LINE-BASED REFERENCING BETWEEN IMAGES AND LASER SCANNER DATA FOR IMAGE-BASED POINT CLOUD INTERPRETATION IN A CAD-ENVIRONMENT

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ABSTRACT:

Photogrammetric 3D object reconstruction can be obtained from images or laser scanner data. Because of their complementary characteristics, these data are suitable for a combined interpretation. In this context, a new option for 3D object reconstruction appears. 3D geometries can be obtained by monoplotting-like procedures, mapping in monocular images and deriving depth information from the laser scanner data. For this purpose, a correct geometric referencing of the data is required. The referencing primarily contains the determination of the exterior orientation of a single image towards a laser scanner point cloud. In architectural applications, linear features can often be extracted easier than points. Hence, the paper describes two methods for image orientation based on straight line features. Both approaches are based on the collinearity equations. The first one uses correspondences between image points and 3D lines extracted from the point cloud, whereas the second approach uses linear features in image space and point cloud.These methods were tested with two different data sets and compared to a classical photo resection using points. For the first data set, a test field with a large number of targets, the results were also compared to the results of a bundle block adjustment. The second data set is a building facade, where natural features rather than signalised points were the basis of image orientation. The results show a different accuracy potential for the three methods. As expected, the best results were obtained with the point-based photo resection, followed by the line-based method with the point-to-line correspondence. But it is also shown that using lines instead of discrete points may be a valuable option for the orientation of single digital images to laser scanner 3D point clouds.

1. INTRODUCTION

The software product *PointCloud* of the company *kubit GmbH* in Dresden is a software module for visualisation and interpretation of large point clouds in *AutoCAD*. In addition to interactive point cloud processing by using the full CAD functionality, a (semi-)automatic data modelling via plane fitting and intersecting these planes is possible. Furthermore, a combined interpretation of digital images and terrestrial laser scanner data in a monoplotting-like procedure is integrated. This means that elements such as points or lines measured in an image can be projected into the point cloud. This procedure makes use of the advantages of both kinds of data: the high geometric resolution and the high visual quality of images as well as the accurate and reliable 3D information of laser scanner data.

The prerequisite for the integrated use of images and point clouds for measurement and interpretation processes is a correct geometric referencing of the data. Hence, the subject of this paper is the geometric referencing of terrestrial laser scanner data and photos taken independently from the laser scanner. The aim is to determine the exterior orientation of a single image by measuring corresponding point and/or straight line features in the image and a point cloud of the same scene. Because many users (for example archaeologists, architects, monument conservators) will take the images with digital amateur cameras, a simultaneous calibration of the camera should be possible by determining the interior orientation and the lens distortion for each image.

Early investigations for line photogrammetry derive from the scope of aerial photogrammetry, e.g. (Finsterwalder, 1941). Since then, a large number of publications have appeared to the topic of line photogrammetry, e.g. (Habib et. al., 1999; Patias et. al., 1995; Tommaselli & Tozzi, 1996; Hemken & Luhmann, 2002). Schenk (2004) distinguishes between two line-based approaches: the collinearity and the coplanarity approach. While the first one is based on the collinearity equations, the second one is based on the assumption that the image line, the object line and the perspective centre are coplanar. Van den Heuvel (2003) determines the exterior orientation of an image by using perpendicular coplanar straight lines. Three line intersection points and the perspective centre form a tetrahedron. Via distance proportions of arbitrarily corner points obtained by a volume approach, the exterior orientation can be calculated.

The two line-based methods for image orientation which will be described in this paper belong to the group of collinearity approaches. They represent a stepwise transition from the classical single photo resection using control points to a spatial resection using straight line features described by line equations. The different approaches were implemented and tested with real datasets. The results will be shown and evaluated in the face of applicability for the referencing of image data and laser scanner data.

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2. POINT-BASED IMAGE ORIENTATION

This section shall only be regarded as a short introduction to the topic of image orientation. The orientation of a single image primarily contains the determination of the exterior orientation. That includes the orientation angles and the position of the perspective centre in relation to the object reference system. The determination of the orientation parameters is realised indirectly by measuring imaged object features in the photo. If these features are control points with known coordinates in the image and in the object reference system given by the laser scanner data, the image orientation can be realised by a classical single photo resection. The applied collinearity model (Eq. 1) describes the projection of an object point onto a two-dimensional sensor of a camera in consideration of the exterior orientation ($X_0, Y_0, Z_0, \omega, \varphi, \kappa$), the interior orientation (c, x_0, y_0) and imaging errors (dx, dy).

$$
\begin{aligned}
x &= x_0 - c \cdot \frac{r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0)}{r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)} + dx \\
y &= y_0 - c \cdot \frac{r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0)}{r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)} + dy
\end{aligned}
\tag{1}
$$

where r_{ij} = elements of rotation matrix
x, y = image coordinates
X, Y, Z = object coordinates

The imaging errors shall here be limited to the radial distortion, whose correction can be described by the following equation based on Brown (1971).

$$
\begin{aligned}
dx &= x' \cdot A_1 \cdot \left(r'^2 - r_0^2\right) + A_2 \cdot \left(r'^4 - r_0^4\right) + A_3 \cdot \left(r'^6 - r_0^6\right) \\
dy &= y' \cdot A_1 \cdot \left(r'^2 - r_0^2\right) + A_2 \cdot \left(r'^4 - r_0^4\right) + A_3 \cdot \left(r'^6 - r_0^6\right) \\
r' &= \sqrt{x'^2 + y'^2}
\end{aligned}
\tag{2}
$$

where r_0 = sensor specific parameter (zero-distortion radius)
x', y' = image coordinates related to the principle point

At least three error-free non-collinear control points are required to calculate the parameters of exterior orientation. The use of more points leads to a non-linear adjustment problem, which is solved iteratively minimising the sum of the squared deviations between the modelled and the observed image features.

If a sufficient number of suitably distributed control points is available, the parameters of the interior orientation and of the lens distortion can be estimated simultaneously. This is mainly useful for photos taken with an amateur camera because the principal point and the principle distance may have to be regarded as variant for all images (Maas, 1998).

3. LINE-BASED IMAGE ORIENTATION

Concerning the geometric referencing of images and laser scanner point clouds, the necessity of measuring discrete points is disadvantageous. As a consequence of the sub-sampling characteristics of laser scanner data, distinctive points are not always well defined in 3D point clouds. This effect grows with decreasing scan resolution and/or increasing distance from the object. By using line-based approaches, it is not necessary to measure identical points in the image and the laser scanner point cloud. Instead, lines in images may be extracted by image processing techniques, and lines in 3D point clouds may be extracted by the intersection of planes fitted into a segmented point cloud, e.g. (Vosselman et. al., 2004). Using lines rather than points may also be advantageous if parts of the object are occluded. Moreover, the automation of extracting lines from 3D point clouds may be considered to be easier than the extraction of discrete points. These are good reasons for switching to methods working with straight lines, which are present in many man-made objects like building facades.

3.1 3D line representation

There are different methods for describing straight lines in Euclidean 3D space. Here, a description with four parameters is chosen, which was published by Roberts (1988) and resumed and varied by Schenk (2004). Apart from its clearness, this line representation has two main advantages. Firstly, it is unique and free of singularities. Consequently, no special cases have to be considered. Secondly, the number of parameters is equal to the degree of freedom of a 3D line. Therefore, this description is particularly suitable for photo intersection and bundle adjustment applications.

The two positional parameters (X_s, Y_s) and the orientation parameters (α, θ) are visualised in Figure 1.

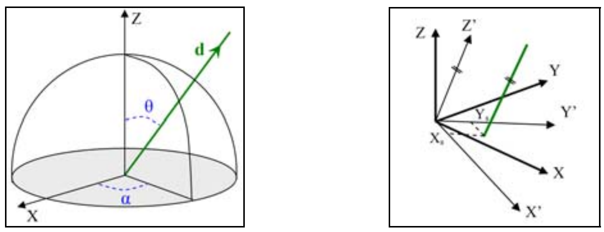

Figure 1. Parameter of 3D line representation

The azimuth α and the zenith angle θ can be deduced from the spherical coordinates of the direction vector ***d*** of the line (Figure 1, left). To get a unique line representation the ranges of the angles have to be limited to $0 < \alpha < 360°$ and $0 < \theta < 90°$. This corresponds with the restriction to the hemisphere of the positive Z-axis.

These angles are used to collimate the Z-axis and the line by rotating the coordinate system. The following matrix describes the rotation about the Z-axis by angle α and the subsequent rotation about the new Y-axis by angle θ.

$$
\mathbf{R}_{\alpha\theta} = \begin{bmatrix} \cos\alpha\cos\theta & \sin\alpha\cos\theta & -\sin\theta \\ -\sin\alpha & \cos\alpha & 0 \\ \cos\alpha\sin\theta & \sin\alpha\sin\theta & \cos\theta \end{bmatrix} \tag{3}
$$

The resulting X'- and Y'-axis reside on a plane which passes through the origin and is perpendicular to the line. The two positional parameters result from the intersection of the line with this plane (Figure 1, right). The intersection point matches the point of shortest distance between the line and the origin.

$$\mathbf{p}' = \begin{pmatrix} X_s \\ Y_s \\ t \end{pmatrix} = \mathbf{R}_{\alpha\theta}\mathbf{p} \tag{4}$$

The rotation of any point ***p*** of the line to the new coordinate system (Eq. 4) leads to the same planimetric coordinates but to different Z-coordinates. Thus, parameter t corresponds to the line parameter of the point-orientation representation of a line. The line equation can be deduced by inversion of Eq. 4:

$$\mathbf{p} = \mathbf{R}^{\mathbf{T}}_{\alpha\theta}\mathbf{p}' = \begin{pmatrix} X_s \cos\alpha\cos\theta - Y_s \sin\alpha + t\cos\alpha\sin\theta \\ X_s \sin\alpha\cos\theta + Y_s\cos\alpha + t\sin\alpha\sin\theta \\ -X_s\sin\theta + t\cos\theta \end{pmatrix} \tag{5}$$

3.2 The point-to-line approach

A line approach using a point-to-line correspondence was published by Kubik (1991). His aim was to determine the seven transformation parameters for the absolute orientation of images by replacing the control points in the reference system by control lines. For aerial triangulation, Schenk (2004) implemented a block adjustment with extended collinearity equations using straight lines. This publication provides the basis for the first method for single photo orientation described in the following.

For the referencing of photos and laser scanner point clouds, point-to-line correspondence means the definition of straight lines in the point cloud and the measurement of points on the corresponding lines in the image. At this, the 3D lines are described by 4 parameters as presented in section 3.1.

For a correct orientation, the projection ray from the perspective centre through the image points should intersect the corresponding object lines (Figure 2).

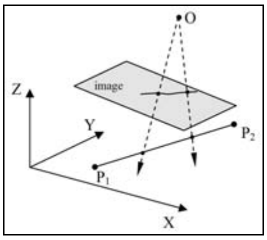

Figure 2. Principle of point-to-line approach

This point-to-line correspondence can be described mathematically by extending the collinearity equations. At this, the object coordinates (*X, Y, Z*) are replaced with the respective row of the line equation in Eq. 5:

Like in the pure point-based method, the parameters of the exterior orientation ($X_0, Y_0, Z_0, \omega, \varphi, \kappa$) are estimated in an iterative process, where the residuals of the observed image coordinates are minimised. Additionally the line parameter t has to be estimated for every image point. Measuring two image points per object line, at least three known non-parallel object lines are required for determination of the exterior orientation[*].

$$x = x_0 - c\cdot\frac{r_{11}\cdot(X-X_0)+r_{21}\cdot(Y-Y_0)+r_{31}\cdot(Z-Z_0)}{r_{13}\cdot(X-X_0)+r_{23}\cdot(Y-Y_0)+r_{33}\cdot(Z-Z_0)}+dx$$
$$y = y_0 - c\cdot\frac{r_{12}\cdot(X-X_0)+r_{22}\cdot(Y-Y_0)+r_{32}\cdot(Z-Z_0)}{r_{13}\cdot(X-X_0)+r_{23}\cdot(Y-Y_0)+r_{33}\cdot(Z-Z_0)}+dy \tag{6}$$

$$\text{with}\quad \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_s\cos\alpha\cos\theta - Y_s\sin\alpha + t\cos\alpha\sin\theta \\ X_s\sin\alpha\cos\theta + Y_s\cos\alpha + t\sin\alpha\sin\theta \\ -X_s\sin\theta + t\cos\theta \end{pmatrix}$$

The parameters of the interior orientation (x_0, y_0, c) as well as the parameters of the radial distortion (A_1, A_2, A_3) can be calculated from at least six known spatially distributed object lines (e.g. in planes with different levels of depth) with two corresponding image points.

For heightening the redundancy and consequently improving the accuracy of the adjustment, the number of image points per object line can be increased.

3.3 The line-to-line approach

This section deals with a line-based approach, which was published by Schwermann (1995). Here, the orientation of a single image is based on the definition of straight object lines in the point cloud and on the measurement of corresponding image lines. The equations of the image lines are defined as:

$$g: \quad y = m\cdot x + n \quad \text{or} \quad x = m'\cdot y + n' \tag{7}$$

where m, m′ = slope
n, n′ = intersection with appropriate axis

Schwermann (1995) used this type of line equations for the description of the object lines as well. Because this representation is only applicable for straight lines with small slopes, there are many special cases that must be considered with respect to appropriate axes. To avoid these case differentiations, the method was varied by applying the 4-parameter line equations presented in section 3.1.

The basic principle of this line-to-line approach is the modification of the collinearity equations in such a way that the image line parameters (*m, n*) are dependent on the parameters of the object line (X_s, Y_s, α, θ) and the parameters of the exterior and interior orientation (principle point and principle distance). In the course of the modification, the unknown line parameter t was eliminated. The resulting equations are shown below:

$$m = \frac{V_2W_1 - V_1W_2}{U_2W_1 - U_1W_2}$$
$$n = y_0 - x_0\frac{V_2W_1 - V_1W_2}{U_2W_1 - U_1W_2} + c\frac{U_1V_2 - U_2V_1}{U_2W_1 - U_1W_2} \tag{8}$$

Where

[*] 6+6 unknowns; 6x2 observations

$$
\begin{aligned}
U_1 &= r_{11}\cos\alpha\sin\theta + r_{21}\sin\alpha\sin\theta + r_{31}\cos\theta \\
V_1 &= r_{12}\cos\alpha\sin\theta + r_{22}\sin\alpha\sin\theta + r_{32}\cos\theta \\
W_1 &= r_{13}\cos\alpha\sin\theta + r_{23}\sin\alpha\sin\theta + r_{33}\cos\theta \\
U_2 &= r_{11}(A - X_0) + r_{21}(B - Y_0) + r_{31}(C - Z_0) \\
V_2 &= r_{12}(A - X_0) + r_{22}(B - Y_0) + r_{32}(C - Z_0) \\
W_2 &= r_{13}(A - X_0) + r_{23}(B - Y_0) + r_{33}(C - Z_0) \\
&\text{with} \\
A &= X_s\cos\alpha\cos\theta - Y_s\sin\alpha \\
B &= X_s\sin\alpha\cos\theta + Y_s\cos\alpha \\
C &= -X_s\sin\theta
\end{aligned}
\tag{9}
$$

In the special case of a vertical image line, the inverse relations of Eq. 10 have to be considered as observations in the non-linear adjustment process.

$$
m' = \frac{1}{m} \quad \text{and} \quad n' = -\frac{n}{m} \tag{10}
$$

The determination of the exterior orientation of an image can be obtained from at least three straight lines defined in the laser scanner point cloud. The model does not comprise any correction terms for lens distortion, because the correction model in Eq. 2 is not applicable. Hence, either there has to be derived another distortion model which is dependent on the image line parameters (*m, n*), or the lens distortion has to be determined in a pre-calibration before the image orientation process. An integrated orientation procedure might be developed using elements from plumb-line calibration (Lerma & Cabrelles, 2007). In the case of pre-correction, the measurement of the image lines would be carried out in the resampled image.

4. COMPARISON OF THE METHODS

4.1 Interaction in the CAD-environment

The presented image orientation methods were implemented in the software product *PointCloud* of the company *kubit GmbH*. The typical workflow of image orientation in *PointCloud* is shown in the following Figure 3.

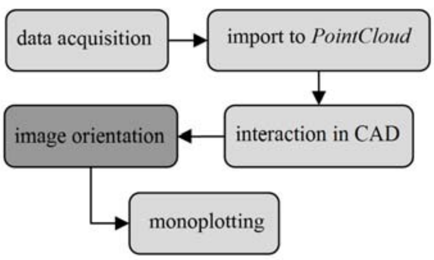

Figure 4. Workflow of image orientation in *PointCloud*

The first step is the import of a terrestrial laser scanner point cloud and an image of the same scene. From that moment all user interactions concerning the image orientation are carried out in the CAD-environment. These interactions include the measurement of point or line features in the image and in the 3D point cloud as well as the approximate setting of camera position and viewing direction to the object.

One big advantage of the CAD is the visualisation which enables the user to control his measurements and the results directly. After referencing the data, the oriented and for lens distortion resampled image is visualised and stored by the *PointCloud* application using a customised *AutoCAD* item. Now the user can choose between measuring interactively in the oriented image and/or in the point cloud itself by making use of the appropriate *PointCloud* tools.

4.2 Datasets

The introduced methods for image orientation were tested with two different data sets. The first data set is a spatial test field with an extension of 2 x 3 meter. It consists of 27 straight lines (8 horizontal, 10 vertical, 9 transversal), which are each marked with four targets. The laser scanner data were acquired with a Riegl LMS Z-420i. Additionally, 23 convergent images were obtained of the test field. In the course of analysing the images in *AICON 3D studio*, the 3D coordinates of the signalised line points were determined. The exterior orientations of the images calculated in the bundle block adjustment act as referee for the single image orientations in *PointCloud*. The object is not very relevant for practical application, but it allows for a thorough evaluation of the accuracy potential due to the large number of well defined targets.

The images of both data sets were acquired with a 6 M pix mirror reflex camera with 7.8 µm pixel size.

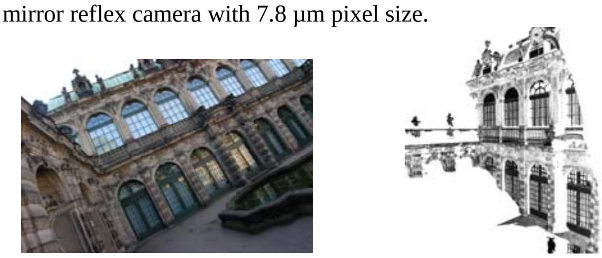

Figure 3. Image and laser scanner point cloud of data set “Nymphenbad”

The Nymphenbad, a part of the historical building “Zwinger” in the city of Dresden, is object of the second data set. The south-eastern facade was scanned with a point spacing of 1.4 ... 13 mm (depending on the scanning distance) and a total of 3 million 3D points (Figure 4).

4.3 Results

4.3.1 Data set “test field”:

The measurement of the signalised line points in the laser scanner data was not possible because of the retro-reflecting characteristics of the signalised points which caused incorrect distance observations of the laser scanner. Therefore, object coordinates obtained from the bundle block adjustment were used for analysing this data set. The exterior orientations of three out of the 23 convergent images were calculated whereat the interior camera orientation was derived from the block adjustment. First, the signalised line points were used as control points for a conventional point-based spatial resection. Then the resection was performed on the basis of straight line features, each defined by two signalised line points, using the two methods as outlined before. The resulting orientation

method	s_0	averaged internal standard deviations of estimated parameters					
		s_{X0} [mm]	s_{Y0} [mm]	s_{Z0} [mm]	s_ω [°]	s_φ [°]	s_κ [°]
bundle block adjustment	0.05 pixel	0.1	0.1	0.1	0.002	0.003	0.008
resection with points	0.40 pixel	0.6	0.4	0.7	0.008	0.008	0.008
resection with lines (point-to-line)	0.75 pixel	1.9	1.1	1.4	0.016	0.024	0.023
resection with lines (line-to-line)	0.0312 [ ]	5.8	3.2	4.0	0.048	0.073	0.072

Table 1. Means of standard deviations of estimated parameters of exterior orientation

method	averaged absolute differences of estimated parameters to bundle block adjustment					
	X_0 [mm]	Y_0 [mm]	Z_0 [mm]	ω [°]	φ [°]	κ [°]
resection with points	1.1	2.5	2.2	0.048	0.012	0.007
resection with lines (point-to-line)	2.2	3.4	3.3	0.064	0.045	0.004
resection with lines (line-to-line)	4.3	13.1	4.0	0.073	0.061	0.028

Table 2. Comparison of exterior orientations obtained by single image resections and bundle block adjustment

parameters bundle block adjustment. The absolute differences averaged over three images are shown in Table 2. The empirical standard deviations of unit weight and of the unknowns (averaged over three images) are summarised in Table 1.

From these tables, a degradation of precision between the three resection methods is obvious. As expected, the best results could be obtained with the conventional point-based photo resection. For instance, its standard deviation is with 0.4 Pixel twice as good as when referencing with the point-to-line approach. The line-to-line approach shows poorer internal precision and much larger differences to the check points. One reason for this is in the neglection of lens distortion in the orientation model.

In a next step, the object coordinates of 33 points were calculated by spatial intersection using the three images each oriented with the three methods. A comparison to control points is shown in Table 3. This test is not relevant for the actual application, but it gives some information on the quality of the orientation parameters. It shows that the precision of the point-to-line method is almost as good as the precision of the conventional resection, while the line-to-line method performs 2-3 times worse.

resection method	RMS ΔX [mm]	RMS ΔY [mm]	RMS ΔZ [mm]
point-to-point	1.03	0.77	0.83
point-to-line	1.23	1.37	1.03
line-to-line	2.52	3.20	2.05

Table 3. RMS of differences between control points and points obtained by intersection

4.3.2 Data set "Nymphenbad":

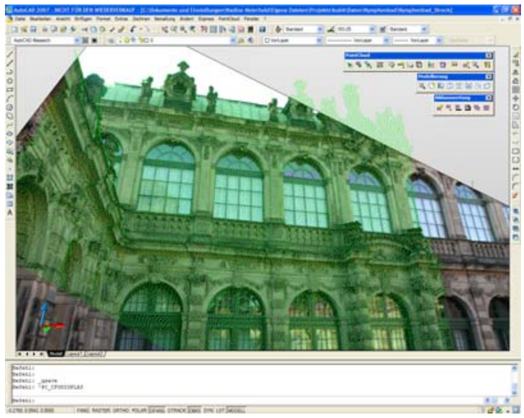

Figure 3. With point-line-method oriented image in *PointCloud* overlaid with the laser scanner point cloud

This data set of a historical building facade was chosen for testing the methods under realistic conditions. In the case of point-based referencing, the orientation of the image is based on 22 natural points (e.g. distinctive corners, crossbars). For the line-based methods, 16 non-parallel straight lines with two points per line were used. Figure 3 shows the oriented image overlaid with the laser scanner point cloud. The features were measured in the image and the laser scanner data interactively. Because of the unknown interior orientation of the camera, it was determined simultaneously together with the radial distortion parameters A_1 and A_2 (lens distortion not in line-to-line method). The comparison of the classical photo resection and the resection methods using linear features are shown in Table 4 and Table 5.

In these tables the same degradation between the methods is appearing. From the smaller standard deviations and the smaller differences, one can conclude that the point-to-line approach yields better orientation results than the line-to-line resection method. Additionally, it is noticeable that the gap between the point-based resection and the point-to-line approach has become smaller.

resection method	s_0	internal standard deviations of unknowns								
		s_{X0} [m]	s_{Y0} [m]	s_{Z0} [m]	s_ω [°]	s_φ [°]	s_κ [°]	s_c [mm]	s_{x0} [mm]	s_{y0} [mm]
point-to-point	1.05 pixel	0.004	0.008	0.003	0.063	0.061	0.064	0.0174	0.0159	0.0291
point-to-line	1.08 pixel	0.011	0.036	0.007	0.094	0.080	0.090	0.0393	0.0257	0.0480
line-to-line	0.1660 [ ]	0.058	0.174	0.062	0.300	0.444	0.382	0.1787	0.1660	0.1850

Table 4. Standard deviations of image orientation by applying the three resection methods

resection method	differences of estimated parameters to point-to-point resection method								
	X_0 [m]	Y_0 [m]	Z_0 [m]	ω [°]	φ [°]	κ [°]	c [mm]	x_0 [mm]	y_0 [mm]
point-to-line	-0.024	0.045	-0.001	-0.084	0.197	0.017	-0.030	-0.072	-0.081
line-to-line	0.046	0.081	0.004	0.067	0.706	-0.172	-0.223	-0.133	-0.057

Table 5. Comparison of orientation parameters obtained by point-based and line-based single photo resection

The almost identical results of the point-based and the point-to-line resection and the poorer precision of all resection methods in comparison to the data set “test field” can primarily be explained by less accurate object coordinates. With an increasing distance of the laser scanner to the object (here 2 ... 18 m), the point spacing increases and the accuracy of 3D features interactively measured in the point cloud decreases. Therefore, it can be expected that the point-to-line resection will perform better than the point-based algorithm if 3D line features are obtained from (semi-)automatic modelling (e.g. by intersecting of planes fitted into the point cloud) rather than from interactive measurements.

5. CONCLUSIONS

Using lines rather than discrete points may be a valuable option for the orientation of single digital images to laser scanner 3D point clouds. Two different algorithms, a point-to-line and a line-to-line correspondence approach, have been developed, implemented and tested. The results show that, compared to discrete points, line features are equally well or even better suited for the referencing between images and laser scanner point clouds. This fact is pronounced with an increasing point spacing.

Accuracy-wise, the point-to-line resection performs better than the line-to-line approach. In addition to a better image orientation, the point-to-line method has another important advantage because of its correspondence between image points and object lines: straight 3D lines do not have to be imaged as straight lines. That means there is no necessity for determination of lens distortion and resampling of the image before image orientation. Consequently, image features can be measured in the original image. If imaging errors of the optical system are not considered, approaches based on straight lines in the image space are only applicable for an approximate image orientation.
While the point-to-line method performs better in (semi-) interactive measurement, the line-to-line approach may depict a better option for a fully automatic system, where linear features can be derived fully automatically in the point cloud and the image. This will be a major issue of future work on the topic.

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