Available online at www.sciencedirect.com
ScienceDirect
ISPRS Journal of Photogrammetry & Remote Sensing 62 (2007) 122–134
PHOTOGRAMMETRY & REMOTE SENSING
www.elsevier.com/locate/isprsjprs

A concept for feature based data registration by simultaneous consideration of laser scanner data and photogrammetric images

Axel Wendt *

Institute of Photogrammetry and GeoInformation, Leibniz University of Hannover, Nienburger Str. 1, D-30167 Hannover, Germany
Institute for Applied Photogrammetry and Geoinformatics, University of Applied Sciences Oldenburg/Ostfriesland/Wilhelmshaven, Ofener Str. 16/19, D-26121 Oldenburg, Germany

Received 17 October 2005; received in revised form 4 December 2006; accepted 5 December 2006
Available online 29 January 2007

Abstract

Surface measurement of complex geometric objects by means of optical techniques, such as laser scanning or photogrammetry, requires multiple views from various stations. The data sets of the views, e.g. point clouds and photogrammetric images, are given in individual coordinate systems. For a complete representation of the objects, the views have to be transformed into one common coordinate system. This task is denoted as registration and involves an estimation of the transformation parameters between different coordinate systems.

In this paper, a concept for a pairwise feature based registration of hybrid laser scanner data sets is proposed. The concept includes the feature extraction and description by simultaneous consideration of laser scanner data and photogrammetric images, as well as the recognition of consistent feature correspondences. The features are viewpoint invariant and are described with a rectified image patch on planar surface geometry in object space.

Two different data sets are used to demonstrate that the proposed concept for feature extraction, feature description and correspondence search is successful to register hybrid laser scanner data sets with a high level of automation.

Keywords: Vision sciences; Photogrammetry; Terrestrial laser scanning; Hybrid sensor; Feature extraction; Registration; Automation

1. Introduction

In order to record large objects using optical measurement techniques, several view points are necessary. From each view point, data sets are recorded and given in local coordinate systems. To orientate the data sets into one common coordinate system, data registration has to be carried out. Three translation parameters and three rotation parameters of each view point coordinate system have to be determined in 3D space. The scale is given by the metric information of the laser scanner data. The data registration is a prerequisite for any further evaluation task involving the common use of the complete represented object, or the transformation between the different coordinate systems of the view points.

Data registration is usually accomplished by formulating it as a correspondence problem: a cost function is set up based on a metric to estimate the distance between corresponding features determined in different views. Hence, the essential difficulty is the identification of conjugate features. Matching techniques are used to solve the correspondence problem. They differ by feature extraction, feature description, as well as by the optimization

* Tel.: +49 441 7708 3606; fax: +49 441 7708 3170.
E-mail address: wendt@ipi.uni-hannover.de.

0924-2716/$ - see front matter
doi:10.1016/j.isprsjprs.2006.12.001

techniques for correspondence search. The goal is to extract view point invariant features, to describe them uniquely and to establish consistent correspondences.

This research investigates a concept for feature based data registration by simultaneous consideration of laser scanner data and photogrammetric images. Experimental testing is carried out with data sets of building facades recorded with a hybrid sensor providing terrestrial laser scanner data and photogrammetric images. The proposed method does not require approximate values for the orientation parameters. The goal is to increase the automation of the registration by simultaneous consideration of terrestrial laser scanning data and photogrammetric images to generate robust features and determine consistent correspondences.

In this paper, an overview of the related work is discussed before introducing our concept of feature based data registration. Further, the feature extraction and description, as well as the processing strategy of the correspondence search is explained. Finally, the concept is evaluated with two data sets.

2. Related work

In this chapter, an overview of existing methods of geometric and radiometric feature extraction, feature description and matching methods is given. These are relevant to the proposed concept of feature based data registration.

2.1. Feature extraction and description

In general, features are distinguished as being either local or global. Local features are points, edges and lines, and regions. Larger features, also called structures, are referred to as global features. Global features are usually composed of different local features. Besides the attributes of the local features, relations between these local features are introduced to characterize global features. These relations can be geometric such as the minimum distance between two local feature points, radiometric such as the difference in grey values or grey value variances between two adjacent regions, or topological such as the notion that one feature is contained within another. Features should be distinctive with respect to their neighborhood, invariant with respect to geometric or radiometric influences and stable with respect to noise.

2.1.1. Features in 3D point clouds

3D point clouds contain points of visible surfaces in 3D object space. Additionally, if topology between the points is given, then the clouds are usually represented with meshes. 3D point clouds can also be represented as range images. The following methods for feature generation refer to different point cloud representations.

Johnson and Hebert (1998, 1999) introduced an approach using all points of the 3D point cloud as feature points. For each feature point, a descriptive image that encodes global properties of the object surface is created. This is referred to as a *spin image*. To generate the *spin image*, firstly a tangential plane is computed as a local basis and secondly the positions of surrounding points on the surface of the object are described by two parameters (Johnson and Hebert, 1998) with respect to the basis. By accumulating these parameters in a 2D array, a descriptive image is created. As the image encodes the coordinates of points on the surface of an object with respect to the local basis, it is a local description of the global shape of the object and is invariant under rigid transformations. He et al. (2005) also introduced a feature called complete plane patches on the basis of analysis of properties of real scenes. An integral volume descriptor using values, which are invariant under rigid transformation and with respect to intrinsic geometric properties of the input shapes is introduced by Gelfand et al. (2005). Vanden Wyngaerd and Van Gool (2002) used bitangency on surfaces, namely bitangent curves as landmarks for pairwise point cloud registrations. Their approach of using curves is an extension of Feldmar et al. (1994) using bitangent points on a 3D surface. Matching bitangent point pairs on different patches is accomplished by comparing the distances between the points of a pair. Point pairs having the same tangent plane are referred to as a bitangent plane.

In some studies, surface geometry and intensity, color information, or further surface attributes have been combined to improve automatic registration. Maas (2002) used airborne laser scanner reflectance images as complementary to the height data for the determination of horizontal shift parameters between the laser scanner strips of flat areas. An extension of the *spin image* description including texture is given by Brusco et al. (2005). Roth (1999) used feature based methods in which interest points and regions are extracted from the intensity images. More often, the intensity information is processed to reduce the search effort of corresponding point pairs, or to eliminate the ambiguities due to inadequate geometric information on the object surface, cf. Weik (1997), Johnson and Kang (1997), Godin et al. (2001).

2.1.2. Features in photogrammetric images

For feature extraction and description in images, local operators denoted as interest operators are typically used.

Within a mask, attributes are calculated and compared to thresholds to assess if a feature exists or not. This step is repeated by moving the mask along the directions of the image coordinate axis.

A short description of interest operators is given in the following: The operator of Moravec (1977) detects points with high grey level variances. A uniform threshold is used for the whole image. No points are detected in low contrast image regions. Förstner (1986) introduced a gradient based operator to detect interest points for feature matching. A feature is selected based on two thresholds in the case, where the grey level signal ellipse of the mask is small and circular. The first threshold is the size of the ellipse and the second, the roundness. The SUSAN (Smallest Univalue Segment Assimilating Nucleus) operator of Smith and Brady (1997) detects interest points with a circular mask placed on each pixel of the image. All pixels within the mask are compared with the center value of the mask. An interest point is given, if the amount of equal pixel values is less than half of the maximum mask size. The authors give also a comparison to alternative operators.

For the description of extracted feature points, Lowe (2004) presents a method that can be used to perform reliable matching between different views of an object or scene. The description is invariant to image scale and rotation, and can deal with a substantial range of affine distortion, noise and change in illumination. Lowe shows that the features are highly distinctive, in the sense that a single feature can be correctly matched with high probability against a large database of features from many images. This approach has been named the Scale Invariant Feature Transform (SIFT), as it transforms image data into scale-invariant coordinates relative to local features.

2.2. Matching methods

The goal of matching is to find consistent correspondences. In the case of feature based registration methods, without using approximate values for the orientation parameters, the task has to be formulated as a global optimization problem to determine the global minimum. To select corresponding candidates the feature descriptions are compared. In general, this problem is an NP-hard (Non-deterministic Polynomial-time hard) problem, where correspondences are searched in all combinations of candidate features. Heuristic or stochastic methods are proposed for obtaining a solution. If a solution is found, it cannot be guaranteed that it represents the global minimum.

For the registration of range images, Silva et al. (2003, 2005) apply Genetic Algorithms in combination with Hill-Climbing heuristics. Huber and Hebert (2003) introduce a method for automatic registration of multi data sets. The procedure uses a combination of discrete and continuous optimization methods to construct a globally consistent model graph from a set of pairwise registration results. Luck et al. (2000) developed a hybrid algorithm that combines the speed of the Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992; Zhang, 1994) with the robustness of Simulated Annealing (Press et al., 1992). Lowe (2004) describes a near real-time approach for object recognition by matching individual features to a database of features using a fast nearest-neighbor algorithm, followed by a Hough transform to identify clusters belonging to a single object, and finally performing verification through least-squares solution for consistent registration parameters. Chen et al. (1999) used for the correspondence search a modified RANSAC method. The RANSAC method, published by Fischler and Bolles (1981), is capable of interpreting data containing a significant percentage of gross errors.

Concepts for matching methods based on approximate values for the orientation parameters have been previously proposed by, e.g. Litke et al. (2005), Pulli (1997), Akca (2005) and Wendt and Heipke (2005). These methods mainly increase the accuracy and consider simultaneously radiometric and range data.

3. Concept of feature based data registration

In this chapter, a new concept for feature based data registration is proposed. An overview of the different processing steps is given in Fig. 1. Firstly, points of promising features are extracted and secondly, a radiometric description for the feature points is generated. This is done for each view point data set.

Then the correspondence search is carried out, consisting of similarity assessment of *candidate correspondences*, sorting according to their similarity and correspondence determination. For correspondence determination, the principle of RANSAC is applied. The work flow will be described detailed in the following sections.

3.1. Feature point extraction

The goal is to automatically extract features located in geometrically planar areas of adequate texture in 3D object space. Hence, errors along geometric edges and corners of the laser scanner data, which occur due

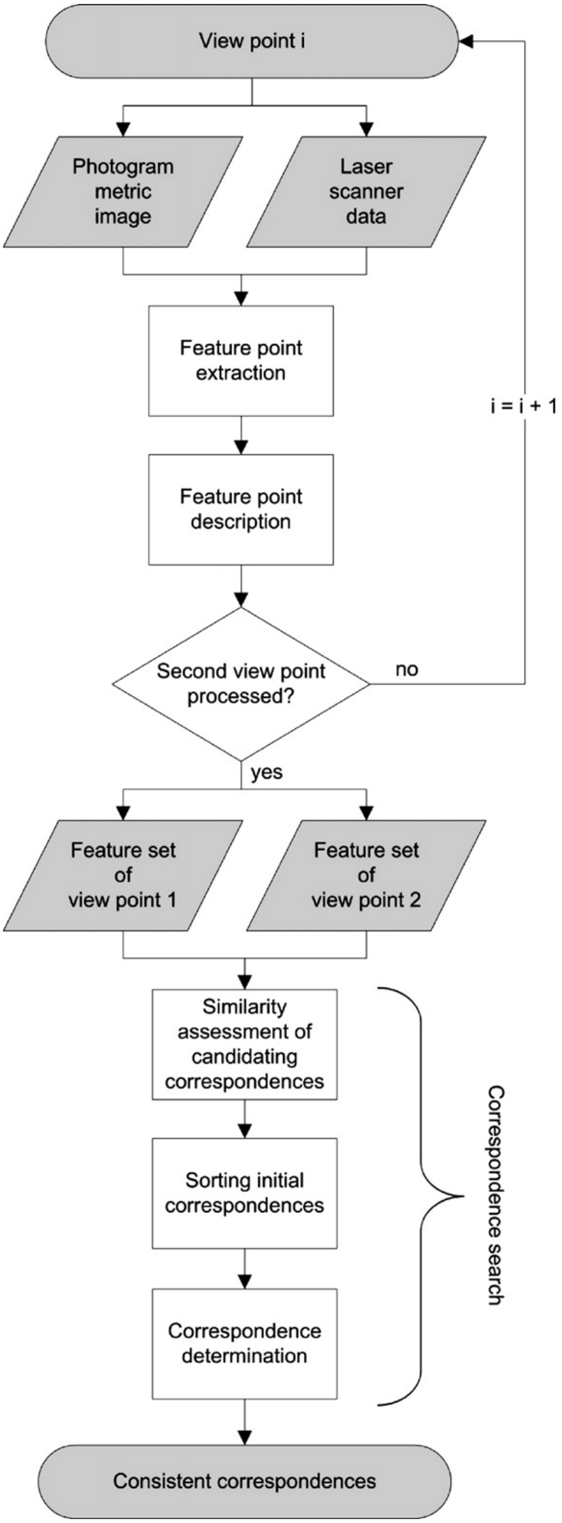

Fig. 1. Work flow of the feature based data registration.

to occlusions and surface discontinuities, have no effect. To generate such features, laser scanner data and photogrammetric images have to be considered simultaneously. To exclude poorly visible features and to get an adequate feature description in object space, the viewing direction in relation to the surface is introduced.

In the case of a hybrid sensor, where a camera is constantly mounted on top of a panoramic terrestrial laser scanner, the field of view (FOV) of the camera is a subset of the FOV of the laser scanner. Therefore, it is more convenient to detect interest points in the photogrammetric image first, and then to check the geometric planarity of the surface and the viewing direction using the point cloud. The resulting features from the first step are denoted as *initial features* and after filtering with the geometric conditions as *accepted features*.

3.1.1. Initial features

For the *initial feature* extraction the SUSAN operator is used. The SUSAN operator is a fast, structure conserving and noise reducing operator for feature extraction. It directly utilises the grey values in the image and does not use derivatives. A mask is placed on each pixel of the image for the feature point detection. All pixels within the mask are compared with the grey value of the center of the mask. By means of the amount of pixels with similar grey values, the existence of a feature point is assessed. The comparison equation is

$$c(u,v) = \begin{cases} 1, & \text{if} \quad |g(u,v) - g_0(u_0,v_0)| \le t \\ 0, & \text{if} \quad |g(u,v) - g_0(u_0,v_0)| > t \end{cases} \tag{1}$$

with

$$u = 1, \dots, w$$

$$v = 1, \dots, h \tag{2}$$

with (u_0, v_0) the position of the mask center with grey value g_0, (u, v) the position of pixel grey value g within the mask, c the output of the comparison, t the difference threshold for the grey value comparison, w the mask width and h the mask height. The sum of these comparisons is given as

$$n_{u_0,v_0} = \sum_{u=1}^{w} \sum_{v=1}^{h} c(u,v) \tag{3}$$

Further, $n_{u0,v0}$ is compared with a threshold s

$$R_{u_0,v_0} = \begin{cases} \text{true}, & \text{if } n_{u_0,v_0} < s \\ \text{false}, & \text{otherwise} \end{cases} \tag{4}$$

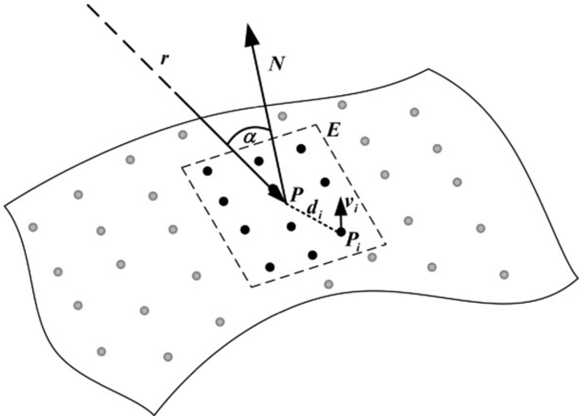

Fig. 2. Visibility and planarity check of feature locations.

and delivers R, the *initial feature* response at position (u_0, v_0). For a feature to be present, n must be less than half of the mask area. Therefore s is set to half of the mask area. The geometric type of the feature is represented by s, while the threshold t has to be set according to the contrast and noise of the grey values. With t the assignment of pixels to the center grey value g_0 and the density of features is controlled.

3.1.2. Accepted features

After these *initial features* are extracted, the 3D position on the surface is investigated through the planarity as well as the viewing direction by estimating the tangential plane (see Fig. 2). The 3D position P of the *initial feature* point is interpolated from n surrounding points P_i, mapped from object into image space. P is estimated through

$$P = \frac{1}{\sum_{i=1}^{n} d_i} \sum_{i=1}^{n} d_i P_i \tag{5}$$

with

$$d_i = p_i - p \tag{6}$$

the distance of a projected 3D point p_i to the *initial feature* point p. As well as the position, the tangential plane E is estimated from these points. The adjusted plane is given through the point P on the surface and the normal vector N as

$$E: \quad N \cdot (X - P) = 0 \tag{7}$$

with X representing any point in the plane. Further, the perpendicular distance of point P_i to the plane (cf. Fig. 2) is given by

$$v_i = |N \cdot (P_i - P)|, \quad \text{with } |N| = 1 \tag{8}$$

with v_i the length of the distance. For the estimation of N, at least 3 points well distributed in 3D space are necessary. In the case of more than 3 points, N is estimated by

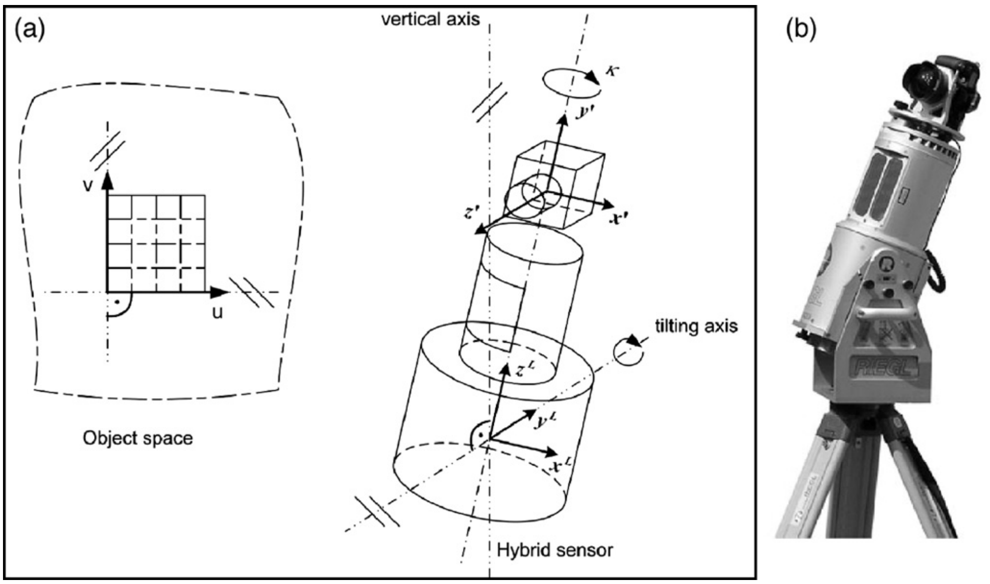

Fig. 3. The principle of a unique image orientation in object space. (a) Projection of the axes of the hybrid sensor onto the tangential plane. (b) Sample of a hybrid laser scanner with a mounted camera (RIEGL LMS-Z420i).

least-squares adjustment. The standard error σ_0 of the plane adjustment is

$$\sigma_0 = \sqrt{\frac{\mathbf{v}^T\mathbf{v}}{n-u}} \tag{9}$$

with $\mathbf{v}$ the vector of residuals including the lengths of the perpendicular distances of n points and u the number of unknowns. Further, the viewing direction α between the normal vector N of the tangential plane and the image ray r of the *initial feature* point is estimated by

$$\alpha = \arccos\left(\frac{<N, r>}{|N| \cdot |r|}\right) \tag{10}$$

If σ_0 is less than 0.1 m, the planarity condition is fulfilled and if α is less than 60 degrees, an adequate viewing direction is given. Both values are set empirically, the value for the viewing direction is also recommended by Johnson and Hebert (1999) for *spin image* locations. If both tests are passed successful the *initial feature* is accepted. The *accepted features* represent potential candidates for the correspondence search.

3.2. Feature point description

In this section, the computation of the feature point description is given. This description is a rectified radiometric image in object space defined on the tangential plane of the *accepted feature* point. Due to the chosen feature extraction approach, it is guaranteed that the geometric characteristics are almost flat and sufficient texture is available on the surface position in 3D object space. For comparison of rectified images of different view points, a unique image grid orientation in object space is necessary. In the case of an unknown object space coordinate system without an approximate object surface, it is not possible to define the unique orientation directly in object space within the 6 degrees of freedom of the registration parameters. By reducing the number of registration parameters to five parameters, the unique image grid orientation can be achieved. In the case of data recording with terrestrial laser scanning devices (Fig. 3), the scanning device typically stands upright and the device is only tilted around one horizontal axis. The unknown registration parameters contain two rotation and three translation parameters. The fixed horizontal axis, the tilting axis, delivers the common orientation axis u for the image grids of all features of all view points. Within the five parameter space, this rectified image is a view point invariant feature description. For the computation of the rectified image, an image grid is defined on the tangential plane in object space. The scale of one surface element (surfel) is related to the scale of the photogrammetric image of the view point. To fill the grid, each surfel is mapped into the corresponding image and the grey value is resampled. For a general compatibility of rectified images of corresponding candidates from different view points, a fixed surfel scale and a unique image size has to be selected. After all features are evaluated, the correspondence search can be executed.

3.3. Correspondence search

In this section, our matching strategy is proposed. In the strategy, the similarity is firstly computed over all combinations of feature correspondences by the use of rectified images with the cross-correlation coefficient. The feature pairs with the highest similarity are denoted as *candidate correspondences*. Secondly, the *candidate correspondences* are sorted according to maximum similarity and finally, the RANSAC algorithm is applied for *consistent correspondence* determination.

Due to the fact that the rectified images have the same geometric resolution, size and orientation in object space, they are directly comparable. Only differences in the grey values have to be considered, which is achieved through the cross-correlation coefficient given in Eq. (11). The cross-correlation coefficient ρ_{fc} quantifies the radiometric similarity.

$$\rho_{fc} = \frac{\sigma_{fc}}{\sigma_f \sigma_c} \qquad \rho_{fc} \in [-1, 1] \tag{11}$$

Here, σ_f is the standard deviation of the grey values of the feature point image, σ_c the standard deviation of the grey values of the corresponding candidate image and σ_{fc} their covariance. ρ_{fc} is calculated over all combinations of feature pairs between the first view point and the second view point. The resulting *candidate correspondences* will include *consistent correspondences* as well as a number of incorrect pairs due to ambiguities in the image pattern.

The *candidate correspondences* are ordered according to similarity. It is assumed that the features with the highest similarity constitute the most *consistent correspondences*. This assumption is used to optimize the RANSAC method by randomly selecting the minimum size of correspondences of high similarity within a threshold. Correspondences with a ρ_{fc} of more

Fig. 4. Considered view points of the *Dresdner Frauenkirche*.

than 0.6 are considered. Then the transformation parameters are determined. With the transformation parameters, the *accepted features* of both data sets are transformed into one coordinate system and the consistency of each feature point is checked with the error tolerance. The error tolerance is compared to the Euclidean distance between the closest feature points of the sets. This procedure is repeated n times with each solution being assessed. It successfully stops when the suggested number of *consistent correspondences* is found. To restrict the iterations the maximum number of tries has to be set. For the RANSAC method, three parameters have to be specified:

- The error tolerance to determine *consistent correspondences*
- The maximum number of tries n
- The suggested number of *consistent correspondences* to imply that the correct transformation parameters have been found.

To estimate the final transformation parameters, all *consistent correspondences* are considered in a least-squares adjustment.

4. Experimental testing

Experimental testing was carried out to demonstrate that:

- The proposed concept for feature based registration leads to successful results, including:
  - Rectified images are a useful feature description
  - The cross-correlation coefficient is an adequate similarity criterion

Table 1
Parameter set for the processing steps

SUSAN t	20 grey values
SUSAN s	50
SUSAN mask size	10 pixels
Viewing direction, max. α	60°
Planarity, max. σ_0	0.1 m
Point search mask size	50×50 pixels^2
Rectified image size	30×30 surfels^2
Surfel scale	8 mm
RANSAC error tolerance	0.2 m
RANSAC performed number of tries	17
RANSAC suggested number of consistent correspondences	91

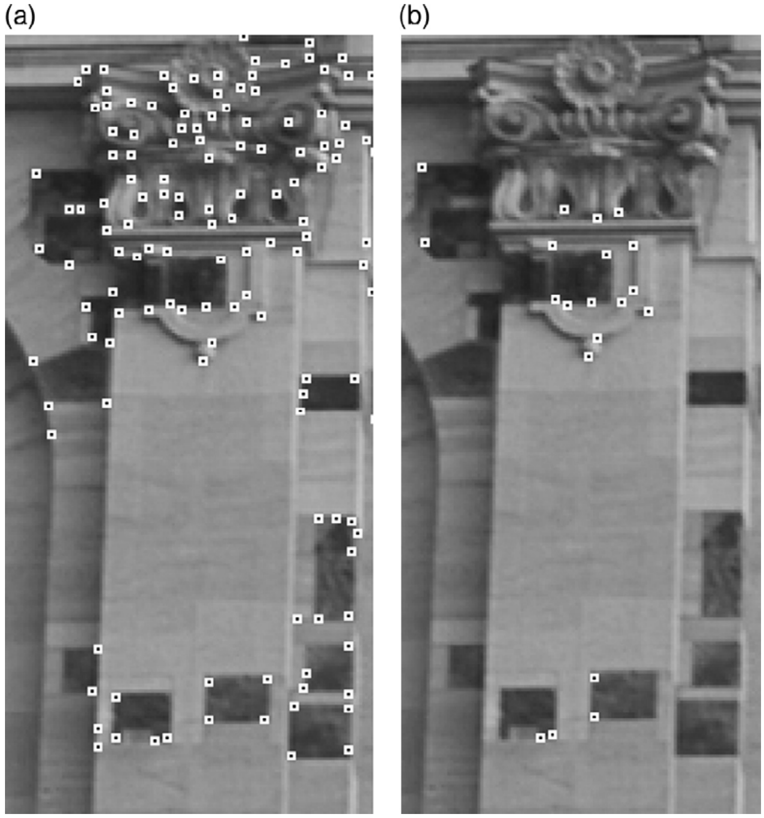

Fig. 5. Feature point extraction. (a) Initial features. (b) Accepted features.

- The proposed correspondence search strategy is successful.

These items are analyzed with data sets of building facades acquired with a hybrid laser scanner, including point clouds and photogrammetric images. Calibration values for the hybrid laser scanning sensor were determined through the standard procedure of the instrument manufacturer. The object scenes represent planar surface geometry and adequate radiometric texture. For analysis purposes, accurate orientation information for the different view points has been determined through standard procedures of terrestrial laser scanner data orientation. Due to the orientation information also the suggested number of *consistent correspondences* was determined. The correspondence search was carried out until the suggested number of *consistent correspondences* has been found. The maximum number of tries was set to 200 iterations. For each data set, the proposed concept of feature extraction, feature description and correspondence search has been applied. The data sets were recorded with the hybrid laser scanner Riegl LSM-Z420i with a

Table 2
Results of the data set *Dresdner Frauenkirche*

Initial features of view point 1	5702
Initial features of view point 2	8167
Accepted features of view point 1	378
Accepted features of view point 2	338
Determined consistent correspondences	91

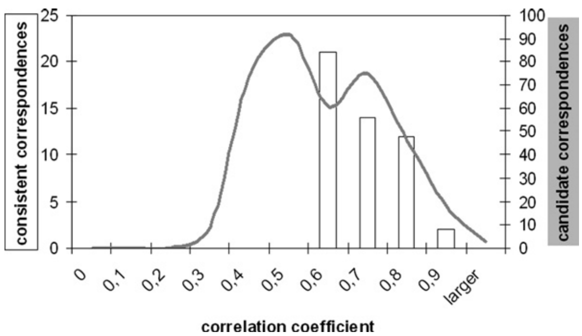

Fig. 6. Histogram of consistent correspondences (bars) and candidate correspondences (line).

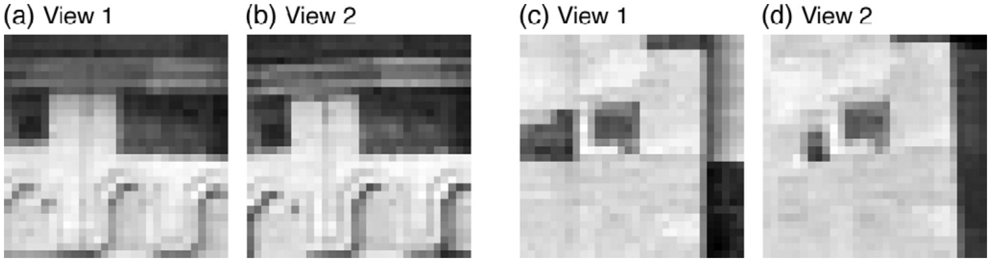

Fig. 7. Rectified images of the consistent correspondences. (a),(b) Highest correlation coefficient ($\rho_{fc}=0.92$). (c),(d) Lowest correlation coefficient ($\rho_{fc}=0.60$).

mounted Nikon D100 camera. The accuracy for a single range measurement is specified at 0.01 m by the manufacturer. The resolution of the camera sensor is 3008 by 2000 pixels.

4.1. Data set Dresdner Frauenkirche

In the following, two view points of the data set *Dresdner Frauenkirche* are used. Fig. 4 shows the photogrammetric images from the considered view points. Strong perspective variation is apparent between the two images as a result of the large baseline, a common feature of laser scanning networks. The described concept is applied with the parameter values listed in Table 1.

In Fig. 5, the principle of the proposed feature extraction is demonstrated. A part of an object scene with discontinuities and some perturbations in the upper region of the church facade is shown. Fig. 5a shows the *initial feature* points delivered by the SUSAN operator, while Fig. 5b represents the *accepted features* after checking the planarity and viewing direction with the proposed concept. As can be seen in this figure, *initial features* are rejected in areas of surface discontinuities along the edges.

With these *accepted features*, the correspondence search is carried out. Table 2 summarizes the results of the different processing steps.

The correspondence search is based on the assumption that the features with the highest similarity constitute the

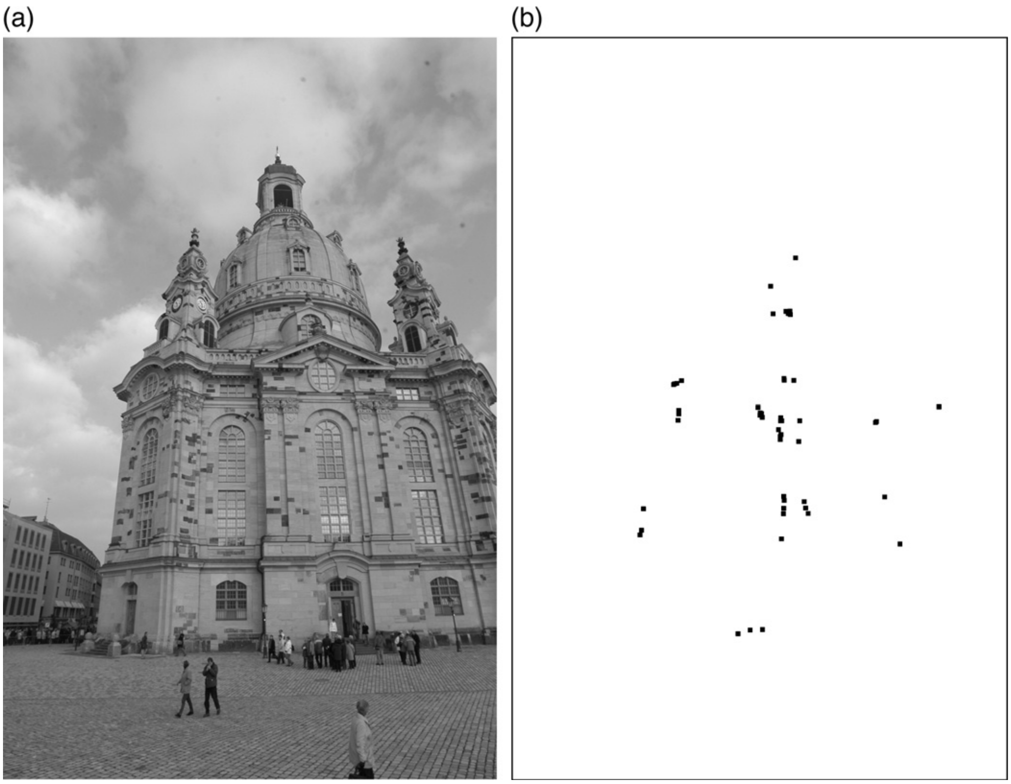

Fig. 8. Distribution of the consistent correspondences in image space of view point 1. (a) Image. (b) Consistent correspondences distribution.

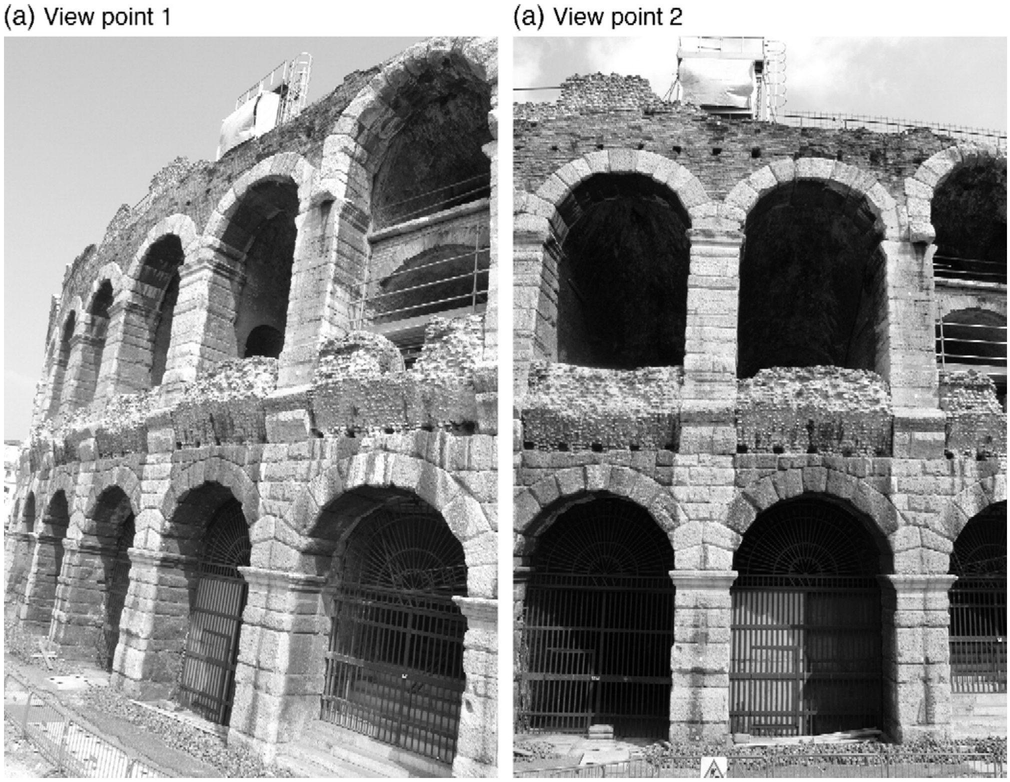

Fig. 9. Considered view points of the *Verona Arena*.

most *consistent correspondences*. This will be analysed in the following before the final results are discussed.

Due to known registration parameters, the amount of 91 *consistent correspondences* is known. The *candidate correspondences* with a correlation coefficient of at least 0.6 include 49 *consistent correspondences*.

In Fig. 6, the histogram of the correlation coefficient of the known 49 *consistent correspondences* is shown in contrast to all *candidate correspondences*. This figure confirms the assumption of the correspondence search concept, that *candidate correspondences* with a high similarity have a high likelihood of being *consistent correspondences*.

Samples of the rectified image pairs are shown in Fig. 7 for *consistent correspondences* with the highest (a, b) and the lowest (c, d) correlation coefficient. The rectified images of the pair with the lowest coefficient differ due to occlusion.

Fig. 8 shows the distribution of the 49 *consistent correspondences* in the image space of view point 1.

To carry out the RANSAC algorithm, the minimum size of 3 correspondences to determine the transformation parameter is chosen randomly from the sorted *candidate correspondences* with a minimum cross-correlation

Table 3
Used parameter for the processing steps

SUSAN t (view point 1)	40 grey values
SUSAN t (view point 2)	50 grey values
SUSAN s	50
SUSAN mask size	10×10 pixels^2
Viewing direction, max. α	60°
Planarity, max. σ_0	0.1 m
Point search mask size	50×50 pixels^2
Rectified image size	30×30 surfels^2
Surfel scale	8 mm
RANSAC error tolerance	0.2 m
RANSAC performed number of tries	166
RANSAC suggested number of consistent correspondences	916

Table 4
Results of the data set *Verona Arena*

Initial features of view point 1	7208
Initial features of view point 2	3386
Accepted features of view point 1	2046
Accepted features of view point 2	1445
Determined consistent correspondences	928

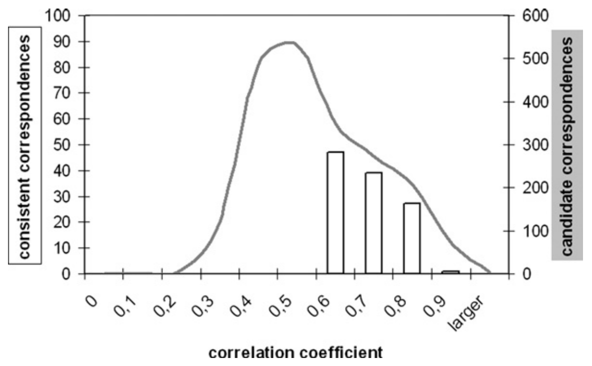

Fig. 10. Histogram of consistent correspondences (bars) and candidate correspondences (line).

coefficient of 0.6 including the analysed 49 *consistent correspondences*. An error tolerance of 0.2 m for the maximum Euclidean distance is selected to determine *consistent correspondences*. After 17 performed tries, 91 *consistent correspondences* could be determined.

4.2. Data set Verona Arena

The second data set *Verona Arena* is used to check the repeatability of the results. The photogrammetric images of the two considered view points are shown in Fig. 9. The perspective deviations are more pronounced than in the first data set, with the texture displaying more potential ambiguities. Also, different image scales exist. For the processing, the parameter values listed in Table 3 have been used.

Because of the high contrast and structure in the texture, the threshold t for the brightness of the SUSAN operator is set higher compared to the first test data set. A different threshold value is also set for each of the photogrammetric images of the view points in order to obtain about the same number of *initial features* within the overlapping area. Still, the total number of *initial features* of view point 1 is higher, as shown in Table 4, because view point 1 covers a larger area of the Arena than view point 2 does.

Compared to the first data set, the resulting values of the different calculation steps show that a larger amount of *initial features*, as well as *accepted features*, are delivered by the processing procedure.

Again, the assumption that the features with the highest similarity constitute the most *consistent correspondences* will be analysed in the following. Due to known registration parameters, it is known that 916 *consistent correspondences* exist and that the *candidate correspondences* with a correlation coefficient of at least 0.6 include 114 *consistence correspondences*.

In Fig. 10 the histogram of the 114 *consistent correspondences* is shown in contrast to all *candidate correspondences*.

The assumption of the correspondence search concept, that *candidate correspondences* with a high similarity have a high likelihood of being *consistent correspondences* is again confirmed.

It should be mentioned, however, that due to strong perspective deviations, a remarkable amount of *consistent correspondences* also have a correlation coefficient of less than 0.6.

Again, the rectified images of the consistent correspondences with the highest and lowest correlation coefficient are shown in Fig. 11 and the distribution of the 114 *consistence correspondences* is shown in Fig. 12. The feature distribution of the *consistent correspondences* covers the whole overlapping area of both view points.

For applying the RANSAC algorithm, the minimum size of 3 correspondences to determine the transformation parameters is again randomly chosen from the sorted *candidate correspondences* with a minimum correlation coefficient of 0.6 including the analysed 114 *consistent correspondence*. An error tolerance of 0.2 m for the maximum Euclidean distance is selected to determine

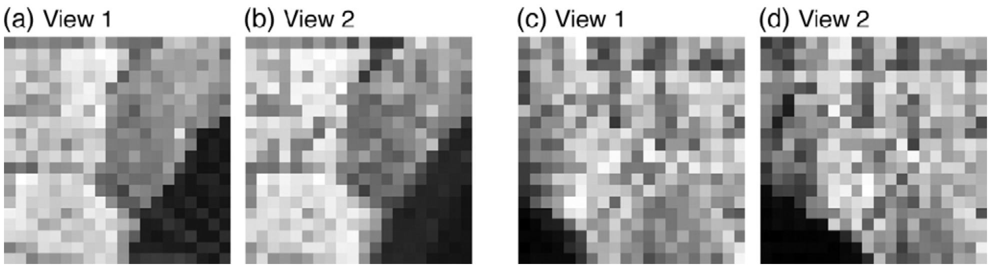

Fig. 11. Rectified images of the consistent correspondences. (a),(b) Highest correlation coefficient (ρ_{fc}=0.90). (c),(d) Lowest correlation coefficient (ρ_{fc}=0.60).

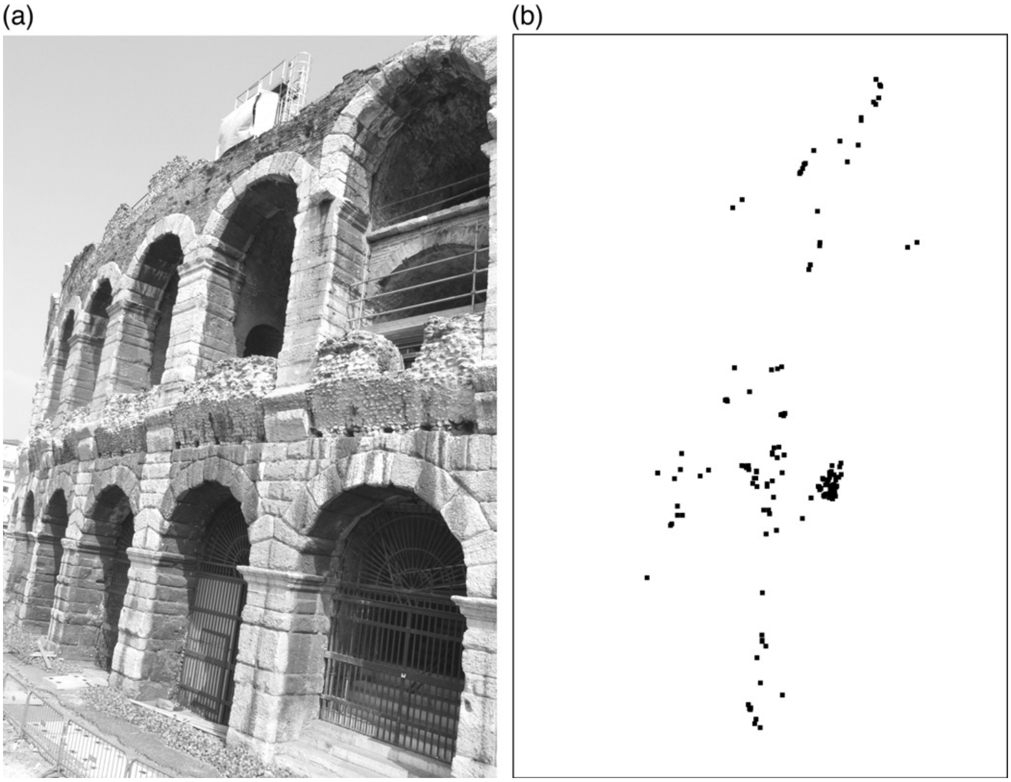

Fig. 12. Distribution of the consistent correspondences in image space of view point 1. (a) Image. (b) Consistent correspondences distribution.

consistent correspondence. After 166 performed tries 928 *consistent correspondences* could be determined.

5. Concluding remarks

In this research, the strength of the combination of laser range data and photogrammetric images of hybrid scanning systems is shown for registration purposes. A concept is developed for feature based data registration without the need of approximate values for the orientation parameter. It illustrates that an adequate feature distribution is available over the complete overlapping area of both view points, which is promising for a robust solution of the registration.

The concept based on the assumption that adequate texture in geometrically planar area is available and rectified images can be generated to describe the features in object space. In the case of the hybrid scanning device, which is principally used for building facades recording, the parameter space can be reduced to five parameters and thus rectified images with identical image grid orientation can be generated to describe features view point invariant. False correspondences occur in cases of ambiguous and weak texture. The introduced tangential planes are only sufficient in cases of small areas. To improve the similarity of the rectified images, the local geometry can be reconstructed with the laser scanner data to generate ortho images. In order to be able to register data sets, which are not recorded by a scanning device which stands upright, the proposed feature description (5 parameter space) can be exchanged with an invariant description in the 6 parameter space, e.g. Lowe (2004). Another future research target is the simultaneous consideration of the intensity data provided by the hybrid laser scanner for *consistent correspondence* determination.

Acknowledgements

Credits go to Christian Heipke from the Institute of Photogrammtry and GeoInformation (IPI), Leibniz University Hannover, Germany for the helpful and informative discussions and Nikolaus Studnicka from the RIEGL GmbH, Austria for providing the hybrid laser scanning data sets.

References

Akca, D., 2005. Registration of point clouds using range and intensity information. In: Grün, A., Van Gool, L., Pateraki, M., Baltsavias, M.

(Eds.), International Workshop on Recording, Modeling and Visualization of Cultural Heritage, Ascona, Switzerland, May 22–27. Taylor and Francis/Balkema, Leiden, pp. 115–126.

Besl, P., McKay, N., 1992. A method for registration of 3-D shapes. IEEE Transactions on Pattern Analysis Machine Intelligence 14 (2), 239–256.

Brusco, N., Andreettoo, M., Giorgi, A., Cortelazzo, G.M., 2005. 3D registration by textured spin-images. Proceedings of the Fifth International Conference on 3-D Digital Imaging and Modeling (3DIM05), Ottawa, Ontario, Canada, pp. 262–269.

Chen, Y., Medioni, G., 1992. Object modeling by registration of laser scanner data. Image and Vision Computing 10 (3), 145–155.

Chen, C.-S., Chen, C.-S., Cheng, J.-B., 1999. Ransac-based darces: A new approach to fast automatic registration of partially overlapping range images. IEEE Transactions on Pattern Analysis and Machine Intelligence 21 (11), 1229–1234.

Feldmar, J., Ayache, N., Betting, F., 1994. 3D–2D projective registration of free-form curves and surfaces. Technical Report INRIA Epidaure, vol. 2434. December, 47 pp.

Fischler, M., Bolles, R., 1981. Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. Communication ACM 24 (6), 381–395.

Förstner, W., 1986. A feature based correspondence algorithm for image matching. International Archives of Photogrammetry and Photogrammetry 26 (Part B3/3), 13–19.

Gelfand, N., Mitra, N.J., Guibas, L.J., Pottmann, H., 2005. Robust global registration. In: Desbrun, M., Pottmann, H. (Eds.), Eurographics Symposium on Geometry Processing, pp. 197–206.

Godin, G., Laurendau, D., Bergevin, R., 2001. A method for the registration of attributed range images. Proceedings of the Third International Conference on 3-D Digital Imaging and Modeling (3DIM01), Quebec, pp. 179–186.

He, W., Ma, W., Zha, H., 2005. Automatic registration of range images based on correspondence of complete plane patches. Proceedings of the Fifth International Conference on 3-D Digital Imaging and Modeling (3DIM05), pp. 470–475.

Huber, D., Hebert, M., 2003. Fully automatic registration of multiple 3D data sets. Image and Vision Computing 21 (7), 637–650 (July).

Johnson, A., Hebert, M., 1998. Surface matching for object recognition in complex three-dimensional scenes. Image and Vision Computing 16 (9–10), 635–651.

Johnson, A., Hebert, M., 1999. Using spin images for efficient object recognition in cluttered 3D scenes. IEEE Pattern Analysis and Machine Intelligence 21 (5), 433–449.

Johnson, A., Kang, S., 1997. Registration and integration of textured 3-D data. International Conference on Recent Advances in 3-D Digital Imaging and Modeling, pp. 234–241.

Litke, N., Droske, M., Rumpf, M., Schröder, P., 2005. An image processing approach to surface matching. In: Desbrun, M., Pottmann, H. (Eds.), Eurographics Symposium on Geometry Processing, pp. 1–10.

Lowe, D.G., 2004. Distinctive image features from scale-invariant keypoints. International Journal of Computer Vision 60 (2), 91–110.

Luck, J., Little, C., Hoff, W., 2000. Registration of range data using a hybrid simulated annealing and iterative closest point algorithm. Proceedings of the 2000 IEEE International Conference on Robotics and Automation San Francisco, CA April 2000, vol. 4, pp. 3739–3744.

Maas, H., 2002. Methods for measuring height and planimetry discrepancies in airborne laser scanner data. Photogrammetric Engineering and Remote Sensing 68 (9), 933–940.

Moravec, H., 1977. Towards automatic visual obstacle avoidance. Proc. of 5th International Joint Conference of Artificial Intelligence. MIT, Cambridge, MA, p. 584. August.

Press, W., Teukolsky, S., Vetterling, W., Flannery, B., 1992. Numerical Recipes in C — the Art of Scientific Computing, 2 ed. Cambridge University Press. 965 pp.

Pulli, K., 1997. Surface Reconstruction and Display from Range and Color Data. Ph.D. thesis, University of Washington, 124 p.

Roth, G., 1999. Registering two overlapping range images. Proceedings of Second International Conference on 3D Digital Imaging and Modeling (3DIM'99), pp. 191–200.

Silva, L., Bellon, O., Gotardo, P., Boyer, K.L., 2003. Range image registration using enhanced genetic algorithms. Proceedings of the International Conference on Image Processing 3-II, pp. 711–714.

Silva, L., Bellon, O., Boyer, K.L., 2005. Robust range image registration using genetic algorithms and the surface interpenetration measure. World Scientific Series on Machine Perception Artificial Intelligence, vol. 60. 176 pp.

Smith, S., Brady, J., 1997. SUSAN — a new approach to low level image processing. International Journal of Computer Vision 23 (1), 45–78.

Vanden Wyngaerd, J., Van Gool, L., 2002. Automatic crude patch registration: toward automatic 3D model building. Computer Vision and Image Understanding 87 (1–3), 8–26.

Weik, S., 1997. Registration of 3-D partial surface models using luminance and depth information. NRC '97: Proceedings of the International Conference on Recent Advances in 3-D Digital Imaging and Modeling. IEEE Computer Society, Washington, DC, USA, pp. 93–100.

Wendt, A., Heipke, C., 2005. A concept for the simultaneous orientation of brightness and range images. In: Grün, A., Van Gool, L., Pateraki, M., Baltsavias, M. (Eds.), International Workshop on Recording, Modeling and Visualization of Cultural Heritage, Ascona, Switzerland, May 22–27. Taylor and Francis/ Balkema, Leiden, pp. 451–457.

Zhang, Z., 1994. Iterative point matching for registration of free-form curves and surfaces. International Journal of Computer Vision 13 (2), 119–152.