry, first correct them. Therefore, for stereoscopy from aircraft, cameras are used that have hardly any distortion [5].

However, this distortion can easily be corrected, but this requires some additional knowledge about the camera lens. The so-called distortion radius closely matches the focal length and can be used to back up digital photos so that they are undeformed. Many software automatically corrects for this camera distortion before the images are used in the photogrammetric process.

Finally, we can say something about the exposure of the pictures. Photogrammetry works through keypresses that are matched based on their color and light intensity. It is therefore important that the pictures of an object have the same exposure. This means that the camera setting for exposure must remain as straight as possible. But also that it is photographed under equal conditions. For example, shadows prove to be very difficult for photogrammetry to map out, later on more.

3.2. SOFTWARE

Traditional photogrammetry methods require a lot of information. Of the images used, the location must be known and the orientation of the camera must be available.

Due to the rise of computers with more computing power, a new method has been developed. One of the new photogrammetry methods is called 'structure from motion' (SfM). SfM uses many large overlap images to create the stereoscopic effect previously described. The great advantage of the structure from motion method is that it can be applied despite the fact that there is no prior knowledge about the location where the picture was taken or the camera [6] orientation.

The software marks characteristic points (keypoints) in the images. A common method for detecting these characteristic points is the SIFT method. SIFT stands for 'scale-invariant feature transform'. The SIFT method uses four filters in succession.

- Scale-space Extreme Detection: Using a difference in Gaussian filter may detect typical points regardless of size, location, or orientation. For example, a dark object in a light background.
- Keypoint localization: At each candidate point, a model is used to determine the scale and orientation around the feature point.
- Orientation assignment: One or more orientations are assigned to an attribute location based on local

gradients in the photo. In this way, the characteristic point is not sensitive to rotating an image.

- Keypoint descriptor: Local gradients in a photo are measured on the selected scale in the area around a characteristic point.

The resulting points make a 3D model. A typical point is searched in multiple photos and then triangulated in the model. In order to do this, the focal length of the camera is required. To increase reliability, a point must be in at least three images, otherwise the point will be rejected. An additional advantage of this requirement is that moving objects are automatically removed. This step is called automated aerial triangulation. Furthermore, points around a chosen point are included in the analysis. A cluster of points is compared to both location, orientation and scale. By means of a least-squares analysis, the location is optimized. Also known as the bundle block adjustment or bundle triangulation discussed earlier (Lowe, 2004). Because no absolute locations are included in advance, the model comes in a relative coordinate system. Using ground checkpoints, a model can be placed in an absolute coordinate system. The translation and rotation can only take place if at least 3 points are entered in the desired coordinate system [7].

Pix4D is the software used in this research to perform the photogrammetric calculations. It is one of the most commonly used programs for drone mapping. Originally based in Switzerland, Pix4D is now expanding with an office in China and America.
One of the handy tools for Pix4D that can be named is that this program has a database for cameras and, for example, their focal lengths. As previously mentioned, these parameters during use will be slightly different from the values from the database for several reasons. The software uses an iterative method to optimize these parameters for a particular project. Thus, the focal length, position and orientation of the camera and the position of the corresponding 3D points are optimized.
In this way, the camera is automatically calibrated. Therefore, the camera's pre-calibration is not necessary. Something that's in a hurry [8].

3.3. FLIGHT PLAN

The flight plan is important to get a good model. The recordings that are used must meet a number of requirements.

- GSD: the ground sampling distance is the distance between two consecutive pixels measured on the ground. The larger the ground sampling distance, the lower the spatial resolution and the fewer details are visible. The higher it flies the greater the ground sampling distance. Lastly, a greater focal length provides a small ground sampling distance.

- Overlap: There must be sufficient overlap between the recordings to ensure optimal software. Depending on the area taken, there is an opinion on the degree of overlap. In order to realize the recommended overlap between the recordings, the speed at which the pictures are taken must also be taken into account. At the time the overlap needs to be increased, the frequency with which the photos are taken up must be increased. Another solution is slower flying. There are also apps that can control drones and can calculate where to take pictures to create enough overlap.

- Oblique / Nadir: Depending on the purpose of the recording, it must be decided whether the recordings are taken oblique (sloping) or nadir (straight down). In the case of a 3D reconstruction, it is recommended to shoot at an angle of 10-35 degrees when a raster pattern is flown. As a result, the side is well visible on the recordings and can be better reconstructed. For more detail, one can choose to fly a cross raster pattern. In addition, there is the possibility of oblique looking at an object from the side in a circular flight.

- GCP: To give the model a better accuracy, Ground Control Points can be deployed. It is important that these GCPs are visible on the photos. The GCPs are measured using GPS equipment [9].

4

Collecting and analyzing data

During this study, there have been two moments to test. The subject of the first test is a house on the Veluwe. During this test all the theory studied has been put into practice at its own discretion. In the second test, two kettle cars were measured at the Kleefse Waard, ProRail test site. EyeFly, a company dedicated to data retrieval, took care of this day. Each test will discuss how it has been measured and how the data is processed into a 3D model.

4.1. Test 1: Veluwe

4.1.1. Measurement Process

Ten ground checkpoints are placed around the house. This takes into account the fact that the ground control points must be visible on the recordings of the drone. The checkpoints have been measured using a Trimble R8 GPS receiver. Checking the checkpoints has happened twice.

In addition to checkpoints, objects with known distances are placed around the house. Several jalons were put down and a tape measure was laid down. In addition, two ground control points are placed five meters apart.

The drone used is a DJI Phantom 2 Vision +. This drone features a 14MP camera. The control of the drone is partly done by hand and partly with the aid of an application called Litchi for P2. This application helps to make a flight plan after which the drone can fly this flight plan independently.

Using the Litchi for P2 application, a circular flight plan has been made. The height is set to 25 meters and the radius of circle is set to 25 meters. Low flight speed has been set so there is an overlap of 80% between the pictures. The camera is at all times focused on the center of the house. This flight plan has been executed twice.

The second flight consisted of a grid with the camera directed perpendicular to the surface. It has flown at a height of 25 meters. Multiple applications have been tried to fly the grid pattern. However, no application could perform the desired grid pattern in combination with the DJI phantom 2. Therefore, it was chosen to carry out the flight by hand. Hand-flying results in a decrease in grid cleanliness. In addition, the overlap between the pictures is less constant.

Lastly, a circular flight was made by hand at a height of 15 meters. This flight had to be done manually because of obstacles around the house. The camera is focused on the house throughout the flight.
In addition to the recordings made with the drone, recordings with a Nikon D3200 have also been made. The recordings with the Nikon are all made at eye level and close to the house. In total, the drone has made 421 recordings and 168 recordings with the Nikon camera.

It is important to check if enough data is collected to generate a good model. To check this, the first step of the Pix4D Mapper software is used. During this step, a quality report is built on five points. These are

Figure 4.1: Result of the generated model from test 1.

the number of keypoints, the calibration of the photos, the camera parameters, the corresponding keypoints between the photos and the deviation of the ground checkpoints. In addition to the five checkpoints from the quality report, a visual inspection can also be done. The generated keypoints should not show distortions relative to reality.

Once both the quality report and the visual inspection have been approved, there is basically enough data collected for a model. However, no quality assurance can be given based on these controls [10].

4.1.2. 3D MODEL PROCESSING

With all the data obtained a 3D model has been built. The 3D model has been accomplished with the help of the Pix4D mapper software, as previously described. The result is shown in figure 4.1.

The used DJI Phantom can save GPS coordinates to the captured photos. However, these coordinates will remain available only when the Pix4D capture application is used. When using other applications to create a flight plan, part of the accuracy of the coordinates will be lost. In this test, the Pix4D capture application is not used for all flights, so the locations of a series of recordings are not accurately known. When these series of recordings are used in Pix4D software, the calibration can be more difficult.

The data sets of the Nikon and Phantom can not be combined from the moment one. The data sets must separate the first processing step separately. This has to do with the different parameters (focal length, etc.) per camera. When both models have a positive quality check, they can be combined. Ground checkpoints and manual control points allow the two data sets to be linked.

After the data sets have been merged and a model of keypoints that included all the pictures has taken place, the addition of the GCPs can continue. This must be done before the densified point cloud is generated to ensure that all points get a proper absolute position. It is important to ensure that all GCPs are clicked accurately, which makes for a more accurate model.

After that, step two of the Pix4D software can be performed. In this step, a densified point cloud and a 3D

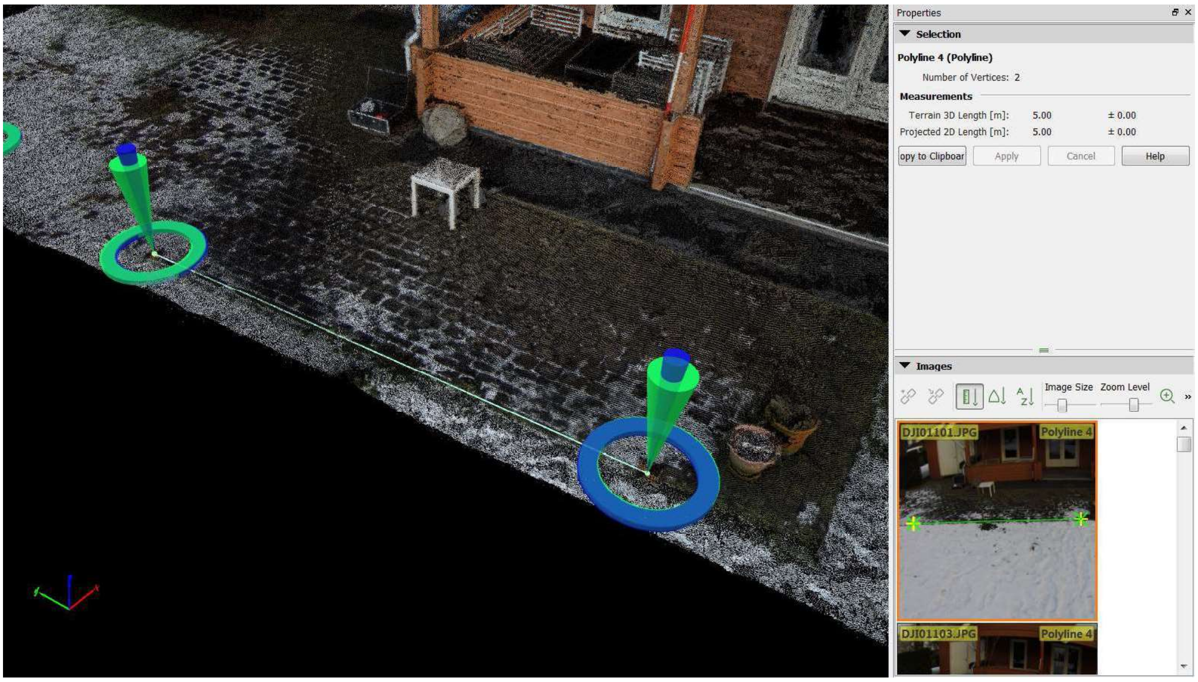


Figure 4.2: Polyline in Pix4D. From the values can be read that the accuracy is better than 1 centimeter. Pix4D can't display more digits in the error estimation.

mesh are generated. Initially, the most extensive options are used. In this setting, the highest quality of the pictures is used to find keypoints. In addition, it is set that a point must be visible on at least four different recordings before it can be used in the point cloud. This to prevent incorrectly generated points.

The resulting point cloud reflects the shape of the house. Although in some places the point density is not big enough to cover everything and some points are not correct. The size of the model, on the other hand, is very accurate. After measuring back the known dimensions, it can be concluded that the model can give distances with an accuracy of 1 cm or smaller. In figure 4.2, the distance between two GCPs is measured. The GCPs are placed 5 meters apart from each other before measurement. This accuracy is relatively within the point cloud. But of course, it could also be calculated with the same accuracy as the GCPs.

In addition to generating a densified point cloud, a 3D mesh is also created in step two. The results of the mesh are varied. In the places where high points are density, the result is good. However, its holes are visible at places where the density is low and the odd shapes are visible on the edges of the roofs, see figure ref. These are mostly visual drawbacks and do not affect the quality of the point cloud. There may be several factors involved in this result.

First of all, Pix4D's settings can provide this result. Perhaps a point in more than four photos must be visible to prevent unjustly generated points. A disadvantageous consequence is that fewer points are generated and thus a less dense point cloud is created. Furthermore, the conditions in which the pictures are taken do not have a positive result on the number of characteristic points that are created. The first test took place in a snowy environment with varying light conditions. As previously described, the software searches for striking points in the picture. Due to the snow, part of the picture is even white. The software can not recognize barely any points here.

Due to the sun set, during a part of the test, a corner of the house occurred in the shadow and the rest in direct sunlight. It is difficult for the software to recognize these differences in exposure. As a consequence, the housings on the shadow side of the housing have not been calibrated. It is difficult to work around an angle and requires a large amount of recordings.

In addition to the fact that fewer points have been created, wrong points have also been created. The cloud

Figure 4.3: Falsly generated points above the rooftop.

cover was very evenly stained on the day of the test. This even distribution has allowed the software to recognize points above the edge of the edge. The contrast of the edge of the rim with the even cloud deck is the same for multiple recordings, so points are awarded by the software. It is better to focus more on the subject and to avoid as much of the sky as possible.

Lastly, it may be possible that too many images have been used. The data set contains images that are taken in the same or almost the same place. In these pictures, only the orientation of the camera has changed. Adding all these pictures to the model adds additional inaccuracy [11].

4.2. TEST 2: KLEEFSE WAARD

4.2.1. MEASUREMENT PROCESS

For the second test, a more realistic situation has been chosen. The test was performed on the Kleefse Waard. An industrial area where ProRail trains to handle accidents. In this area two boiler cars were measured during a ProRail training. The survey was done by EyeFley, a professional drone company with professional equipment.

This test also used ground control points. The ground control points are highlighted in two different methods. First, metal plates are used with white and black blocks. In addition, control points were created by spraying the same pattern with paint as the metal plates around a nail that was hit in the ground. These ground checkpoints were then measured with Trimble GPS equipment. To increase accuracy, this is done 3x for flying with the drone and again 3x after the flight with the drone. In this way it can be determined that the ground control points have not been moved during the flight.

The drone control was done by EyeFly. Two pilots were present to capture everything. One pilot was responsible for flying and the other pilot for shooting the images. For the flying of the races and rounds, the pilots used the pix4D capture app. This app allows the drone to fly autonomously preset patterns. For this test, use was made of a DJI Inspire 1 with an X4S camera. This camera has a 20 megapixel CMOS sensor and includes a leaf shutter to counteract the rolling shutter effect.

The flight plan is largely the same as the flight plan of the first test. A double raster has been flown 30 meters high with the camera at a 70 degree angle. As a result, the camera does not look perpendicular to the ground and takes more detail from the sides. By flying a double grid, more details from all sides are included. The overlap between the pictures is 90% in both forward and lateral directions.

The second flight also consisted of a double grid flown at 20 meters height with the camera perpendicular to the surface. The same overlap is maintained as in the first flight.

In addition, three rounds were flown with the camera facing the center of the two boiler cars. The rounds are done at 10 meters, 20 meters and 30 meters high. In this case, the 6 degrees take a picture, which yields 60 recordings per flight.

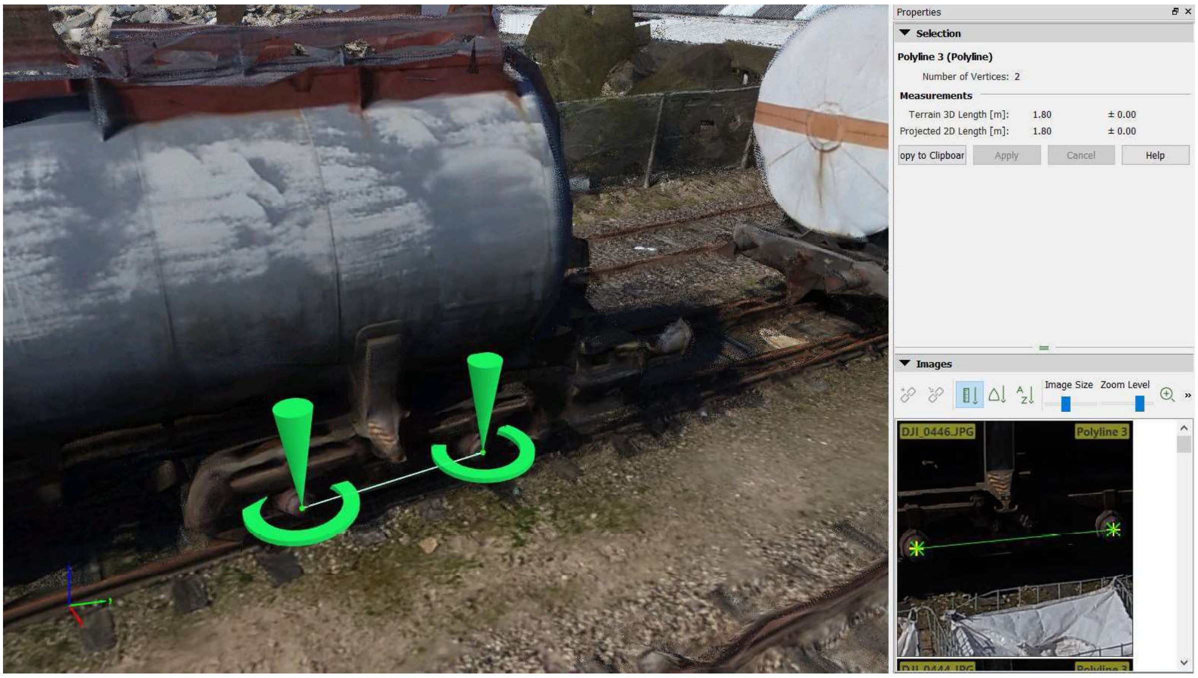


Figure 4.4: Measurement of the wheelbase in the point cloud with an error estimation smaller than 1 centimeter.

Finally, a round was made with the drone in hand. This is done to capture additional details from eye level. In this way, photographs have been taken of the situation between the boiler cars.

In addition to the drone, a total station has been deployed. With the total station, the ground control points have been measured. This allows the distances between ground control points to be determined in a relative system.

Finally, a static scanner, a Leica P30, is used to create a second point cloud of the boiler cars through an alternative method. The static scanner is positioned at multiple locations around the boiler cars to create point clouds. The resulting point clouds are linked together to a large point cloud.

In total, the second test took 3 hours and 38 minutes. This is the full duration of the test including land-sliping, landing of the drone, setting of different flight plans, flying of 6 flights, measuring ground control points with both GPS and total station and performing A check to see if enough data is collected.

4.2.2. 3D MODEL PROCESSING

EyeFly has the task of processing the data of the second test. Ultimately, EyeFly has delivered two points clouds. The first point cloud is generated using photogrammetry and the recordings made by the drone in the Pix4D program. EyeFly has tried several configurations of settings in Pix4D. There are also varied flights used to build the model. The different configurations have been used to execute step 2 of the Pix4D software.

Eventually, the three circular flights are used. Pix4D was set to use half the image size, generate an optimal point density, and a point must be visible in at least 3 photos. The average GSD comes with these settings at 1.14 cm per pixel.

The point cloud, figure 4.5 did not show any distortions and many details are visible. EyeFly has cleaned the point clouds by hand, where necessary, to get a nite result. Incorrect points are manually deleted. In the 3D mesh, not all details are displayed correctly because there are too few point points in some places. This is visible, among other things, at the railing on top of the boiler car and at the bottom of the boiler.

By using only circular flights, there are distortions in the ortho mosaic. These distortions take place outside

Figure 4.5: Resulting textured mesh test day Kleefse Waard

the area of interest and are therefore not important. These deletions can be prevented by adding a grid flight to the dataset. The difference between the orthomosaics can be seen in figure 4.6.

It also looked at the possibility of adding the photos made on the ground with the drone in the model created with the circular flights. However, this proved to be even more difficult than thought because there was not enough overlap in this ground of pictures. As no ground plan can be made for these land photos, these are based on personal estimation. This could be better in future to include more detail from the sides.

After performing the Bundle Block Adjustment, the uncertainties in relative camera positions are known. The values of the ellipsoids can be found in table 4.1. In this case the x-axis is oriented in the longitudinal direction of the train set. The y-axis perpendicular to the x-axis and parallel to the ground surface. The z axis is perpendicular to the x and y axis. Omega, Phi and Kappa are the rotations about the x, y and z axes, respectively, with a positive rotation counterclockwise.

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.003	0.003	0.003	0.009	0.007	0.009
Sigma	0.001	0.001	0.001	0.002	0.001	0.005

Table 4.1: Relative camera positions and orientation uncertainties. [12]

The giving of a geo-reference to ground checkpoints leads to greater uncertainty. The uncertainty in GPS measurements has its effect on the uncertainty of absolute camera positions. In illustration 4.7 and table 4.2 the magnitude and values of the uncertainty ellipsoids of absolute camera positions are displayed.

From the images it can be deduced that the uncertainty on the GCPs is very small. The greater the distance to

Figure 4.6: Difference in orthomosaic with the raster flight on the right side taken along and not on the left.

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.008	0.006	0.008	0.019	0.013	0.018
Sigma	0.002	0.001	0.001	0.006	0.004	0.009

Table 4.2: Absolute camera positions and orientation uncertainties. [12]

the GCPs, the greater the uncertainty of ellipsoids. The orientation of the uncertainty ellipsoids is related to the spread of the GCPs. In the last test, the GCPs are placed around the train set. Due to the elongated pattern in the GCPs, uncertainty will increase in the direction perpendicular to the aforementioned pattern.

The second point cloud consists of the results of the static scanner. The static point cloud has a 3d accuracy of 3mm to 50m and offers a very accurate reflection of reality.

The loose point clouds obtained from the different positions of the static scanner are aligned together with a fault margin of up to 1 cm. In both point clouds, the same GCPs are used to compare the data.

Together with EyeFly, the results of the two test days have been discussed. It has been looked at which flights were performed and which flights are necessary to meet the required requirements. It may be concluded that three flights are necessary. First, a grid flight with the camera nadir to create an overview of the situation. The second and third flight consists of circular flights. The camera focuses on the center of the situation. The circular flights are performed at different heights and therefore with a different camera angle.

Processing the data into a 3D model has produced little problems. The software can produce a good point cloud in all situations. This point cloud can be cleaned manually. Cleaning the point cloud leads to a better 3D mesh.

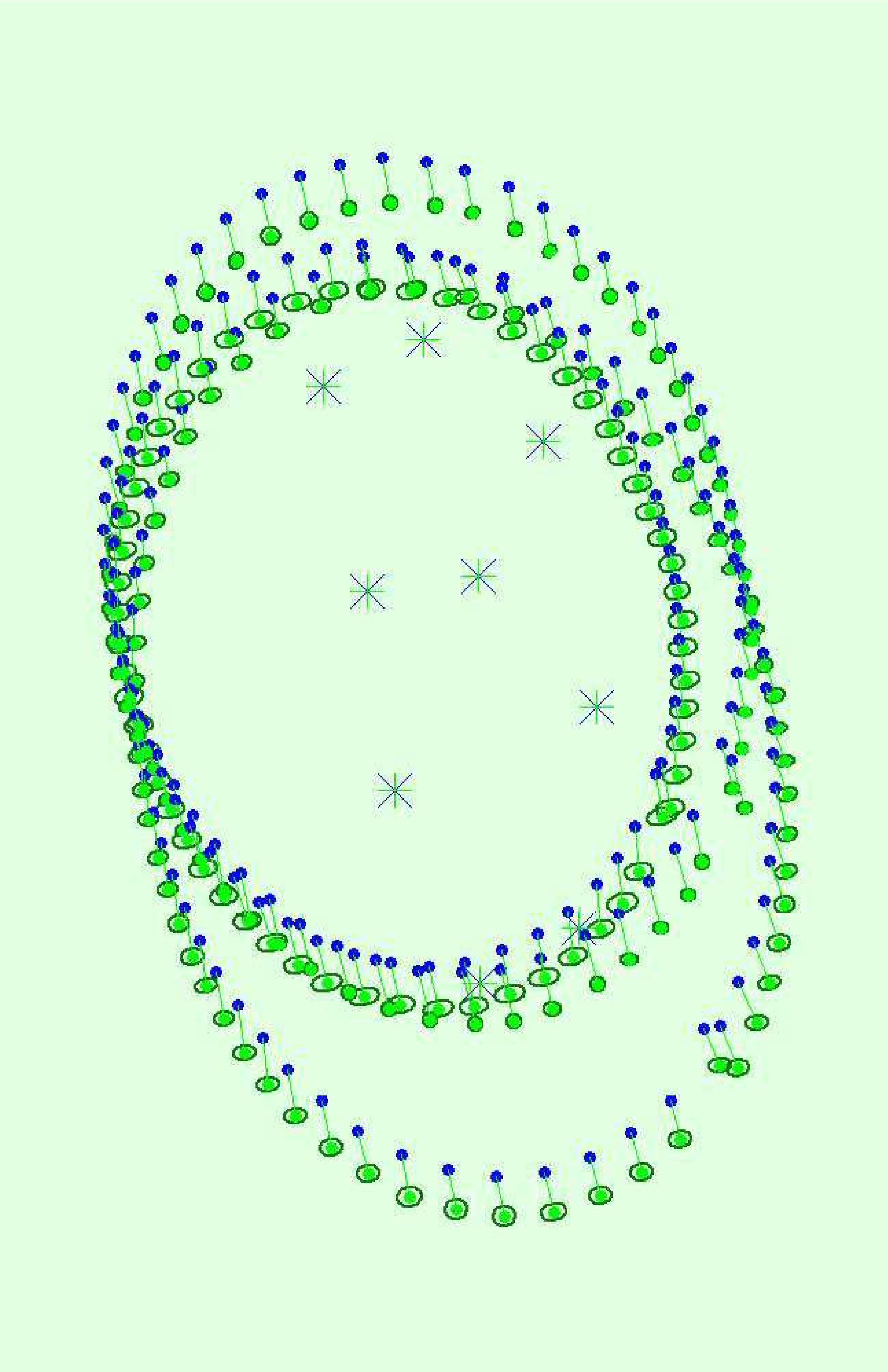


Figure 4.7: Uncertainty ellipsoids of absolute camera positions are indicated by dark green. The initial positions of the GCPs are recognized by the blue crosses. The green crosses are the calculated positions of the GCPs. [12]

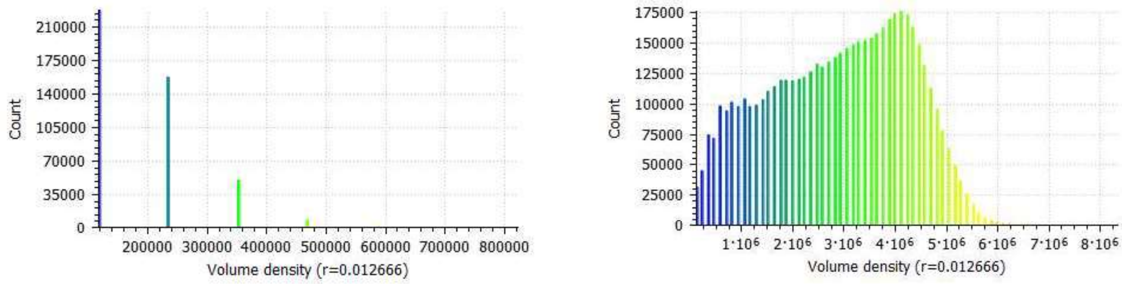
5

RESEARCH RESULTS

5.1. TEST ACCURACY

In order to show that the point cloud created with the drone produces a reliable result, two tests are performed. First, the drone point cloud is compared to the laser scanner point cloud to see what the distances between the point clouds are. Thereafter, known distances are measured in the drone point cloud to verify that these distances are correct.

A number of things will occur when the points clouds are compared. The first thing to notice is the difference in point density between the points clouds. The laser scanner's point cloud not only has a more evenly distributed density, but also a much higher density in the area around the boiler cars. This can be seen in the histograms in figures 5.1. On the horizontal axis can be seen that the density of the laser scanner point cloud is a order 10 higher compared with the drone point cloud.



(a) Density point cloud drone

(b) Density point cloud laser scanner

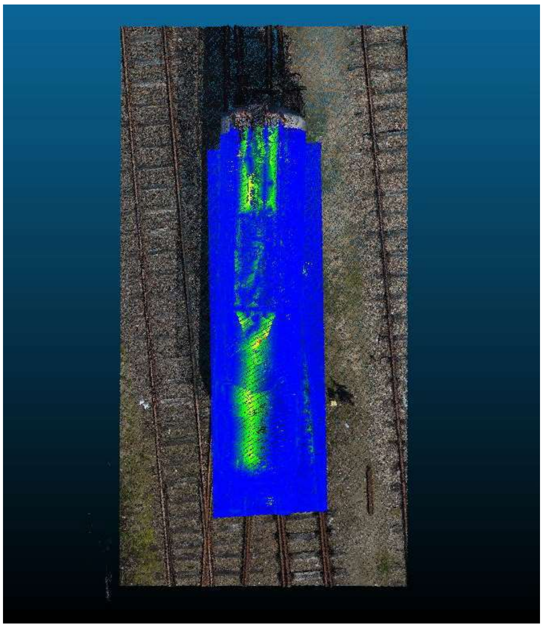
Figure 5.1: Density of points clouds around the train sections

Secondly, there are holes in the points clouds. These holes are located in different locations. At the laser scanner point cloud, it can be seen that there is a hole on top of the kettle. The laser scanner is set at an altitude of 1.80 meters. As a result, the top of the boiler can not be captured. The opposite is the case with the drone. Because the drone has made recordings at 30 meters, it has not been possible to capture the bottom of the tanker in detail. As a result, fewer points can be seen at the bottom of the boiler in the point cloud created with the drone.

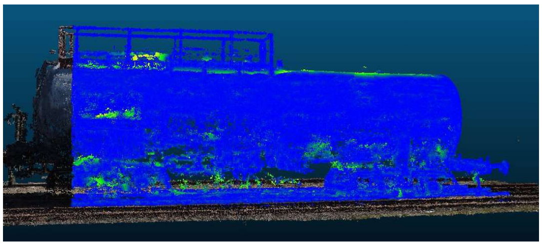
Finally, there is another hole in the point cloud created with the drone, on the left side of the side view. A completely even painted piece on the tanker is probably the cause of this. The even plane causes a lack of distinctive points, which then causes the software to not create any points.

These differences are apparent when the distance between the points clouds is calculated. Using the CloudCompare program, the laser scanner point cloud is set as reference and compared to the drone. In figure 5.2

the distances are displayed. The distances increase as the color changes from blue to green and yellow. The differences between the points clouds discussed earlier become visible. On top of the kettle, large green and yellow areas can be seen due to a lack of laser data on top of the kettle. Further on the left is a green area to be seen and at the bottom are green areas to be observed due to a lack of data in the point cloud created with the drone. More details about the colors will be given in a few paragraphs from here.



(a) Top view of the distances between the points clouds



(b) Side view of the distances between the points clouds

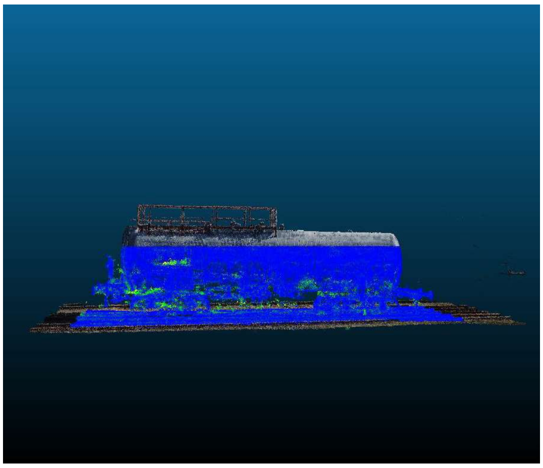
Figure 5.2: First calculation of the distances between the points clouds. The distances increase as the color changes from blue to green to yellow.

In this study, the laser scanner point cloud is used as a reference to compare the drone point cloud. For this reason, the areas where the laser scanner point cloud does not contain any points are removed. This way, data is always available to compare with the drone point cloud.
The results of the so-called "Cloud to Cloud" calculation are visible in the figures 5.3a, 5.3b en 5.3c.

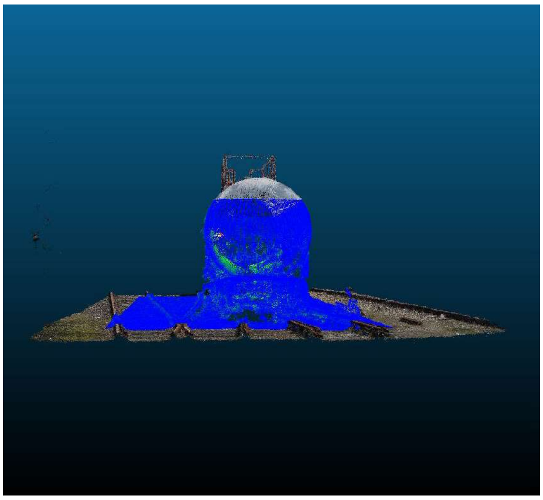
The values of the differences can be read from the corresponding colors in the histogram in figure 5.4, although other colors than blue are hard to find. The histogram further indicates that 58% of the differences are smaller or equal to 1 centimeter, 78% of the differences are smaller or equal to 2 centimeters and 93% of the differences are smaller or equal to 5 centimeters. The histogram follows the Weibull distribution with scale parameter equal to 1.025, the shape parameter equal to 0.011 and the shift equal to 0.000. These parameters result in a mean of 0.003 meter with a standard deviation of 0.0106 meter.

In the figures 5.5 and 5.6 the deviations are larger than 5 centimeters removed. As a result, the deviations smaller than 5 centimeters can be better distinguished. The colors can more easily distinguished and the colors in the figure correspond with the colors in the histogram.

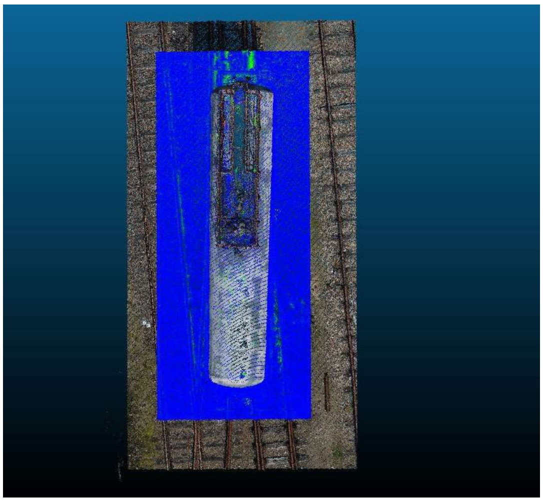
Differences larger than 2 centimeters can be found in the area where a hole is in the drone point cloud, see figure 5.7. Logically, the distance to the laser scanner point cloud is larger in the middle of an area where no points are from the drone point cloud. The other areas where differences occur more than 2 centimeters are all located at the bottom of the boiler. The reason for this is, as previously mentioned, too short points below the boiler. This automatically increases the distances relative to the laser scanner's cloud.
One way to make the distances between the point clouds smaller is by improving the point cloud created with the drone. Opportunities for improvement are mainly at the bottom of the boiler. Making photos around the tank at eye level can improve the quality of the point cloud at the bottom of the tank. The higher the quality of the drone point cloud, the smaller the distances compared to the laser scanner point cloud.



(a) Side view of the distances between the points clouds



(b) Front view of the distances between the points clouds



(c) Top view of the distances between the points clouds

Figure 5.3: Second calculation of the distances between point clouds after analysis of laser scanner point cloud. The distances increase as the color changes from blue to green to yellow.

In addition to viewing the distances between the points clouds, we have also looked at known distances. In the point cloud of the drone, 5 known distances have been measured using the Pix4D program. The distances can be seen in table 5.1. The estimated errors are all smaller than 1 centimeter. The Pix4D software wasn't able to give estimated error in more digits.

	Measured Distance [m]	Estimated Error [m]
Boiler car 1 - Distance between buffers	15.30	0.00
Boiler car 1 - Distance single axle	1.80	0.00
Boiler car 1 - Distance between the axes	8.60	0.00
Boiler car 2 - Distance between buffers	8.80	0.00
Boiler car 2 - Distance between the axes	4.50	0.00

Table 5.1: Measured distances and estimated errors. Pix4D can't display more digits in the estimated error. So the only conclusion can be that the estimated error is smaller than 1 centimeter.

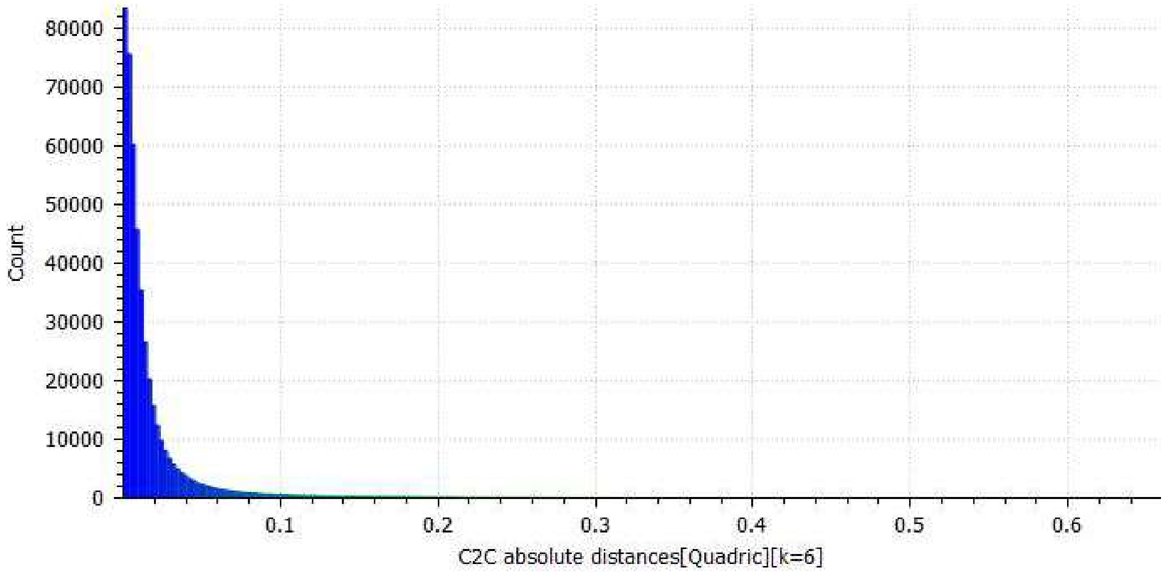


Figure 5.4: Histogram of the distances between the points clouds. The distances are given in meters.

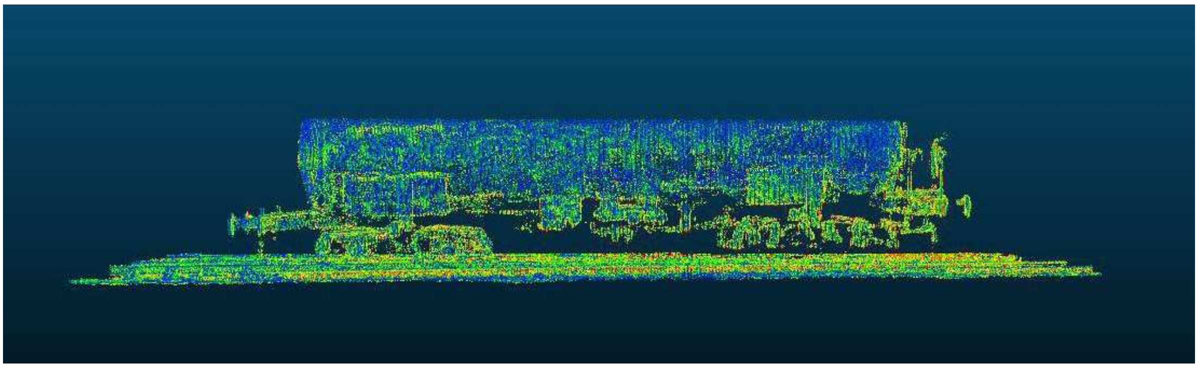


Figure 5.5: The differences between the points clouds. Histogram 5.6 shows the meaning of the colors.

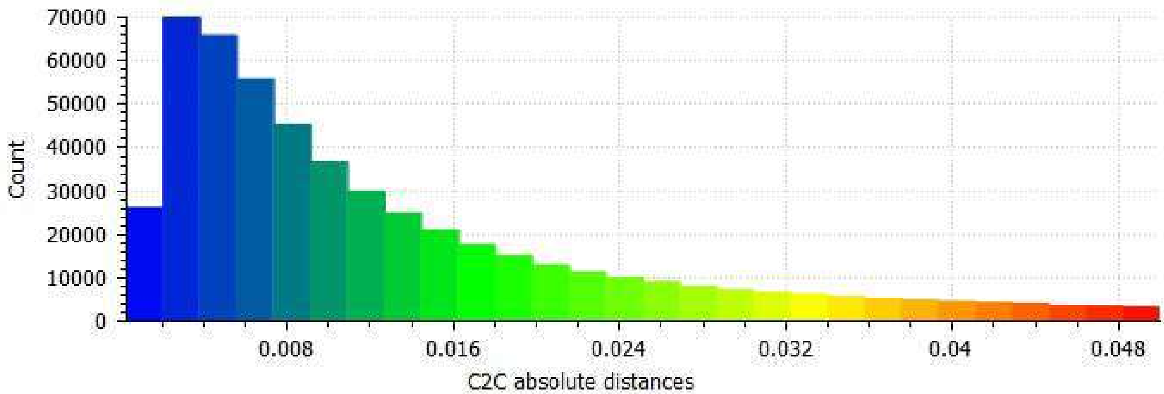


Figure 5.6: Histogram of the distances between the points clouds. The distances larger than 5 centimeters have been removed for a better insight. The colors correspond to the colors in figure 5.5

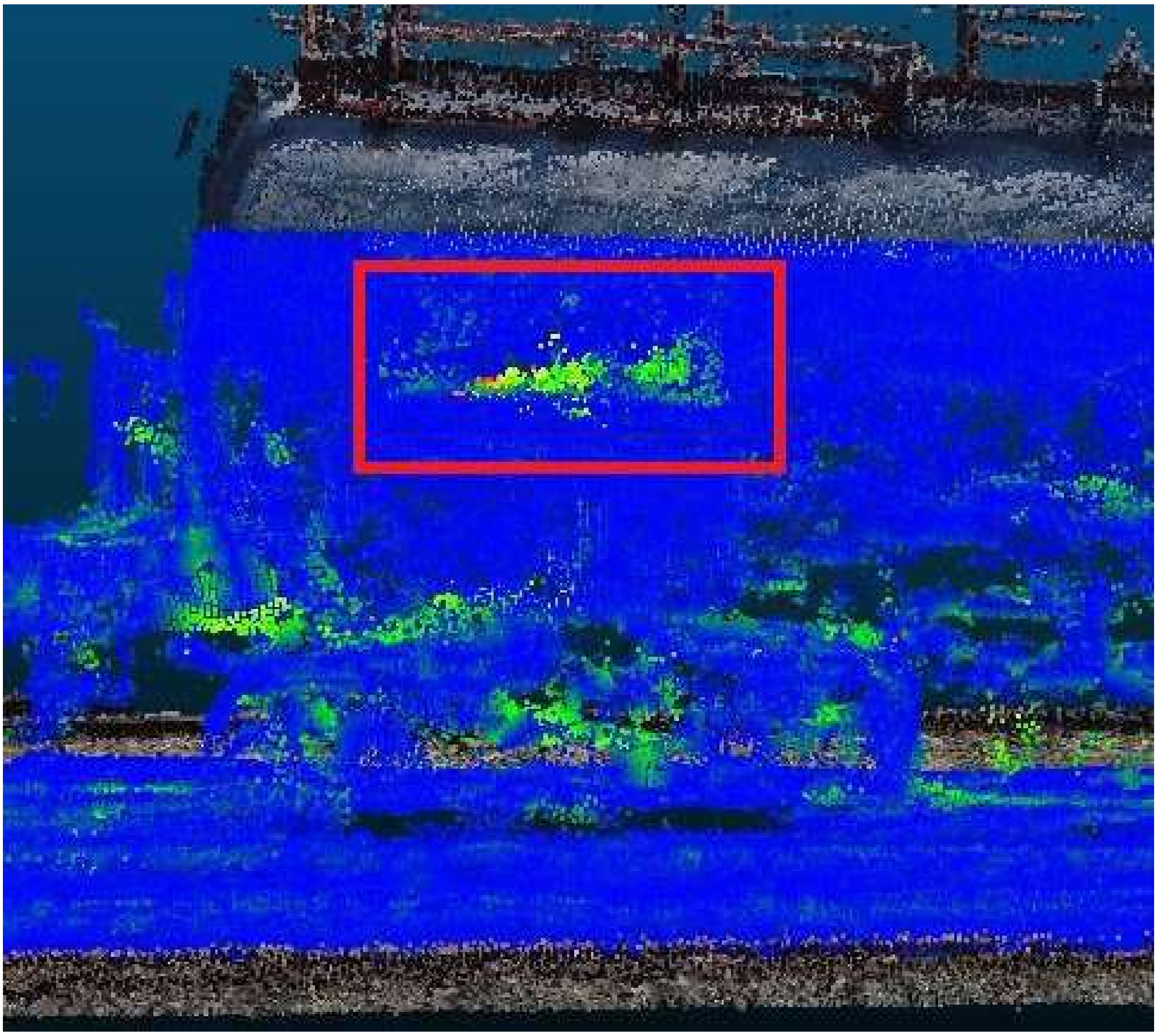


Figure 5.7: A hole in the drone point cloud results in large distances in the "Cloud to Cloud" calculation

6

Conclusion and Discussion

6.1. Discussion

From this study it can be concluded that using drones equipped with cameras a 3D model can be created of an incident on the track. From the recordings, a 3D model can be made using photogrammetry. In this model it is possible to measure post distances with an estimated error of less than 1 centimeter. The distances between the laser scanner point cloud and the point cloud created with the drone are in 78% of the cases smaller or equal to two centimeters.

In order to further reduce the distances, photos can be added at the eye level. These recordings do not have to be made with the same camera. In the event that the camera is not equal, the recordings must be able to generate a point cloud on its own before the data sets can be merged.

Placement and measurement of ground control points took about 40 minutes during the second test day. The three drone flights required to achieve the 1 centimeter accuracy requirement cost about 30 minutes. After that, it takes 20 minutes to ensure that enough data is collected. This means that the capture of the accident situation can be realized in 1 hour and 30 minutes.

When drones are deployed, a lot of attention is being paid. In the Netherlands there is a lot of regulations regarding the use of drones. This makes it impossible to use a drone professionally without permission. ProRail has to train drone teams or use an external party like EyeFly.

The same regulations allow drones to fly safely over people. Flights must be made redundant so that even in case of failure of parts, the drone can stay in the air and be safely grounded.

6.2. Evaluation of the research

During the test days, several weather conditions have overtaken. The first day consisted of a cloudy day of snow with a low sunshine later in the day. On the second test day there was no cloud and the sun shone all the time. Despite these different circumstances, the results in both cases are positive.

In the test days a house and a train have been the subject. Although a house and a train are not the same, the results are consistent. This shows that the technology may be used for more purposes.

6.3. Feedback to research question

Can ProRail reduce the lead time and cost of measuring train incidents through 3D photogrammetry with drones while improving quality? The research question can be cut into three parts. First, the lead time in measuring train incidents. Here it can be concluded that lead time can be reduced very sharply. Certainly if it can be agreed between parties that measuring a drone for all parties is a good option.

The second part is the cost. Precise costs are not available. However, it is certain that when a track can be reused faster, costs are saved.

The last part is the quality. The quality will improve if the technology under investigation is applied. This increase will be due to the fact that the model gives a good overview of the situation and afterwards additional measurements can be made. This is of great value in handling a train incident. In addition, it is possible to measure objects across the board.

6.4. SUGGESTIONS FOR FOLLOW-UP RESEARCH

Following this research, there are several subjects that can be investigated further. It can be checked whether the quality of the model can be improved. For example, how many images are needed for a certain accuracy, whether too many images can be used and how the GSD can be minimized. A automated check of the point density can be very useful to make the model watertight.

Furthermore, research into the use of thermal images in the research can be investigated. Thermal images can help determine the cause of the accident. In addition, thermal images can help with situations where combustible and other hazardous substances are involved. The latest developments make it possible to equip a drone with a laser scanner. The benefits of this will have to be investigated.

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A

Quality Report EyeFly

CGI Nederland - PoC ProRail Arnhem

Kwaliteitsrapportage

Nauwkeurigheid fotogrammetrie vs Statisch

Door:
Anne-Paul Schuur – Geomaat
Remco Kootstra - Eyefly

Inleiding
Op het industriepark Kleefse Waard te Arnhem heeft Eyefly in samenwerking met Geomaat een situatiemeting uitgevoerd met een statische scanner en een drone. Beide metingen zijn met behulp van grondslagpunten op elkaar gelegd. De grondslagmeting is uitgevoerd met behulp van GPS en Total Station.

Met de drone zijn luchtfoto's gemaakt. Met behulp van fotogrammetrie is een pointcloud gemaakt.
Ook hebben we een pointcloud gemaakt met de statische scanner. De data van de statische scanner is nauwkeuriger dan de data van de drone.
In dit verslag wordt het verschil van de drone data en de statische scanner data getoond.

Nauwkeurigheid Grondslag

Statische Scan
De statische scanner die is ingezet is de Leica P30. Er is gescand met een resolutie van 3.1mm op 10 meter.
De scanner heeft een afstandsnauwkeurigheid van 1.2 mm + 10 ppm over zijn volledige bereik.
De hoeknauwkeurigheid is 8" horizontaal en 8" verticaal.
De 3d nauwkeurigheid is 3mm op 50 meter en 6 mm op 100 meter.

Constraint ID	ScanWorld	ScanWorld	Type	Status	Weight	Error	Error Vector	Group Error	Group Error Vector	Group
9003	8: SW-006 (Le...	778301_G1.txt...	Coincident: Vertex - Vertex	On	1.0000	0.004 m	(0.004, 0.000, 0.000) m	n/a	n/a	Ungrouped
9004	9: SW-007 (Le...	778301_G1.txt...	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(-0.001, 0.002, -0.001) m	n/a	n/a	Ungrouped
9005	6: SW-004 (Le...	778301_G1.txt...	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(-0.002, -0.002, 0.001) m	n/a	n/a	Ungrouped
9007	3: SW-001 (Le...	778301_G1.txt...	Coincident: Vertex - Vertex	On	1.0000	0.004 m	(-0.003, -0.003, 0.000) m	n/a	n/a	Ungrouped
9014	4: SW-002 (Le...	778301_G1.txt...	Coincident: Vertex - Vertex	On	1.0000	0.004 m	(0.002, 0.003, 0.000) m	n/a	n/a	Ungrouped
Cloud/Mes...	4: SW-002 (Le...	5: SW-003 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.009 m	aligned [0.003 m]	n/a	aligned [0.003 m]	Ungrouped
Cloud/Mes...	6: SW-004 (Le...	7: SW-005 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.005 m	aligned [0.003 m]	n/a	aligned [0.003 m]	Ungrouped
Cloud/Mes...	8: SW-006 (Le...	9: SW-007 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.007 m	aligned [0.003 m]	n/a	aligned [0.003 m]	Ungrouped
Cloud/Mes...	3: SW-001 (Le...	4: SW-002 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.006 m	aligned [0.004 m]	n/a	aligned [0.004 m]	Ungrouped
Cloud/Mes...	7: SW-005 (Le...	8: SW-006 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.013 m	aligned [0.006 m]	n/a	aligned [0.006 m]	Ungrouped
Cloud/Mes...	5: SW-003 (Le...	6: SW-004 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.005 m	aligned [0.005 m]	n/a	aligned [0.005 m]	Ungrouped
Cloud/Mes...	3: SW-001 (Le...	9: SW-007 (Le...	Cloud: Cloud/Mesh - Cloud...	On	1.0000	0.004 m	aligned [0.004 m]	n/a	aligned [0.004 m]	Ungrouped

Afwijkingsrapport statische scan
De scans zijn onderling cloud to cloud aan elkaar gerekend. De error die we aflezen is de grootste afwijking die tussen twee clouds inzit.
De 9000 nummers zijn de afwijkingen tussen de pointcloud en de grondslag.

Drone data

Voor het uitvoeren van de vluchten is er gekozen voor de DJI Inspire 2 met een X4S camera.
Er is voor de X4S camera gekozen omdat deze een zogenoemde leafshutter heeft. De leaf shutter heeft ten opzichte van een digitale shutter géén rolling shutter wat voor een grotere onnauwkeurigheid in de data zou kunnen zorgen.

De X4S camera heeft een 1" 20 megapixel CMOS-sensor en er is gekozen voor een vaste sluitertijd van 1/1600 (shutter priority). De witbalans werd automatisch bepaald en de ISO werd vastgezet op de laagste setting van 100 omdat er weinig tot géén bewolking was.

De data is op alle manieren geprocessed alleen voor het vergelijken van de statische scan data is er gekozen om alleen met de 3 orbit missions te werken. Dit zal bij de bespreking verder toegelicht worden.

De vluchten zijn uitgevoerd op 10, 20 en 30 meter AGL (Above Ground Level) en er zijn 60 foto's per vlucht gemaakt. Ofwel, iedere 6 graden werd er een foto gemaakt. (360/6=60 foto's) Er is een gemiddelde GSD (Ground Sampling Distance) van 1,14cm per pixel behaald. Zie onderstaand quality report voor de details:

Summary

Project	pr2 orbit
Processed	2017-03-30 10:32:05
Camera Model Name(s)	FC6510_8.8_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	1.14 cm / 0.45 in

Quality Check

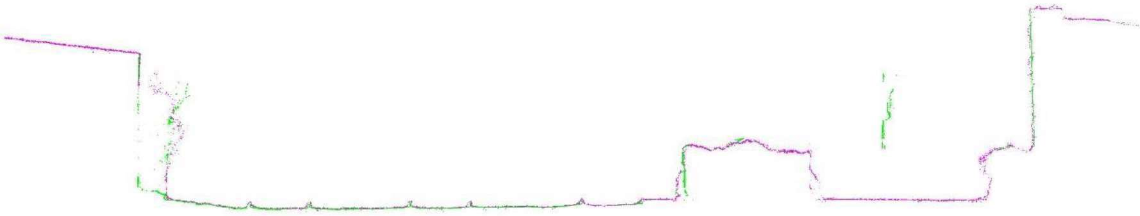
Images	median of 48889 keypoints per image	✓
Dataset	180 out of 180 images calibrated (100%), all images enabled	✓
Camera Optimization	2.03% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 21735.5 matches per calibrated image	✓
Georeferencing	yes, 9 GCPs (9 3D), mean RMS error = 0.003 m	✓

De kwaliteitsrapportage van Pix4D ziet er goed uit en er zijn géén abnormale waardes gezien. Het enigste is dat de Inspire 2 de hoogtes op dit moment nog niet goed kan registreren. Daarom zien we een hoge RMS Error onder 'Absolute Gelocation Variance' in de Z kolom. Door het toevoegen van de GCP's heeft dit niet geresulteerd in een afwijking in de data.

Kortom, de data in Pix4D ziet er erg goed uit.

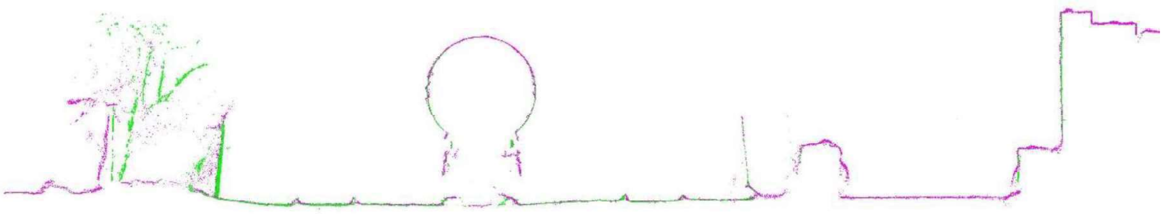
Scangebied

Op de profielen A-A t/m D-D zien we de vergelijking tussen de data van de Drone en de statische scanner
Wat opvalt is dat de plakdikte van de drone data varieert van 1 cm tot 4 cm. De statische data varieert de plak dikte van 1 mm tot 2cm.

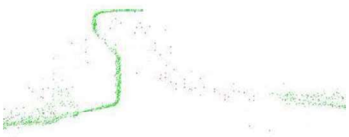


Profiel A-A

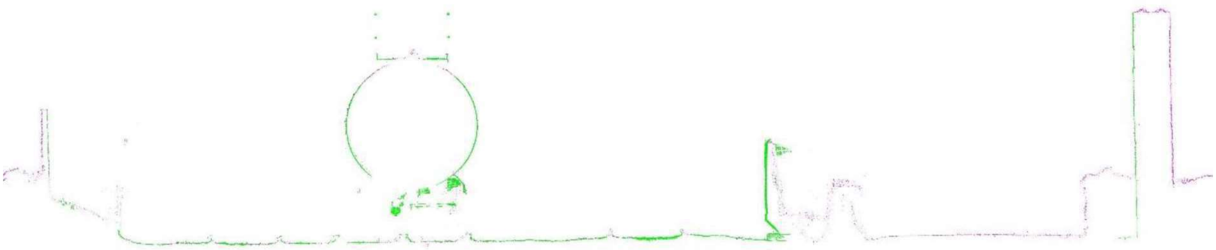
Groen Statisch Paars Drone



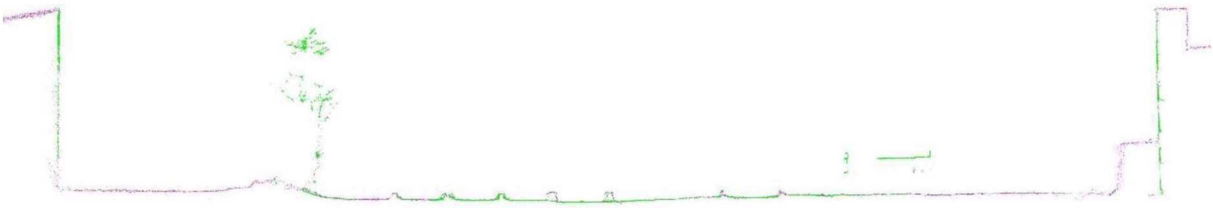
Profiel B-B Groen Statisch Paars Drone



Detail Spoorstaaf Profiel B-B Groen Statisch Paars Drone



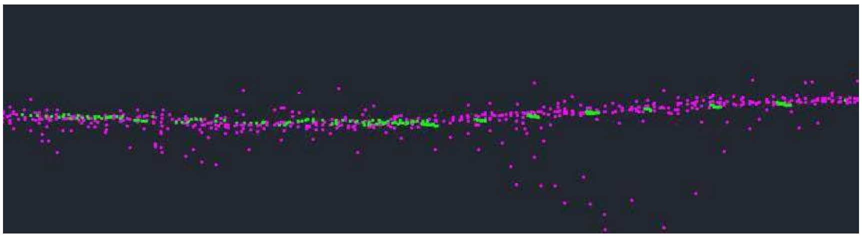
Profiel C-C Groen Statisch Paars Drone



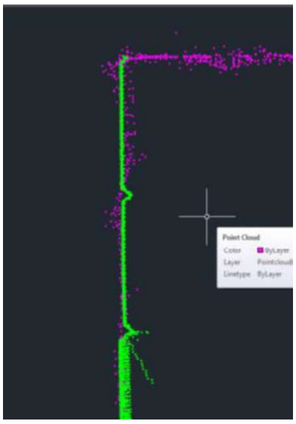
Profiel D-D Groen Statisch Paars Drone

Als er ingezoomd wordt op een profiel en steekproefsgewijs maten worden gemeten tussen de statische en de drone data wordt er een maximale afwijking van 20mm gemeten.

Op de grote horizontale vlakken, denk aan het asfalt en het grind, zitten weinig afwijkingen tussen de dronedata en de statische data.



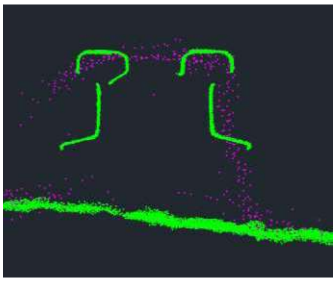
Ingezoomd op een horizontaal vlak afwijking 1 mm tot 1 cm



Ingezoomd op verticaalvlak afwijking 1 tot 2 cm

Het grote profiel van de drone data toont weinig grote afwijkingen ten opzichte van de statische data.

Wordt er gekeken naar kleinere details in het profiel zoals spoorstaven dan wijkt het meer af. De vorm van de staven zijn in de drone data nauwelijks te herkennen, zoals in de statische data.



Ingezoomd Spoorstaaf

Tot slot
De conclusie die getrokken kan worden uit de behaalde resultaten van de statische scan data ten opzicht van fotogrammetrie is dat een relatieve nauwkeurigheid van 10 tot 20mm aangetoond is.

Eyefly en Geomaat zijn erg enthousiast over het behaalde resultaat en denken dat deze nauwkeurigheid voldoende is voor ProRail.

Mochten er naar aanleiding van dit document nog onduidelijkheden, vragen en/of opmerkingen zijn dan horen wij dit graag.

Met vriendelijke groet,

Anne-Paul Schuur – Specialist Geomaat B.V.
Remco Kootstra – Bedrijfsleider Eyefly B.V.

B

Quality Report Pix4D

Quality Report

Generated with Pix4Dmapper Pro version 3.1.23

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	pr2 orbit
Processed	2017-03-30 10:32:05
Camera Model Name(s)	FC6510_8.8_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	1.14 cm / 0.45 in

Quality Check

Images	median of 48889 keypoints per image	✓
Dataset	180 out of 180 images calibrated (100%), all images enabled	✓
Camera Optimization	2.03% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 21735.5 matches per calibrated image	✓
Georeferencing	yes, 9 GCPs (9 3D), mean RMS error = 0.003 m	✓

Calibration Details

Number of Calibrated Images	180 out of 180
Number of Geolocated Images	180 out of 180

Initial Image Positions

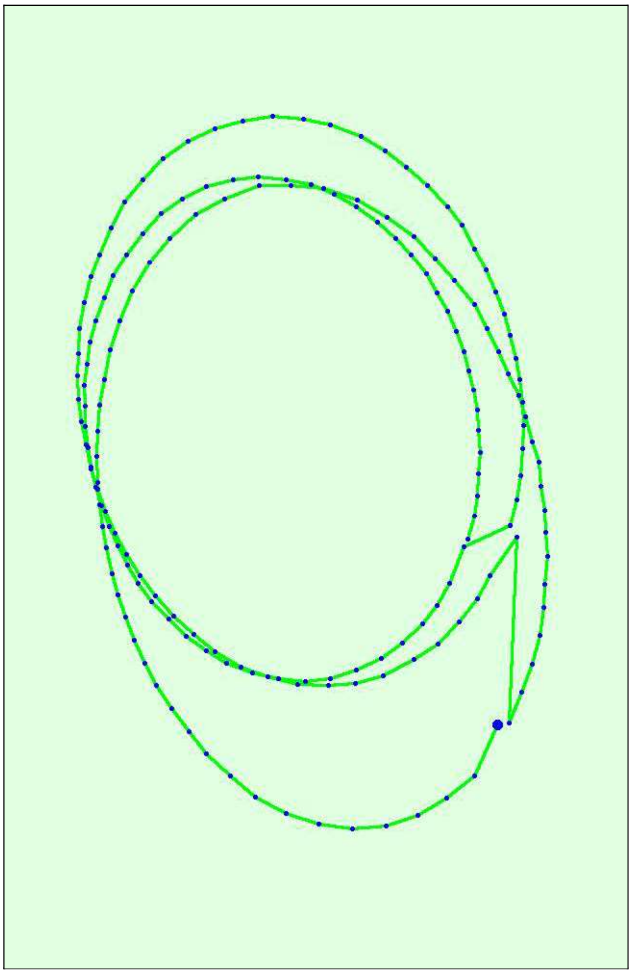
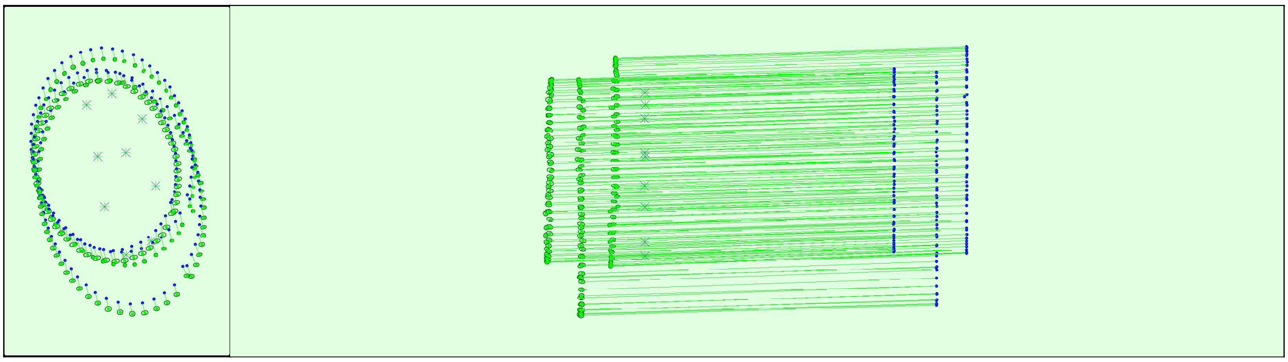
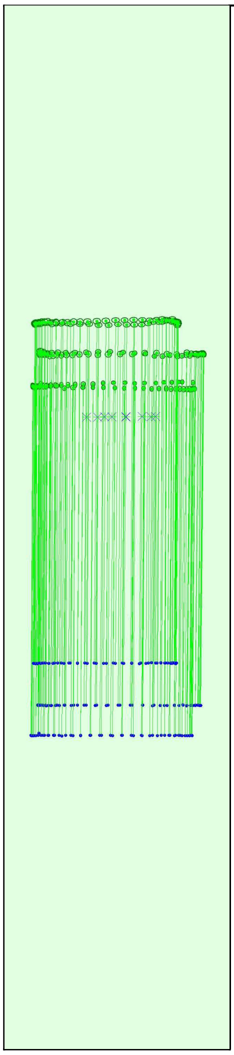


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions





Uncertainty ellipses 100x magnified

Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.008	0.006	0.008	0.019	0.013	0.018
Sigma	0.002	0.001	0.001	0.006	0.004	0.009

Bundle Block Adjustment Details

Number of 2D Keypoint Observations for Bundle Block Adjustment	3706986
Number of 3D Points for Bundle Block Adjustment	1212131
Mean Reprojection Error [pixels]	0.187

Internal Camera Parameters

FC6510_8.8_5472x3648 (RGB). Sensor Dimensions: 12.833 [mm] x 8.556 [mm]

EXIF ID: FC6510_8.8_5472x3648

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2

Initial Values	3752.229 [pixel] 8.800 [mm]	2736.000 [pixel] 6.417 [mm]	1824.000 [pixel] 4.278 [mm]	0.000	0.000	0.000	0.000	0.000
Optimized Values	3676.019 [pixel] 8.621 [mm]	2737.415 [pixel] 6.420 [mm]	1817.127 [pixel] 4.262 [mm]	0.006	-0.010	0.009	-0.001	0.001
Uncertainties (Sigma)	0.340 [pixel] 0.001 [mm]	0.397 [pixel] 0.001 [mm]	0.419 [pixel] 0.001 [mm]	0.000	0.001	0.001	0.000	0.000

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization.

2D Keypoints Table

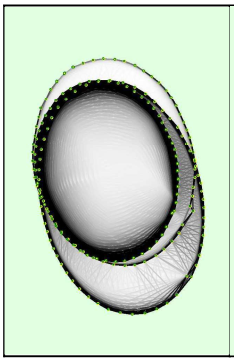
	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	48889	21735
Min	28288	3338
Max	68058	34301
Mean	48740	20594

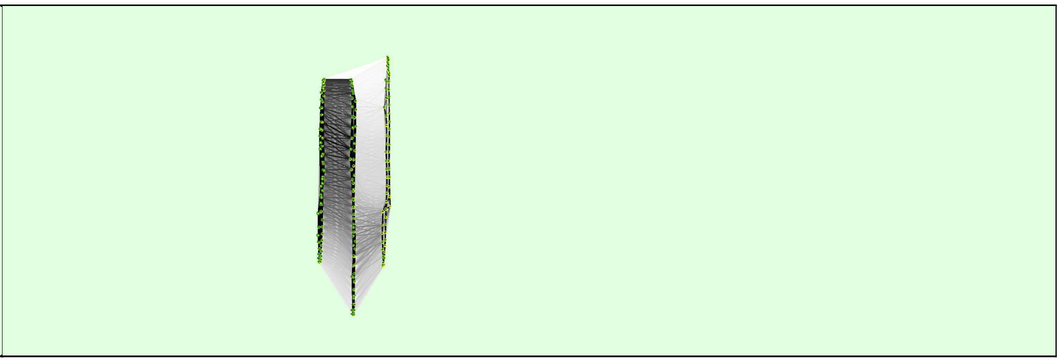
3D Points from 2D Keypoint Matches

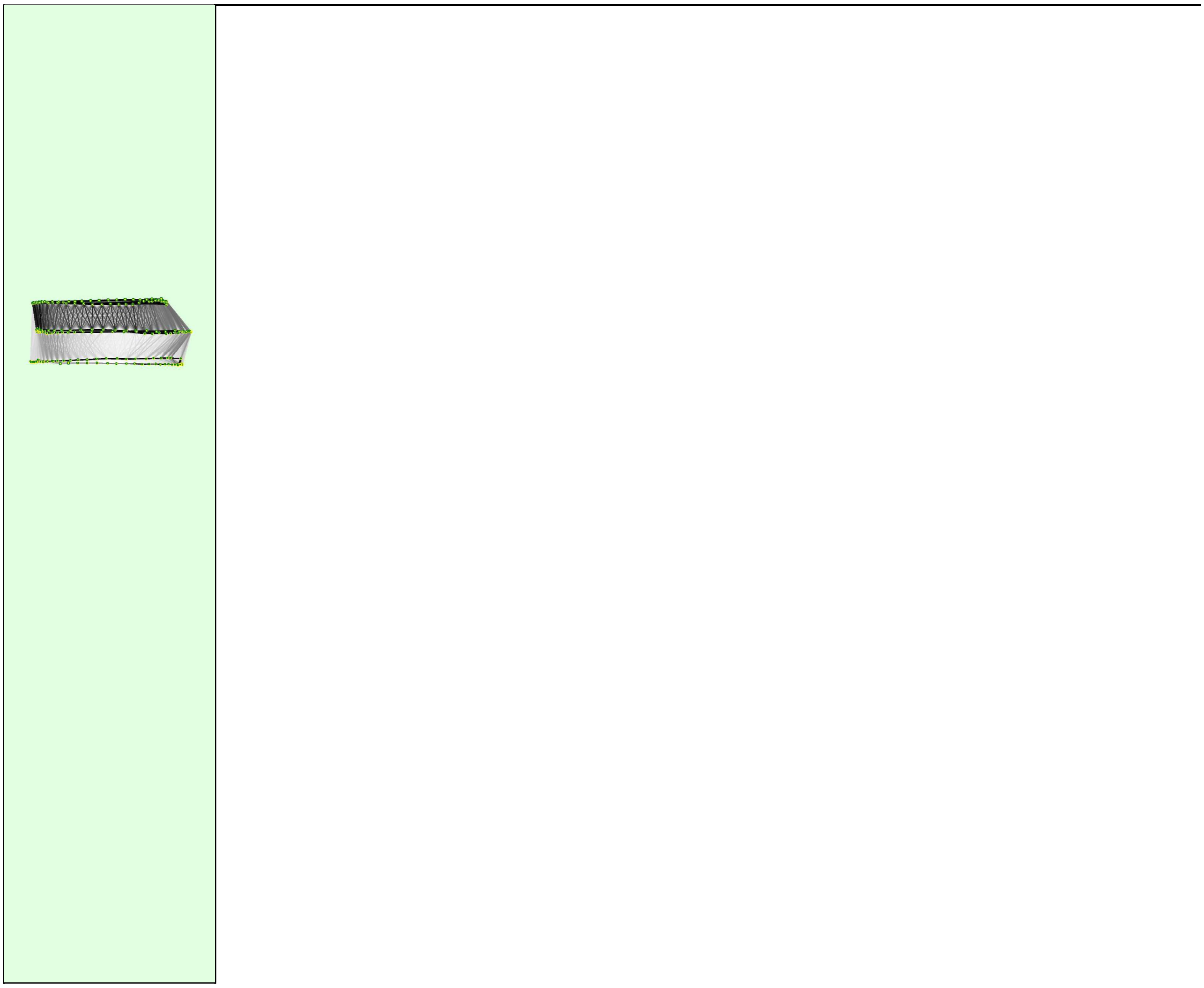
	Number of 3D Points Observed
In 2 Images	757509
In 3 Images	209012
In 4 Images	91780
In 5 Images	49968
In 6 Images	30406
In 7 Images	20028
In 8 Images	13529
In 9 Images	9525
In 10 Images	6936
In 11 Images	5154
In 12 Images	3978
In 13 Images	2838
In 14 Images	2201
In 15 Images	1717
In 16 Images	1374
In 17 Images	1060
In 18 Images	846
In 19 Images	691
In 20 Images	591
In 21 Images	463
In 22 Images	364
In 23 Images	305
In 24 Images	246
In 25 Images	205
In 26 Images	171
In 27 Images	147
In 28 Images	143
In 29 Images	100
In 30 Images	93
In 31 Images	97
In 32 Images	70
In 33 Images	68
In 34 Images	47
In 35 Images	42

In 36 Images	37
In 37 Images	43
In 38 Images	32
In 39 Images	29
In 40 Images	30
In 41 Images	28
In 42 Images	11
In 43 Images	24
In 44 Images	15
In 45 Images	16
In 46 Images	12
In 47 Images	14
In 48 Images	17
In 49 Images	8
In 50 Images	6
In 51 Images	9
In 52 Images	13
In 53 Images	10
In 54 Images	6
In 55 Images	5
In 56 Images	5
In 57 Images	4
In 58 Images	7
In 59 Images	6
In 60 Images	4
In 61 Images	2
In 62 Images	2
In 63 Images	4
In 64 Images	4
In 65 Images	1
In 66 Images	3
In 68 Images	1
In 69 Images	2
In 70 Images	1
In 71 Images	4
In 72 Images	1
In 73 Images	1
In 74 Images	3
In 78 Images	1
In 79 Images	2
In 81 Images	1
In 85 Images	1
In 88 Images	1
In 90 Images	1

2D Keypoint Matches







Uncertainty ellipses 100x magnified

Number of matches 25 222 444 666 888 1111 1333 1555 1777 2000

Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X [m]	Y [m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.003	0.003	0.003	0.009	0.007	0.009
Sigma	0.001	0.001	0.001	0.002	0.001	0.005

Geolocation Details

Ground Control Points

GCP Name	Accuracy XY/Z [m]	Error X [m]	Error Y [m]	Error Z [m]	Projection Error [pixel]	Verified/Marked
9002 (3D)	0.020/ 0.020	0.004	0.003	-0.009	0.548	113 / 113
9003 (3D)	0.020/ 0.020	-0.006	0.004	0.006	0.487	120 / 120
9005 (3D)	0.020/ 0.020	-0.003	0.001	0.001	0.429	98 / 98
9006 (3D)	0.020/ 0.020	0.001	-0.002	0.006	0.584	118 / 118
9008 (3D)	0.020/ 0.020	0.004	0.001	0.007	0.552	90 / 90
9014 (3D)	0.020/ 0.020	0.001	-0.005	-0.006	0.525	124 / 124

9902 (3D)	0.020/ 0.020	0.002	0.000	0.002	0.441	98 / 98
9004 (3D)	0.020/ 0.020	-0.004	0.001	-0.001	0.397	82 / 82
9007 (3D)	0.020/ 0.020	0.000	-0.003	-0.008	0.499	74 / 74
Mean [m]		-0.000038	-0.000024	0.000008		
Sigma [m]		0.003238	0.002716	0.005752		
RMS Error [m]		0.003238	0.002716	0.005752		

Localisation accuracy per GCP and mean errors in the three coordinate directions. The last column counts the number of calibrated images where the GCP has been automatically verified vs. manually marked.

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.00	0.00
-6.00	-3.00	0.00	0.00	0.00
-3.00	0.00	47.22	41.11	54.44
0.00	3.00	52.78	58.89	45.56
3.00	6.00	0.00	0.00	0.00
6.00	9.00	0.00	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		-0.700773	3.271021	-106.067398
Sigma [m]		0.245034	0.339830	1.462721
RMS Error [m]		0.742377	3.288626	106.077484

Min Error and Max Error represent geolocation error intervalsbetween -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the intial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Geolocation Bias	X	Y	Z
Translation [m]	-0.700773	3.271021	-106.067398

Bias between image initial and computed geolocation given in output coordinate system.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	100.00	100.00	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-6700 CPU @ 3.40GHz RAM: 64GB GPU: NVIDIA GeForce GTX 770 (Driver: 9.18.13.4052), RDPDD Chained DD (Driver: unknown), RDP Encoder Mirror Driver (Driver: unknown), RDP Reflector Display Driver (Driver: unknown)
Operating System	Windows 7 Professional, 64-bit

Coordinate Systems

Image Coordinate System	WGS84 (egm96)
Ground Control Point (GCP) Coordinate System	Amersfoort / RD New (egm96)
Output Coordinate System	Amersfoort / RD New (egm96)

Processing Options

Detected Template	No Template Available
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes Bundle Adjustment: Classic

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: High Resolution Color Balancing: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Matching Window Size	9x9 pixels
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Advanced: Limit Camera Depth Automatically	yes
Time for Point Cloud Densification	01h:17m:57s
Time for 3D Textured Mesh Generation	20m:17s

Results

Number of Generated Tiles	1
Number of 3D Densified Points	16498347
Average Density (per m^3)	3860.75

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (1.15 [cm/pixel])

DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no
Time for DSM Generation	24m:21s
Time for Orthomosaic Generation	38m:31s