Reconstruction of a Medieval Wall: Photogrammetric Mapping and Quality Analysis by Terrestrial Laser Scanning

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Abstract. Photogrammetric mapping is an important tool for the documentation of cultural heritage for renovation. Especially when a renovation involves the disassembling and later identical reassembling of a structure, it is important to determine the position and orientation of all elements within the measured objects, like the stones in a wall. High resolution photogrammetric documents make it possible to rebuild a structure as it was before the disassembling. In this article, the generation of an orthophotoplan and a 3D model, based on terrestrial photogrammetry will be discussed. Based on an overview of possible error sources in photogrammetric 3D modeling, the calculated geometric model is compared with a reference point set, acquired by terrestrial laser scanning to evaluate the quality of this model. Although terrestrial laser scanning itself does not generate a radiometric image of the object, it is very useful for the geometric reconstruction of the measured object and thus to measure the quality of geometrical photogrammetric products. A phase-based Leica HDS 6100 laser scanner is used to generate this reference point set on which the photogrammetric model is projected. The statistic error model of the final photogrammetric product enables the calculation of overall displacements and local deviations.

Keywords. Cultural heritage, Terrestrial photogrammetry, Terrestrial laserscanning, Façade mapping, Quality analysis

1. Introduction

The research presented in this research covers an accuracy assessment of radiometric modeling by using both terrestrial photogrammetry (TP) and terrestrial laser scanning (TLS). Both techniques are used side by side for the documentation and reconstruction of ancient buildings, ruins or erected archaeological structures [1, 2, 3, 4]. Since orthorectified photos and the accompanying 3D envelope models have a relatively high geometric quality, the resulting products of this technique are considered to be valuable sources for the reconstruction of all kinds of vertical constructions [5]. Even more important for TP is the quality of the radiometric information that can be obtained by the results. The latter is the biggest strength of TP in comparison with TLS. TLS is more recent than TP, but is nevertheless very useful for the fast acquisition of a huge amount of accurate detail points of an object of interest. This acquisition technique is not only used in archaeology, but is well known in civil engineering, e.g. in the detection of changes in a construction [6, 7]. In contrast with the first technique, the laser scanner does not necessarily acquire an image or equidistant grid, but the resulting point set directly contains 3D coordinates, possibly supplied with an intensity value or, when an internal camera is present, a RGB-value (Red-Green-Blue).

On behalf of 3D modeling, the use of TLS and high resolution terrestrial photos results in a combination of the best of two worlds: high resolution images by means of TP and high density point sets by means of TLS. Besides archaeological modeling, both techniques are for example used for the modeling of façades [5] or paintings [8]. Different techniques exist to generate 3D models,
where mobile and static laserscanning are mostly used for geometrically accurate reconstruction an object and photogrammetry for texturing [9].

The use of laser scan data and high resolution terrestrial photos may result in a few issues. Gaps and discontinuities of the accuracy and density of the data will result in erroneous models in a data based modeling approach [10]. Another issue on the combination of TP and TLS is the assessment and control of the accuracy of the resulting multisource models. Even though the error sources and resulting decrease of accuracy are well defined for both TP [11] and TLS [12, 13], the question arises if the acquisition of photographic recording can be combined with the TLS dataset from the same position, without separate orthorectification and with respect to known accuracy criteria. In this research, a point set will be textured by a perspective image, taken from the scanning position. The resulting dataset is compared statistically with the radiometric information of the color enriched points for corresponding points of the orthophoto. Linking the point set and the images is achieved using a manual target based approach, as discussed in [14] and [7].

The structure of this article is as follows: in section 2, the brief overview of the study object will be given. The acquisition techniques of the terrestrial photography and terrestrial laser scanning will be discussed in section 3. A discussion of the texturing process of the point sets will be given in section 4, followed by an accuracy analysis in section 5. These results are interpreted in section 6 and the conclusion is given in the last section.

2. Study area

The ‘Porte de Landelies’ is located at the site of the ‘Abbaye d’Aulne’ (Figure 1) in the village of Thuin, 50 km south of Brussels, Belgium. The complex has a rich history, starting between 657 and 879 and was a wealthy Cistercians abbey until the 15th century. Thereafter, the buildings have been destroyed and plundered by the Burgundians, Beggars (Geuzen) and the French royal army. After a last major attempt to reconstruct the abbey in the 18th century, most of the complex has been destroyed in the aftermath of the French revolution. Some remains of the abbey are rebuilt as a rest home, a new church and a reconstructed gate. The old abbey church was the subject of a photogrammetric record in 2003 [15]. The study object of this research, the ‘Porte de Landelies’, is one of the four gates of the complex, and also is the former main gate of the abbey. This gate has been renovated between 1940 and 1942, and nowadays serves as a tavern and a residence. The entire object is erected in local limestone and contains a passageway to the gardens of the abbey and the entrance to the residence.
3. Terrestrial photogrammetry and terrestrial laser scanning

3.1. Terrestrial photogrammetry

The images of the façade on the front of the gate have been acquired by a Rolleiflex 6008 metric camera with 40 mm lens in 2006. This camera contains internal fiducial marks and the photos are recorded on an analogue film of 6 x 6 cm and a light speed of 100 ASA. One stereo couple is taken to cover the façade with 85% overlap and the resulting two photos are scanned with a resolution of 900 dpi. The Virtuozo photogrammetric processing software is used for the generation of a digital elevation model with a point density of 10 mm. Based on this DEM, an orthophoto is calculated with a scale of 1:100 and a pixel size of 5 mm. During the calculation of the DEM and the generation of the orthophoto, the quality of the resulting products is evaluated, based on a set of ground control points. These points are measured topographically with a total station. For both the absolute orientation and the evaluation of the DEM, this results in the following statistics (Table 1).

<table>
<thead>
<tr>
<th>Table 1: Quality of the conventional terrestrial orthophoto, calculated by the Virtuozo software (De Ryck, 2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute orientation</td>
</tr>
<tr>
<td># GCPs</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

Based on these values, it can be concluded that the absolute error in 3D is significantly larger than the planimetric error. This is caused by the fact that the optical axis of the camera does not intersect the façade in the center, but at eye level, resulting in a bigger range of z-values. The parameters describing the DEM indicate a very good fit of the DEM, as described by the mean average displacement (ME) and that the most present errors are caused by outliers. The high root mean square error and absolute mean error are indicators of this statement.

Figure 1: Bird's-eye view on the ‘Abbaye d’Aulne’ in Thuin, Belgium (Debie, 2004)

Figure 2: Conventional terrestrial orthophoto of the 'Porte de Langelies' (De Ryck, 2006)
3.2. Terrestrial laserscanning

A dense point set of the façade has been acquired with a Leica HDS 6100 laser scanner in 2011. This phase-based laser scanner is able to measure a huge amount of coordinates in a very short time range (e.g. approximately 80 million points with an acquisition time of 3.5 minutes). Based on Table 2, it can be stated that this scanner is very useful for applications in civil engineering and cultural heritage, where high accuracy is indispensable and the distance between the scanner and the object to measure is confined. Based on this table, and corresponding with an mean distance between the scanner and the façade of 25 meter, the expected accuracy of the scanner will be higher than the absolute orientation of the photogrammetric products. The given positional error is namely valid for both planimetry and altimetry. The final data set contains an \((x,y,z)\)-coordinate and an intensity value of the reflected signal for each point. The point set was acquired with a horizontal and vertical angular incremental \(\alpha\) of 0.018°. With an average distance \(s\) between the scanner and the façade of 25 m, a minimum point spacing of 8.0 mm can be calculated \((s \times \tan(\alpha))\).

Table 2: Specifications of the Lexica HDS 6100 terrestrial laser scanner (www.leica-geosystems.com/hds)

<table>
<thead>
<tr>
<th>Laser Scanner System</th>
<th>System Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Phase-based</td>
</tr>
<tr>
<td><strong>Accuracy of single measurement</strong></td>
<td></td>
</tr>
<tr>
<td>Position *</td>
<td>5 mm, 1 m to 25 m range; 9 mm to 50 m range</td>
</tr>
<tr>
<td>Angle (horizontal and vertical)</td>
<td>125 μrad/125 μrad, one sigma</td>
</tr>
<tr>
<td>Range</td>
<td>79 m ambiguity interval; 79 m @90%; 50 m @18% albedo</td>
</tr>
<tr>
<td>Scan rate</td>
<td>Up to 508,000 points/sec, maximum instantaneous rate</td>
</tr>
<tr>
<td>Scan resolution</td>
<td></td>
</tr>
<tr>
<td>Spot size</td>
<td>3 mm at exit (based on Gaussian definition) + 0.22 mrad divergence; 8 mm @25 m; 14 mm @50 m</td>
</tr>
</tbody>
</table>

* At 127,000 pts/sec scan rate, one sigma

3.3. Combined acquisition

The laser scan data of the measured façade is enriched with color information by taking images with a Canon EOS 450D camera. This is a single lens reflex camera, used in combination with a fixed 20 mm lens. The camera contains a 12.2 MP CMOS sensor, with a size of 22.2 x 14.8 mm and a single diode size of 5.2 μm. The true pixel size of the acquired image can be estimated taking the width of the façade in number of pixels, based on the image taken from the bracket, and the true width, based on the point set. Since 2300 pixels of the image correspond with a true façade width of 16 m, the average real world pixel size is 7 mm.

As in photogrammetry, the acquisition of a point set by TLS results in occlusion zones. To obtain similar occlusion zones in the image as the single point set, the image needs to be taken from the same location as the acquisition location of the laser scanner, which is the so called ‘no-parallax point’ (NPP) (Figure 3 and [16]). Several databases exist to determine this point for a given camera and lens, like PanoTools Wiki [17]. The better this location is reached by the focal point of the camera, the more the view of the camera equals the view of the laser scanner. The position of the camera in relation with the center of the laser scanner is calculated by the sum of the tripod mount
Stal, C. et al.: Reconstruction of a medieval wall: Photogrammetric mapping and quality analysis by terrestrial laser scanning

length (L1, Figure 3 - left) - which is 39.0 mm for the Canon EOS 450D - and the entrance pupil length (L2, Figure 3 - right). For the used lens, a value of 30.5 mm is taken. The total offset of the NPP and the tripod mount location of the camera is 69.5 mm, but this value will differ for each camera frame and lens.

![Figure 3: Tripod mount length (L1, left) and entrance pupil length (L2, right) (Source: (http://wiki.panotools.org, 2011)](image)

The total offset is also demonstrated in Figure 4. By this figure, it will become clear that rotating the camera around the z-axis will keep the NNP on the same position.

![Figure 4: TLS set-up and corresponding camera offset](image)

The placement of the NPP of a camera on the same location as the optical midpoint of the scanner can be achieved using the Nodal Ninja 3II camera bracket Figure 5. These systems are used for panoramic photographing as well [18].

![Figure 5: Camera bracket (Nodal Ninja 3 II, www.nodalninja.com)](image)
4. Texturing point sets

Texturing the point set is done by creating a set of corresponding points, which are points that are unambiguously recognizable in the point set and on the image [7]. During the preparation of this campaign, 11 circular black and white targets with a radius of 7 cm were glued on the façade according an equal spread, as illustrated in Figure 4. Linking points in the point set with pixels in the image follows the same procedure as the registration of multiple point sets after a regular TLS campaign, where recognition of the targets is made possible by the big contrast of the intensity values of these targets.

The acquired point set is textured using Leica’s Cyclone point processing software. The ‘Texture Mapping’ tool in this software package enables the draping of a photo on a point set, using a minimum of 4 points for orthorectified photos and a minimum of 7 points for perspective photos. In both cases, the photo will be referenced on the point set, based on unambiguous matching points. These points will be selected in both the point set as on the image, as demonstrated in Figure 6.

![Figure 6: Registration point in the photo (left) and the point set (right)](image)

The selected pairs of points will be used to calculate the translation, rotation and scaling parameters using the Direct Linear Transformation [19]. The system of linear equations will be solved in order to obtain the internal and external image parameters. Optionally, dens distortion parameters are determined using iterative collinear equations [20, 21]. The algorithm uses user defined threshold criteria are in order to accept or reject the result, based on the root mean square error (RMSE). The distribution of the targets is illustrated in Figure 7.

![Figure 7: Target placement](image)

After linking all required targets in the point set and photo, a RMSE (Root Mean Square Error) value is calculated. If a registration is performed using the targets as unambiguous ports, an RMSE value of 0.77 pixels is calculated. The registration of the point set and the image based on other recognizable features in the data results in a feasible RMSE value of 0.98 pixels. With an average dis-
tance between the camera and the façade of 25 meter, this corresponds with an RMSE of less than 5 mm for the image draping of both the perspective photo as the orthophoto. The final result after texturing is a new point set, containing the measured (x,y,z)-coordinate and the intensity of the reflected signal including the RGB-value of the corresponding pixel of a photo. Figure 5 demonstrates a screenshot of the textured point set based on the perspective photo. In the left figure, the intensity is visualized by a color value, going from low (red) to high (blue). The right image demonstrates the textured point set with RGB-values.

![Figure 8: TLS point set with intensity (left) and RGB-values (right)](image)

5. **Accuracy analysis**

5.1. **Exchangeability of the data**

Since the perspective photo and the orthophoto have different radiometric properties, the two color enriched point sets cannot be evaluated in the first instance. Although both images illustrate the same object, the radiometric information of the images is different. Therefore, the RGB-values of the color enriched point sets must be normalized by histogram equalization. This equalization uses the cumulative distribution function to equally resample the value of a given band within the range [0 ; 255]. For every point in each separate band, a rank is given, and the locations of this rank in relation to the lowest rank, determine a new value of this point in this band [22]. The results of this transformation are illustrated by the statistics in Table 3, and for the green band in the histograms on Figure 6.
Based on Table 3, similarity of the corrected RGB-values can be stated, since the statistical values are very near to each other. This can be stated by a paired samples t-test [23] as well, where for each color the means are compared. It can be concluded that for all pairs, the difference between the two sets is significantly not different zero (P > 0.05, df = 98115). In other words, for a given point i in the data set enriched with RGB-values from the orthophoto, the corresponding RGB-value from the perspective image taken with the camera bracket does not differ significantly.

Table 3: Basic statistics of the original and corrected datasets

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>Original</td>
<td>132.56</td>
<td>40.533</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>128.59</td>
<td>74.007</td>
</tr>
<tr>
<td>Green</td>
<td>Original</td>
<td>130.13</td>
<td>42.485</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>128.53</td>
<td>73.982</td>
</tr>
<tr>
<td>Blue</td>
<td>Original</td>
<td>122.51</td>
<td>42.112</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>128.50</td>
<td>73.952</td>
</tr>
<tr>
<td>Ortho</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>Original</td>
<td>157.60</td>
<td>50.023</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>128.57</td>
<td>74.114</td>
</tr>
<tr>
<td>Green</td>
<td>Original</td>
<td>147.66</td>
<td>51.948</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>128.52</td>
<td>74.062</td>
</tr>
<tr>
<td>Blue</td>
<td>Original</td>
<td>140.31</td>
<td>52.617</td>
</tr>
<tr>
<td></td>
<td>Corrected</td>
<td>128.42</td>
<td>74.093</td>
</tr>
</tbody>
</table>

5.2. Local color distance of the two datasets

It has been demonstrated that the used images are statistically identical. This assumption enables the local comparison of each RGB-value of the perspective image and the orthophoto. The color cube
of A. Hiecketier [24] is used to evaluate the local radiometric accuracy of the model, where the three color components are represented by one axis of the cube. If a unit length of 255 is assumed for the axis, it will be possible to define each possible color within this cube. The difference between two RGB-values $\Delta(R,G,B)$ can be made by calculating the Euclidian distance between these two colors in the cube, so:

$$\Delta(R,G,B) = \sqrt{(R_{TLS} - R_{ORTHO})^2 + (G_{TLS} - G_{ORTHO})^2 + (B_{TLS} - B_{ORTHO})^2}$$

Based on this formulation, it is clear that a perfect match between the two images corresponds with a distance equal to zero (Figure 7).

6. Interpretation of the color cube distances

In both photos, there are different cast shadows and objects have different reflectance properties. The differences result in unequal RGB-values of both datasets, which can be explained by the time between the acquisition of the two images, which is almost 4 years. Besides, the time of the day is not taken into account during the comparison. As discussed in this research, normalization of the different images to make the images comparable with each other is a known technique in remote sensing for the analysis of time series, like relative land cover change detection [25]. A crucial aspect of this analysis technique is the identical positioning and orientation of the datasets. With the given accuracy parameters of the orthophoto, it becomes clear that an error of 2 pixels of this image in relation with the point set and an overall root mean square of 20.7 mm could result in a significant color shift within the two models.

Still, it is possible to detect structural radiometric differences between the two point sets. The RGB-distances within the color cube are converted to intensity values between 0 and 255. Using these values makes it possible to detect the mentioned differences between the images, as illustrated in Figure 8. In this figure, red and orange colors correspond with small distances within the cube. Green and blue colors correspond with large distances.
Stal, C. et al.: Reconstruction of a medieval wall: Photogrammetric mapping and quality analysis by terrestrial laser scanning

Figure 8: RGB distances projected on the point set

Figure 8 demonstrates the same distribution of the distances within the color cube than the distribution as demonstrated in Figure 7 (left). The red points in Figure 8, corresponding with a distance less than 100 color units within the cube, dominate the figure and represent the geometrical shift that generates a color difference between the white limestone and the grey joints between the stones. More stringing in the figure are some clusters with extreme distance values below the windows. These differences are caused by the presence of red roses in the orthophoto of Figure 2. In the perspective image of Figure 3 (right), no flowers are present. As a consequence of this big color contrasts and the resulting distances, these changes could be detected easily.

7. Conclusion

In this research the radiometric comparability of conventional terrestrial orthophotos and the combination of perspective photogrammetry and TLS is investigated. After the acquisition of two separate datasets of a historical object, it has been stated that both the data set extracted from the ALS and the data set extracted from the orthophoto are in general radiometrically identical. This statement is based on the analysis of the means of all paired data sets, respectively red, green and blue. The local differences between some corresponding RGB-value are significant, based on the analysis of the distance between the color values within a color cube. Another reason for local differences is the different timeframe of the two images.

As a result, color enriched point sets from the combination of TLS with perspective photogrammetry can be used as a better or at least comparable alternative for conventional terrestrial photogrammetry when the accent of the research is on both the geometric and radiometric modeling of an object. The radiometric information of both models will not necessarily be identical, but sufficient for the fast creation of 3D models. Change detection is also possible by the comparison of the different color enriched point sets by projecting the distances within the color cube on this point set. This approach can be used in situations where regulations forbid the change view of urban cultural heritage. A periodic mobile acquisition of images and point sets and the comparison of this data with the original data source enables the detection of potential changes in post processing. The results of this research demonstrate the potential of laser scanning for change detection on façades. Especially when both geometric and radiometric information is acquired, the given technique will
enable the possibility of automatically detect changes in protected urban areas. A correct approach of the origin of the TLS and the NPP is very important when using this method: this can be achieved using a camera bracket and parameters from several available databases on the internet.

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