REGISTRATION OF TERRESTRIAL LASER SCANNING DATA USING PLANAR PATCHES AND IMAGE DATA

Christoph Dold, Claus Brenner

Institute for Cartography and Geoinformatics
Leibniz University of Hannover
Appelstr. 9A, 30167 Hannover
{christoph.dold},{claus.brenner}@ikg.uni-hannover.de
http://www.ikg.uni-hannover.de/3d-citymodels.html

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ABSTRACT:

The fully automatic registration of terrestrial scan data is still a major topic for many research groups. Existent methods used in commercial software often use artificial markers which are placed in the scene and measured from each scan position. This is a reliable method to get the transformation parameters, but it is not very efficient. These manual or semi-automated registration techniques should be substituted by new methods in order to make terrestrial laser scanning also profitable for larger projects. In this paper we present a registration method based on the extraction of planar patches from 3D laser scanning data. A search technique is used to find corresponding patches in two overlapping scan positions. Since laser scanning instruments are nowadays often equipped with an additional image sensor, we also use the image information to improve the registration process. Assuming that the calibration parameters of a hybrid sensor system are known, the extracted planar patches can be textured automatically. The correlation between corresponding textured patches can be calculated and the registration method is improved by shifting the patches until they fit best.

1. INTRODUCTION

The use of terrestrial laser scanners for object acquisition is increasing. With laser scanners a dense and accurate three-dimensional point cloud of the surface of an object is recorded. For example the instruments are used for architectural purposes, detailed city modeling, monitoring measurements, documentation of historic buildings and monuments and also terrain surveying. One problem in the data acquisition process is the registration process of multiple scans. Single scans from different scan positions are acquired within a local coordinate frame defined by the instrument. For visualization and further data processing of the point cloud the single scans must be transformed into a common coordinate frame. This process is termed as registration.

Different approaches for solving the registration task are existing and also used in practice. Using the standard technique, several artificial targets are measured by the laser scanning instrument from each scan position. Such targets are often labeled with retro-reflective foil, which makes it easier to detect them in the scans. Then identical targets are identified and the measured coordinates are used to calculate the transformation parameters. This registration technique is usually supported by the operating software of commercial terrestrial laser scanning instruments (Ullrich et al., 2003). Different markers like spheres, retro-reflective cylinders or planar markers are used as tie points between the scan positions. One drawback is the additional required survey time for the registration process. The reason is that the markers must be distributed in the field and additionally scanned with a high resolution in order to achieve a sufficient accuracy for the transformation parameters. Also the distribution of the targets in the survey area often is a problem. Due to accessing restrictions of the surveyed objects, a distribution of the targets often is possible only within a small sector of the survey area, usually near the ground. This affects adversely the quality of the registration when scanning high buildings or constructions in particular.

Another registration technique is the direct georeferencing of the laser scanner instrument. This method is especially used for mobile systems, where the laser scanner instrument is mounted on a vehicle. External sensors, usually a combination of a GPS and an IMU sensor are used for tracking in order to achieve orientation data. For example Talaya et al. operated a laser scanning instrument as a pushbroom sensor on a moving vehicle (Talaya et al., 2004). Asai et al. also combinate a terrestrial laser scanning instrument with a GPS/IMU system and laser scans are recorded from a vehicle in a stop and go method (Asai et al., 2005). The major drawback of this technique are the high costs for the external sensors and the synchronisation between the external sensors and the laser scanning instrument.

Many research groups aim at solving the registration task fully automatically without the need of artificial markers or external sensors. Various registration algorithms have already been proposed. Often existing algorithms like the iterative closest point (ICP) algorithm (Besl and McKay, 1992) and various variants are integrated in registration processes. Since ICP requires good initial values, the algorithm is often used for a fine registration stage in order to improve previous achieved results. But also many algorithms based on feature matching are proposed to compute the transformation between overlapping scan positions. The presented methods usually calculate features, which are derived from the scan data and matched afterwards. Either only few significant features are extracted from the scan data or lots of less significant features are derived. The used matching strategy required for registration is then adapted to the derived features.

A method for automatic point cloud registration is presented by Rabbani et al. (Rabbani and van den Heuvel, 2005). They model simple objects like planes, cylinders and spheres in industrial environments and use the geometric information of these models instead of artificial targets. A constrained search detects corresponding objects in a pair of scans, which are used to determine the transformation parameters. He et al. (He et al., 2005) present a method based on extracted planes. Only so called *complete plane patches* are used to compute the transformation. Such planes must not be occluded by other points in the same range image and must not be located on the boundary. Corresponding planes are searched using an interpretation tree proposed by Grimson and Lozano-Pérez (Grimson and Lozano-Pérez, 1987).

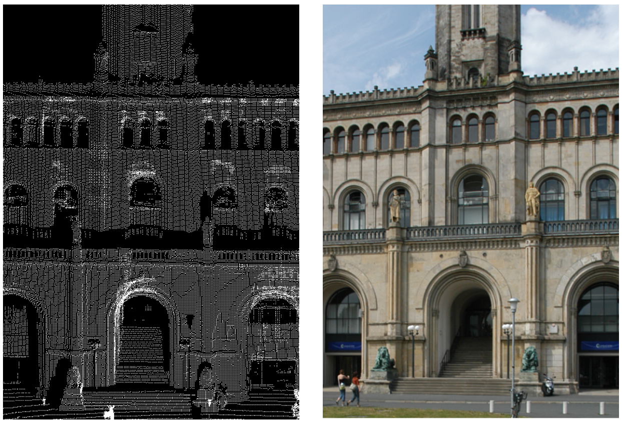
An area, co-feature and two-matched-feature constraints are introduced to reduce search space. Bae and Lichti (Bae and Lichti, 2004) propose a method for the registration of partially overlapping point clouds using geometric primitives and neighbourhood search. The change of geometric curvature and normal vectors of the surface formed by a point and its neighbourhood are used to determine the possible correspondence of point clouds. Another registration algorithm divided in a coarse and fine matching stage is presented in (Mian et al., 2004). The authors suggest an automatic correspondence technique for pair wise registration of different views of a free-form object. They define local 3-D grids over the object's surface and represent the surface inside a grid by a fourth order tensor. The derived tensors are matched using a correlation technique. The solution is refined using a variant of the ICP algorithm. Gruen and Akca propose a method that estimates the transformation parameters between 3D surface patches by minimizing the euclidean distances between corresponding surfaces by least squares. The matching is achieved by minimizing a goal function. Since the functional model for least squares matching is non-linear, initial approximations for the parameters must be provided (Gruen and Akca, 2004). An image based registration method for 3D-range data is proposed by Bendels et al. They use 2D-image features with intrinsic scale information for finding characteristic areas. The correspondent 3D information from the range data is then used for a pairwise two-step registration method. Finally a multiview registration is performed using graph relaxation (Bendels et al., 2004).

Our registration method proposed in this paper is based on extracted planar patches from 3D terrestrial laser scanning data. The matching of correspondent patches is supported by geometrical features derived from the data. We also work with a hybrid sensor system and also take advantage of recorded image data. In the next section hybrid data acquisition sensors and the combination of 3D point data and 2D image data are described. Then the registration technique using geometric constraints and finally the integration of the image data into the registration process is discussed. We conclude this paper with a summary and outlook.

2. HYBRID SENSORS

Laser scanning sensors are often combined with image sensors. Such hybrid laser scanning and imaging sensors are common for terrestrial surveying purposes. The 3D information captured by the laser scanner instrument is complemented with digital image data. In general the resolution of the data collected from the image sensor is higher than the resolution of the laser scanner data. The image data can be used for coloring the laser scanner data, texturing extracted patches and for measurements. For instance Becker et al. (Becker et al., 2004) describe a system for processing laser scanning and photogrammetric data simultaneously. There the point cloud delivers the missing third dimension in the images. Figure 1 shows an example for the complementary data of a hybrid sensor system.

Nowadays many scanner systems are equipped with an additional image sensor. Different techniques for the combination of laser scanners with digital cameras are used. One method is the integration of a camera in the body of the scanner. Another concept is to mount a digital camera externally on the top of a laser scanning instrument. Both techniques have several advantages and disadvantages. The major drawback of externally mounted camera units is the weak calibration of such systems. The advantage lies in the flexibility of the used sensors. Depending on the application, cameras with a different resolution can be used for data acquisition. Concepts for the calibration task of such sensors are discussed in (Wendt and Dold, 2005).



(a) Scan data (b) Image data

Figure 1. Different resolution of laser scanning (0.12°) and image data (0.03°)

The complementary laser scanning and image data provides valuable information for processing algorithms. By using the combined data sets a better automation in processing and more reliable results are achieved. In the following some main aspects of data fusion are mentioned and it is shown shortly how to combine laser scanning and image data. The sensors are related to each other by a fixed connection, but each sensor defines by its position and orientation an own coordinate frame. Figure 2 shows the laser scanning and camera coordinate frames.

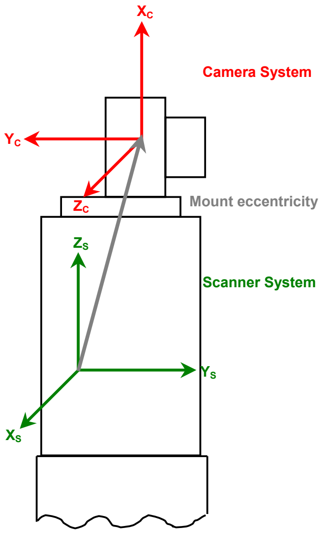


Figure 2. Laser scanning and camera coordinate frame

The laser scanning frame is termed as $\mathbf{X}_S$ and the camera frame as $\mathbf{X}_C$. The transformation between two coordinate frames contains a rotation and a translation component. The scale is defined by the laser scanning device. It is not required for the transformation, since the camera simply accepts the scale of the laser scanning device. The transformation is termed as mounting matrix and equation 1 shows the parameters in homogeneous coordinates.

$$M_{Mount} = \begin{pmatrix} R & T \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (1)$$

The image acquisition is usually done by several images in different directions, if the image sensor is mounted externally. Therefore the hybrid sensor in addition is rotated around the z-axis of the scanning system. This means that additional to the mounting eccentricity a rotation of the sensor must also be considered for calculating the transformation between the sensor systems. Equation 2 defines this rotation component.

$$M_{Camera} = \begin{pmatrix} \cos\phi & -\sin\phi & 0 & 0 \\ \sin\phi & \cos\phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (2)$$

Finally, the overall transformation chain between a 3D point in the laser scanning and camera coordinate frame is given by:

$$\mathbf{X}_C = M_{Mount} \cdot M_{Camera}^{-1} \cdot \mathbf{X}_S \qquad (3)$$

In a last transformation step the 3D coordinates of the camera system must be related to the 2D image coordinates. The transformation is given by a camera model, used in the Open Source Computer Vision library (Intel, 1999-2001). The relationship between a 3D point in the camera system and its image projection is given by the formula:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} f_u & 0 & c_u \\ 0 & f_v & c_v \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} \qquad (4)$$

In equation 4, u, v, w are undistorted homogeneous image coordinates, f_u and f_v are the focal length in both image directions and c_u and c_v are the coordinates of the principal point. The different focal lengths are used to cope with different pixel sizes in x- and y-direction. Usually the image coordinates must also be corrected by using the significant lens distortion parameters. The distorted image coordinates are calculated by the functions

$$\begin{aligned} u^{'} &= f\left(u, v, f_u, f_v, c_u, c_v, k_1, k_2, k_3, k_4, p_1, p_2\right) \\ v^{'} &= f\left(u, v, f_u, f_v, c_u, c_v, k_1, k_2, k_3, k_4, p_1, p_2\right) \end{aligned} \qquad (5)$$

whereas k_1-k_4 are radial and p_1-p_2 tangential lens distortion parameters.

Now the laser scanning and image sensor are fully oriented and we are able to transform each 3D point of the laser scanning coordinate frame into 2D image coordinates. This transformation chain, for instance, can be used to assign a color value to each measured 3D point.

3. REGISTRATION METHOD

Since terrestrial laser scanning data often contains more than a million points per scan, registration algorithms based on all points are not suitable for such data. Also, due to the scanning mechanism, it is not assured that the same point is exactly scanned twice in different scans. For this reason objects are extracted from the scan data and in a second step these objects are matched.

3.1 Determination of the transformation parameters using planar patches

Our suggested registration algorithm does not need artificial targets. Planar patches are derived from the single scan positions of the laser scanner data. The patches are estimated fully automatically using a region growing algorithm, which was adapted to handle 3D laser scanning data. The algorithm is described in detail in (Dold and Brenner, 2004).

In the second step corresponding planar patches between two scan positions are selected from the overlapping areas of the scans. The transformation parameters are calculated on the basis of the matched planar patches. At least three corresponding pairs of planar patches are required to determine all six degrees of freedom. The calculation of the transformation parameters is split into the determination of the rotation component and a subsequent determination of the translation component.

The rotation component can be calculated using vector operations from two corresponding planar patches, as long as the patches are not parallel. For more than two pairs the calculated parameters are averaged. Another method to determine the rotation component is to solve an optimization task using quaternions. In this case the rotation parameters are mathematically averaged, if more than two pairs of planar patches are used. The determination of the rotation component is reduced to the solution of an eigenvalue problem. The determination of the translation component is done using an adjustment method. It is assumed that the normal vectors of corresponding planar patches are equal up to a measurement error. The shifted planes of a unregistered scan position coincide with the corresponding planes of the reference scan position. The translation is defined by three pairs of corresponding planes. If more than three pairs are available, a least squares adjustment is performed (Jiang and Bunke, 1997; Dold and Brenner, 2004).

The problem in the registration of terrestrial scan data using corresponding planar patches lies on the one hand in the matching of the patches and on the other hand, that for a successful calculation of the transformation parameters planar patches are required whose normal vectors cover all major directions in space.

The matching of pairs of planar patches can be automated using a search technique. The directions of the patch normal vectors are scene dependent and cannot be influenced. From a certain number of planes it is necessary to reduce the search, because of the high number of possibilities to explore. At this point geometrical and laser scanning attributes are used to exclude implausible correspondences.

3.2 Matching of planar patches by an unrestricted search technique

If an unrestricted search is used, all possible variations of correspondences are taken into account. Using combinatorics, the number of possible combinations for three pairs of corresponding patches can be calculated. We assume that from two overlapping laser scanning positions S_1 and S_2 a set of p and q extracted planar patches and their normal vectors are given. If the transformation parameters are calculated from k $(k \geq 3)$ identical patches, then the total number of possible combinations is:

$$\binom{p}{k} \cdot \binom{q}{k} \cdot k! \qquad (6)$$

We have p over k possibilities from the first scan position and q over k from the second. To pick a combination of patches, the permutations of the k identical planes must also be considered, which yields an additional factor of $k!$. According to equation 6, the search space will reach an enormous size, even for only three identical patches as shown in table 1.

Patches per scan	Possibilities
10	86 400
20	7 797 600
30	395 606 400

Table 1. Number of possible combinations for a unrestricted search using three identical patches

Using an unrestricted search technique, the algorithm explores all possibilities and then the solution with the smallest error is regarded as the best solution. One improvement is to cut off the search, rather than exploring all possibilities. In this case the algorithm terminates if an acceptable result is found. But nevertheless, such an approach is only practicable for a few extracted planar patches per scan position because of the huge search space.

In order to reduce the search space another improvement of the algorithm was implemented. Therefore efforts in a preselection of suitable patches for the calculation of the transformation parameters have been made. As mentioned before, a reliable determination of the parameters is possible, if the normal vectors of a triple of planar patches are perpendicular and consequently cover all directions in space. Thus the triple product of the normal vectors is calculated. It results in the volume given by the parallelepiped of the vectors. For normalized vectors the absolute value of the product results in 1, if the vectors are perpendicular.

Thus, the triple product is calculated for all combinations of each scan position. A list of $\binom{p}{3}$ and $\binom{q}{3}$ triples of patches are obtained. The list is sorted according to the value of the triple product and then the transformation parameters are calculated for each combination. Again the permutations must also be considered. The advantage lies in the quicker cut off of the search, because most promising solutions are attempted in the beginning of the search.

3.3 Geometrical and laser scanning attributes as constraints

A significant reduction of the number of combinations in the matching process is achieved by using geometrical constraints. Attributes are derived from the planar patches which allow to find corresponding matches without the exploration of the the whole search space. For the calculation of geometrical features the convex hull of points supporting a planar patch is derived at first. Therefore the 3D points are projected onto the planar patch and the coordinates are transformed in a way, that one coordinate axis coincides with the patch normal. So 2D points are achieved and a 2D convex hull is calculated. The following features derived from laser scanning data are determined:

- **Area**
  The area of the convex hull which forms a closed polygon is calculated by:

$$F = \frac{1}{2} \cdot \sum_{i=1}^{n} \left((x_i + x_{i+1}) \cdot (y_i - y_{i+1}) \right) \qquad (7)$$

- **Length of the boundary**
  Also the length of the boundary is simply derived from the convex hull according to:

$$L = \sum_{i=1}^{n} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \qquad (8)$$

- **Bounding box**
  For calculating the bounding box the longest edge in the convex hull is searched. Along this edge the box is oriented and the size of the box is determined by transforming the points referred to the edge and searching the minimum and maximum values. A characteristic feature of the bounding box is the ratio between the edges.

- **Mean intensity value**
  Usually all laser scanner instruments also record the intensity of the reflected laser beam. The intensity value depends on the surface of the measured object. Assuming the planar patches consist of the same surface conditions over the whole area, the intensity of the reflected laser beam is almost constant. So a mean intensity value is also a characteristic feature of an extracted planar patch.

Figure 3 shows on the left side the segmentation results of two different scan positions. Since in addition to the segmentation image the complete 3D information of the object is present from the laser measurements, the segmented planar patches can be plotted in their correct geometry. This is shown on the right side of the figure. Patches derived from different point of views have a similar geometry. Table 2 contains the values of the derived features from the respective patches. The values imply that using only one feature may lead to wrong conclusions. But if several features are combined, the matching process yields correct correspondences. By excluding combinations of features with a bad match, the number of possible combinations is significantly reduced and the solution for the transformation parameters is determined more efficiently.

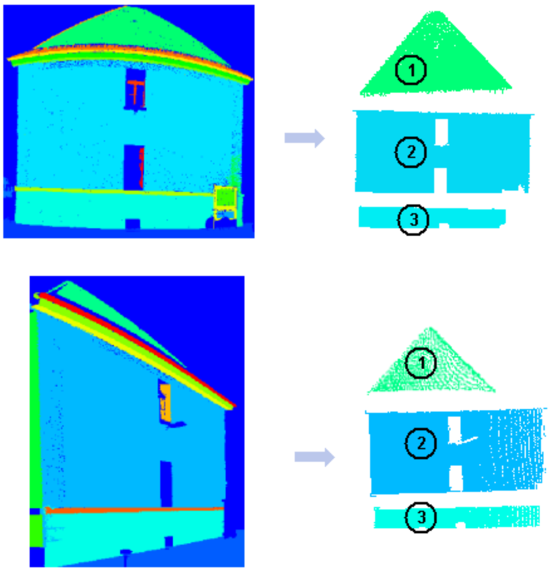


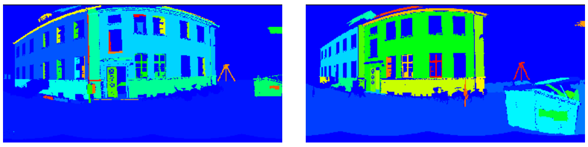
Figure 3. Segmentation result (left) and example for derived geometry (right) of two different scan positions

	Scan 1			
	Area	**Length**	**BB (L/W)**	**Intensity**
Patch 1	52.2	30.9	11.94 / 7.19	0.21
Patch 2	90.7	40.8	14.31 / 6.47	0.36
Patch 3	19.1	26.1	11.67 / 1.65	0.34
	Scan 2			
	Area	**Length**	**BB (L/W)**	**Intensity**
Patch 1	30.6	25.6	10.23 / 5.68	0.22
Patch 2	99.8	42.1	14.45 / 7.75	0.32
Patch 3	22.8	29.5	13.18 / 1.84	0.29

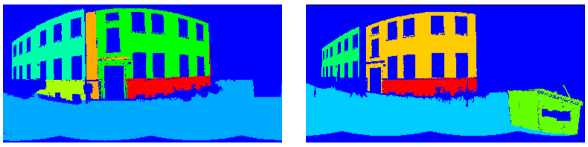
Table 2. Extracted feature constraints

3.4 Results

We recorded two scan positions of a building from different point of views and orientations using a Riegl LMS laser scanning instrument. The unregistered scan data is depicted in figure 5 (a). Figure 4 shows the segmentation results. The images (a) and (b) show variant 1, where a couple of extracted planar patches in each scan position has been used. In images (c) and (d), variant 2, only a few extracted planes have been used for the registration process. The critical difference of variant 2 in comparison to variant 1 is the fact, that only planar patches are extracted, whose normal vectors cover only two major directions of the coordinate axes. This situation simulates a typical street scene.



(a) Patches scan 1 (b) Patches scan 2



(c) Reduced patches scan 1 (d) Reduced patches scan 2

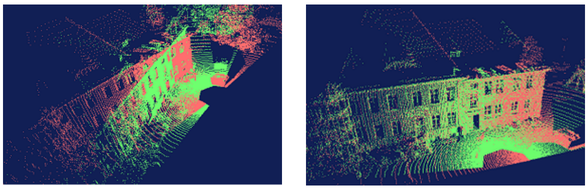
Figure 4. Extracted planar patches from the laser scanning data

Table 3 shows the results of the applied registration process. The results of variant 1 are very close to the reference values. Planar patches in every direction in space are available and a stable rotation and translation component is computed. In variant 2 only the rotation component is well determined, since two planar patches are enough to compute the respective angles. But significant differences are observed in the translation component. This results from the lack of planar patches being perpendicular oriented to the dominant directions. This problem is depicted in figure 5 (c). It shows the correct orientation of the laser scanning data, but the translation component is erroneous. Part (b) of the figure shows the correctly registered scan data, that results from the registration process of variant 1.

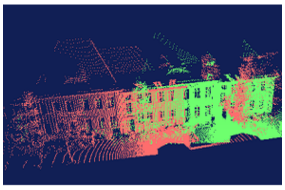
	$\omega[^\circ]$	$\phi[^\circ]$	$\kappa[^\circ]$	X [m]	Y [m]	Z [m]
Ref.:	0.65	0.17	20.78	1.36	5.54	0.15
Var. 1:	0.86	0.14	20.81	1.34	5.52	0.12
Var. 2:	0.55	-0.27	20.28	-2.64	-12.86	-0.30

Table 3. Determined transformation parameters

But the registration algorithm should be able to handle data similar to the one in variant 2. Especially when measuring houses and streets, the dominant extracted planar surfaces within these scenes often cover only two main directions in space. Therefore additionally to the laser scanning data acquired image data by a hybrid sensor system is integrated into the registration process, in order to stabilize the result.



(a) Unregistered (b) Registered



(c) Erroneous Translation

Figure 5. Result of registration using planar patches

4. INTEGRATION OF IMAGE DATA

Our intention is to record complete street scenes using the terrestrial laser scanning technique. Therefore the system is mounted on a vehicle and the data is recorded via a stop and go data acquisition method. Thus the registration technique using extracted planar patches is well suited for this task in general. But as depicted in the scheme of figure 6, typical street scenes contain buildings in a row parallel to the street axis. After extracting planar patches from such scenes, the dominant directions of the normal vectors point to the directions across the streets and upright coming from the facades of houses and the ground or street (depicted by the green one sided arrows). Due to the lack of characteristic planar patches where the normal vectors should point along the street, the transformation between different scan positions is underdetermined as shown in section 3.4. This fact is highlighted in figure 6 by the red double ended arrow.

At this point in addition to the laser scanning measurements, image data delivers valuable information. Assuming that the calibration parameters of the hybrid sensor system are known, the extracted patches can be textured automatically. The idea is now to calculate a correlation coefficient between two corresponding textured planar patches. The result can be used to verify the correspondence of the patches and furthermore the uncertain translation component of the transformation can be determined by shifting and correlating the texture patches until they fit best.

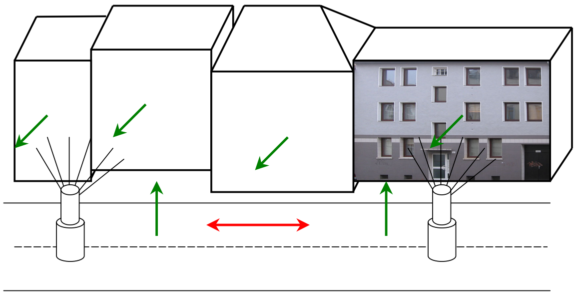


Figure 6. Scheme of a typical street scene

We calculate textured patches from each scan position that have the same geometric resolution. Therefore we use the extracted bounding box feature and define a grid over this box in a given resolution. Using the equations 3, 4 and 5 the respective position of the defined raster in the image is calculated and the color values are assigned to the grid. The result of this process is a planar textured grid containing the complete 3D information of the scene and image data in a defined geometrical resolution. Then the corresponding patches are treated as an image and the correlation between two patches is calculated using the standard correlation formula. In order to find the best correspondence between two images, one image is shifted over the other until the calculated correlation value r reaches a maximum. Now we obtain from the underlying grid data information about the values of the shift. The additional observations are integrated into the computation of the searched transformation parameters.

In the example of section 3.4, the results for variant 2 can be improved using the described technique. Four pairs of corresponding planar patches have been textured with a resolution of 2cm. The position of the maximum correlation for each pair of images was calculated. The resulting shift in pixel coordinates can be directly transformed into 3D using the underlying grid. Then the translation component of the transformation is corrected using the 3D information from the shift and also from the vertices of the textured patch. The updated averaged translation component using the four patches results in:

$$T_{updated} = \begin{pmatrix} 1.45 \\ 5.49 \\ 0.22 \end{pmatrix} \tag{9}$$

Comparing to the results depicted in table 3, the erroneous translation component is corrected using the additional image data. The problem of the misalignment coming from the lack of planar patches being perpendicular orientated is solved.

The information obtained from the image correlation is only usable, if the content of the textured patches is suitable for a correlation technique. Difficulties arise from repetitive patterns in building facades. In this case the correlation technique may yield ambiguous solutions. But if facades are correlated, which contain the complete window structure and also doors or other objects, the facades usually contain enough contrast and a unique solution is detected. A disadvantage of such large texture patches is the increasing computation time for the search of the maximum correlation value. But a few patches are sufficient to verify or to compute the correction of the translation component and the proposed method can be adopted to most scenes efficiently.

5. SUMMARY AND OUTLOOK

We presented a registration technique based on extracted planar patches. The patches are derived using a specialized region growing algorithm. Corresponding planar patches are identified using a search strategy. In order to reduce the search space most promising correspondences are processed in the beginning of the search by computing the triple product of possible candidates. Then geometric constraints based on a derived convex hull of each patch have been introduced in order to reduce the search space again. Successful matching results and possible problems were shown. For improving the registration process, a possibility to integrate image data collected from a hybrid sensor system is discussed. Additional registration information supporting translation component is obtained from correlated textured patches.

In the future we plan to put emphasis on the further integration of image data. The image data could also support the matching step and additional constraints can be derived and lead to a further reduction of the search space for identifying corresponding planar patches.

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REFERENCES

Asai, T., Kanbara, M. and Yokoya, N., 2005. 3D modeling of outdoor environments by integrating omnidirectional range and color images. In: Proceedings of the Fith International Conference on 3-D Digital Imaging and Modeling, Ottawa, Ontario, Canada, pp. 447–454.

Bae, K.-H. and Lichti, D. D., 2004. Automated registration of unorganised point clouds from terrestrial laser scanners. In: International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, Part B5, Proceedings of the ISPRS working group V/2, Istanbul, pp. 222–227.

Becker, R., Benning, W. and Effkemann, C., 2004. 3D Monoplotting, Kombinierte Auswertung von Laserscannerdaten und photogrammetrischen Aufnahmen. Zeitschrift für Vermessungswesen 2004(5), pp. 347–355.

Bendels, G. H., Degener, P., Wahl, R., Körtgen, M., and Klein, R., 2004. Image-based registration of 3D-range data using feature surface elements. In: Y. Chrysanthou, K. Cain, N. Silberman and F. Niccolucci (eds), The 5th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, Eurographics, pp. 115–124.

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

Dold, C. and Brenner, C., 2004. Automatic matching of terrestrial scan data as a basis for the generation of detailed 3D city models. In: International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, Part B3, Proceedings of the ISPRS working group III/6, Istanbul, pp. 1091–1096.

Grimson, W. E. L. and Lozano-Pérez, T., 1987. Localizing overlapping parts by searching the interpretation tree. In: IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 9(4), pp. 469–482.

Gruen, A. and Akca, D., 2004. Least squares 3D surface matching. In: H.-G. Maas and D. Schneider (eds), Proceedings of the ISPRS working group V/1, Panoramic Photogrammetry Workshop, Vol. XXXIV, Part 5/W16, Dresden.

He, W., Ma, W. and Zha, H., 2005. Automatic registration of range images based on correspondence of complete plane patches. In: Proceedings of the Fith International Conference on 3-D Digital Imaging and Modeling, Ottawa, Ontario, Canada, pp. 470–475.

Intel, 1999-2001. Open Source Computer Vision Library. Order number: 123456-001 edn, Intel Corporation.

Jiang, X. and Bunke, H., 1997. Gewinnung und Analyse von Tiefenbildern. Springer-Verlag Berlin Heidelberg.

Mian, A. S., Bennamoun, M. and Owens, R., 2004. Matching tensors for automatic correspondence and registration. In: Lecture Notes in Computer Science, Computer Vision - ECCV 2004, Vol. 3022, pp. 495 – 505.

Rabbani, T. and van den Heuvel, F., 2005. Automatic Point Cloud Registration Using Constrained Search for Corresponding Objects. In: 7th Conference on Optical 3-D Measurement Techniques, Vienna, Austria.

Talaya, J., Alamus, R., Bosch, E., Serra, A., Kornus, W. and Baron, A., 2004. Integration of a terrestrial laser scanner with GPS/IMU orientation sensors. In: International Archives of Photogrammetry and Remote Sensing, Vol. Commission 5, ThS 17, Istanbul.

Ullrich, A., Schwarz, R. and Kager, H., 2003. Multistationsausgleichung für ein Laserscanner-System mit aufgesetzter Kamera. Österreichische Zeitschrift für Vermessung und Geoinformation (VGI) 91. Jahrgang(4), pp. 271–280.

Wendt, A. and Dold, C., 2005. Estimation of interior orientation and eccentricity parameters of a hybrid imaging and laser scanning sensor. In: R. Reulke and U. Knauer (eds), Proceedings of the ISPRS working group V/5, Panoramic Photogrammetry Workshop, Vol. XXXVI-5/W8.