An Advanced Approach for Automatic Extraction of Planar Surfaces and their Topology from Point Clouds

Andreas Schmitt & Thomas Vögtle, Karlsruhe

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Summary: Terrestrial laser scanning has become a standard method for a fast and accurate acquisition of 3D objects. While data capture has attained a high level of development, the analysis of point clouds is still characterised by a remarkable amount of manual interaction. In this article an advanced generic approach for the extraction of surface primitives is presented. In a first step the 3D measurement domain is subdivided into volume elements (voxels) and the centre of gravity of the interior laser points is calculated for each voxel as representative geometric position. Normal vectors are determined for each voxel by means of all possible combinations of two vectors to the 26 neighbouring barycentres. If the local surrounding contains plane surface parts, a couple of these normal vectors have similar directions. These vectors will be aggregated (mean direction) and the number of involved vectors (NOV) is stored. For a planar surrounding a clear majority will be obtained. A region growing algorithm extracts plane surfaces by merging adjacent voxels if their main normal directions are similar (homogeneity criterion). If two majorities can be observed it is an edge point, for three main directions a corner point can be assumed. These topological points will be stored as a base for the subsequent 3D modelling process. First experiences with synthetic and real world data of buildings have shown the suitability of this advanced approach and the robustness concerning noise, surface roughness and outliers. A disadvantage may be a certain generalisation effect.

Zusammenfassung: *Ein erweiterter Ansatz zur automatischen Extraktion ebener Flächen und ihrer Topologie aus Punktwolken.* Terrestrisches Laserscanning ist zu einer Standardmethode der Erfassung von 3D-Objekten geworden. Während die Datenerfassung einen hohen Entwicklungsstand erreicht hat, ist die Auswertung der Punktwolken noch durch einen erheblichen Anteil an manuellen Arbeiten gekennzeichnet. In diesem Beitrag wird ein erweiterter generischer Ansatz zur Extraktion von Oberflächenprimitiven vorgestellt. In einem ersten Verfahrensschritt wird der dreidimensionale Messraum in Volumen-Elemente (Voxel) unterteilt und für jedes Voxel der Schwerpunkt der darin gelegenen Laserpunkte als repräsentativer geometrischer Ort berechnet. Für jedes Voxel werden dann Normalenvektoren bestimmt, die sich aus allen Kombinationen zweier Vektoren zu den Schwerpunkten der 26 benachbarten Voxel ergeben. Enthält die lokale Umgebung ebene Oberflächenteile, so werden mehrere Normalenvektoren nahezu in die gleiche Richtung weisen. Diese Vektoren werden unter Berechnung der mittleren Richtung zusammengefasst und die Anzahl der beteiligten Vektoren (NOV) gespeichert. Im Falle einer Ebene als lokale Umgebung wird sich eine deutliche Mehrheit der Normalenrichtungen ergeben. Ein Flächenwachstumsverfahren extrahiert ebene Flächen durch Fusion benachbarter Voxel, deren Haupt-Normalenvektoren nur eine geringe Richtungsabweichung voneinander aufweisen (Homogenitätskriterium). Ergeben sich zwei Hauptrichtungen, so handelt es sich um einen Punkt auf einer Kante, bei drei Hauptrichtungen kann eine Ecke angenommen werden. Diese topologischen Punkte werden als Basis für die anschließende 3D-Modellierung gespeichert. Erste Erfahrungen mit synthetischen wie auch realen Daten von Gebäuden haben die Eignung dieses Ansatzes sowie seine Robustheit gegenüber Rauschen, Oberflächenrauhigkeit und Ausreißern erwiesen. Ein Nachteil könnte ein gewisser Generalisierungseffekt aufgrund der Voxel-Rasterung sein.

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1 Introduction

During the last decade terrestrial laser scanning (TLS) has become a standard method for a fast acquisition of 3D data with high accuracy. Meanwhile a lot of various applications use TLS techniques like network planning in urban areas, industrial production, plant engineering and construction, forest inventories, forensic applications or film industry. One of the most important ones is the recording and modelling of buildings, e. g., for generation of 3D city models, infrastructure and environmental planning, tourist guide systems, architecture, archaeology or conservation of cultural heritage.

While data capture has attained a high level of development the analysis of point clouds is still characterised by a remarkable amount of manual interaction – especially for objects of complex structure like buildings or industrial products. Therefore, automation is an important topic of recent international research and a couple of methods can be found in the literature to extract 3D objects from point clouds which offer different levels of automation.

In this article an advanced generic approach will be presented which combines the flexibility of data driven approaches concerning the possible variety of object shapes with the automatic extraction of topologic relations between the extracted surface primitives as well as data and noise reduction, typical for model driven approaches. For 3D modelling neighbouring surface elements are intersected or connected by means of this topological information. Even if it aims at automatic building modelling it is also applicable to other suitable objects from the industrial domain.

In the next section a selection of related work from literature will be shortly presented and commented, while in section 3 our advanced approach is explained in detail. In the following section some practical tests and applications are described which clarify the advantages and disadvantages of this method. Concluding remarks and possible further developments will finish this contribution.

2 Related Work

For modelling of a great variety of building shapes – as well as for other objects – only a generic approach seems to be suitable, while only a limited number of different object types may be acquired by model-driven approaches (Grün 1997, Haala & Brenner 1997, Maas 1999a, Maas 1999b). Generic data-driven methods extract surface primitives (planes, cylindric or conic elements, etc.) from the point cloud and combine them to 3D object models. Therefore, a higher flexibility concerning the variety of object shapes can be obtained. A general problem of a subsequent 3D modelling based on these approaches is, that topological relations between the single surface parts have to be extracted separately in a second step by a more or less extensive algorithm.

Some of these approaches reduce the spatial distributed point cloud (3D) to 2.5D by creating image information (depth image or a matrix sorted according to horizontal and vertical angles of the laser measurements). The extraction of surface primitives is now based on either image processing routines or 2-dimensional Delaunay triangulation (Kern 2003). A restrictive precondition is that only separate original scans can be used as input data and therefore extracted primitives have to be merged in the overlapping parts of several single scans after registration. Another method is the reduction of the point cloud into 2D. (Schwalbe et al. 2005) determine in a first step the main orientation and contour of a building by generating horizontal cross-sections in different heights. After rotation of the point cloud into the main building directions planes are represented by linear parts of high point density which can be used to extract these planes. (Bienert 2006) uses horizontal cross-sections in different heights to extract a set of contour lines. From each contour line the linear elements are determined. By combining corresponding linear elements of adjacent contour lines building planes could be derived.

In other approaches a 3D triangulation of the point cloud is carried out. (Bernardini et al. 1999) approximate 3D objects by triangles without extracting primitives. Therefore, no data reduction and a high redundancy for objects of lower complexity will be obtained. (Verbree & van Oosterom 2003) start with a 2D triangulation. Tetrahedrons are created by adding further points which fulfil specific conditions (data dependent TIN), e. g., minimal area of surface or minimal volume which leads to a so-called Delaunay tetrahedronised irregular network. Again no significant data reduction and high redundancy will occur. (Tovari & Pfeifer 2005) determine normal vectors using *n* nearest neighbours of a point and extract surface segments by a region growing process based on special homogeneity criteria, e. g., similarity of normal vectors, point distance to an adjusting local plane. (Filin & Pfeifer 2006) propose a similar approach working in a slope adaptive neighbourhood to reduce the influences of noise and micro structures of the object surface. The extraction of surface segments is obtained by a feature-based clustering. A very robust method with regard to noise is an approach based on the well-known RANSAC algorithm (Boulaassal et al. 2007, Hansen 2007). Elementary surface primitives (in these cases planes) are extracted by a great amount of random combinations of three laser points and the combination with the smallest residuals of the laser points is chosen. Normally this leads to an acceptable solution even if it is not the optimal one. (Visintini et al. 2006) and (Crosilla et al. 2007) present a method which uses not only planes as surface primitives but also elements of higher order, e. g., hyperbolic, parabolic and elliptic surface parts, taking a distance dependent weighting function into account. Each primitive is determined in a local surrounding and can be described easily by features like Gaussian, mean or main curvature which is characteristic for these basic geometric shapes. A region growing algorithm merges adjacent elements to planes, cylindrical, spherical or hyperbolical object surfaces.

Another way to handle large point clouds – commonly millions of points – is a subdivision of the measurement domain into volume elements (voxels) and a sorting of the laser points according to their corresponding voxel. For each voxel (Hansen 2006) determines a local dominant plane by means of the RANSAC algorithm. The planes of neighbouring voxels are merged if their normal vectors are similar. Therefore, a remarkable data reduction can be obtained. (Bucksch & Lindenbergh 2008) subdivide the 3D space in octree cells by defined rules to obtain sets of points and describe the links between them (graph description). The critical point of these approaches may be the choice of a suitable edge length of the voxels.

3 IPF-Approach

Due to the discussion of existing algorithms, the benefits and advantages of an advanced approach should have are:

- High flexibility: approximation of any object shape (buildings, industrial objects etc.) in a generic data-driven way. Additionally applicable to any point cloud (not only to single scans).
- Topology extraction: determination of edges and corners at the boundary of extracted surface elements for subsequent 3D modelling.
- Robustness concerning noise, surface roughness, remaining errors after registration and outliers.
- Level Of Detail / Generalisation: selectable degree of generalisation by user-defined parameters.

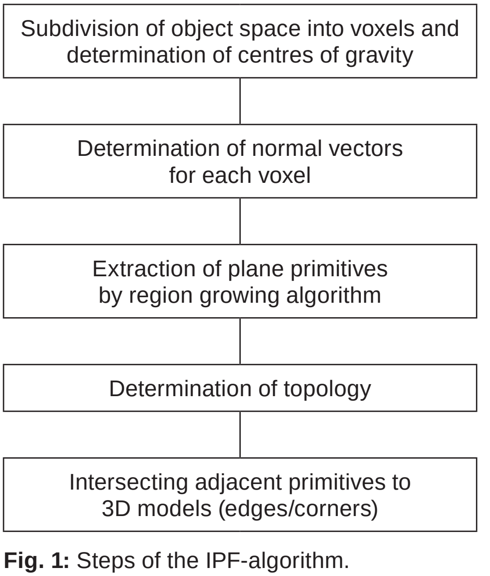

Fig. 1: Steps of the IPF-algorithm.

Another aspect is minimisation of running time, but it is not required in advance. To have a view of the procedure, the single steps are presented in a scheme (cf. Fig. 1) and explained in the following paragraphs.

3.1 *Subdivision of Object Space into Voxels*

The initial idea is to subdivide the object space into regular volume elements (voxels). To each of these voxels their corresponding laser points are related (cf. Fig. 2). The minimum number of related measurement points is used as criterion to reject voxels that probably only contains outliers. The centre of gravity is determined for each voxel as a representative geometric location for the points inside. Therefore, a high degree of data reduction will be obtained. The parameters (voxel size, minimal number of points per voxel etc.) are user-defined because they highly depend on the complexity of the object and the intended level of detail of the application. The voxel size can, e. g., be defined by the dimension of the smallest detail which should be acquired. Thus, the user can control the generalisation effect by these parameters.

3.2 *Determination of Normal Vectors for Each Voxel*

For each voxel the vectors starting from its centre of gravity to all (existing) neighbouring voxel barycentres are determined (dark vectors in Figs. 2 and 3). Normal vectors are calculated based on all possible combinations of two of these vectors – almost parallel vectors are excluded by a minimum angle criterion – by the cross product, i. e., in Fig. 2 there are 21 suitable combinations. In the case of a plane most of these normal vectors have similar directions. Those normals differing less than a maximum acceptable deviation are fused (mean direction) and the number of involved vectors (NOV) is stored. Afterwards the remaining normals are sorted by their NOV. If one vector (the grey one in Fig. 2) is obviously more frequent than all the others, there is one main direction of the normals and this voxel centre is situated on a local planar surface (cf. Fig. 2). If there are two main directions found, the voxel contains an edge (two main normal vectors in Fig. 3), in case of three it is a corner.

3.3 *Region Growing Process and Robust Plane Estimation*

Every normal vector of a voxel belonging to a local plane surface can become seed region in

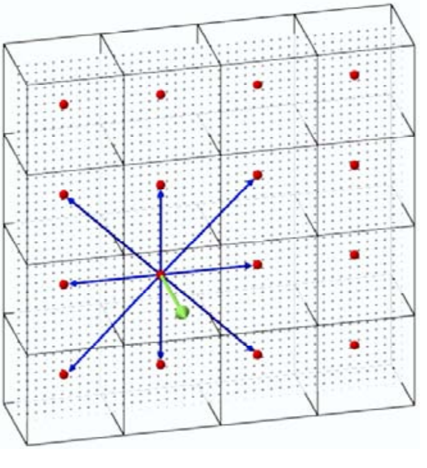

Fig. 2: Main normal vector (green) derived from the centres of gravity (red points).

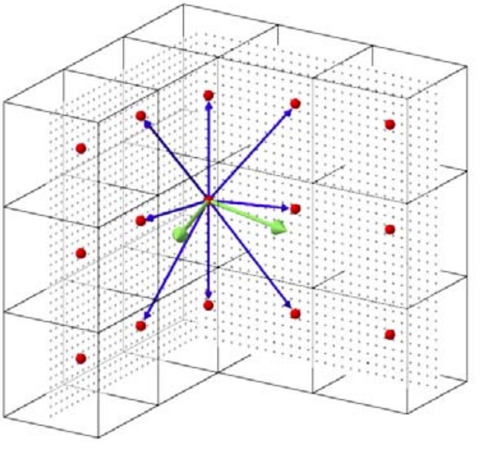

Fig. 3: Two main normal vectors (green) derived from centres of gravity at an edge.

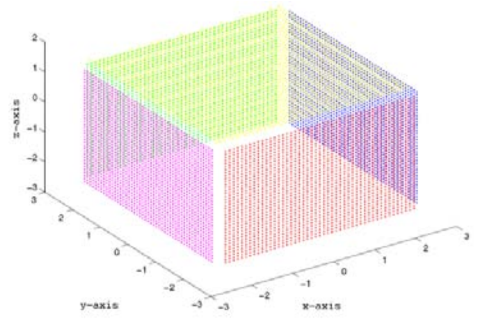

Fig. 4: Extracted planes in a synthetic point cloud of a cuboid (without ground area).

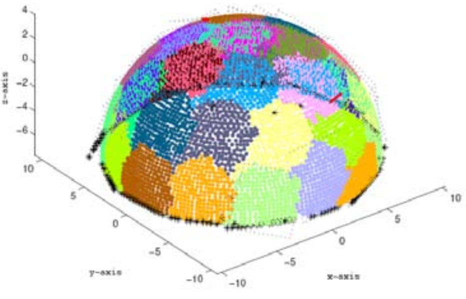

Fig. 5: Segmentation of a synthetic point cloud of a hemisphere.

the subsequent region growing process. Two criteria define the homogeneity for a new attached voxel:

- The deviation of the (main) normal vector directions has to be smaller than a maximum acceptable angle.
- The number of vectors (NOV) of the new attached voxel has to exceed a certain minimal number.

The averaged normal vector (based on the attached normals) is continuously re-calculated. If no more suitable voxels are found the process stops. To estimate the optimal plane equation a L1-norm estimator is used. This procedure weights down the influence of probably false classified voxels und fits the plane iteratively to the remaining centres of gravity (cf. Fig. 4). Even if this procedure is applied on curved surfaces like a hemisphere (cf. Fig. 5) approximate plane surface parts are achieved. Surfaces which are too small can be rejected by their low number of attached voxel centres.

3.4 *Determination of Edges and Corner Points*

As explained above voxels whose normal vectors show more than one main direction can be assigned to several planes. They represent edges and corners (cf. Fig. 6). In the example of Fig. 6 all edges and three corners out of four are detected, the missing one may be caused by noise or an unfavourable relative position

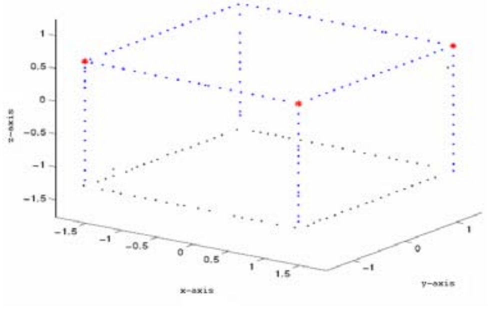

Fig. 6: Extracted edge (dark) and corner points (grey) in a synthetic point cloud of a cuboid without ground area (cf. Fig. 4).

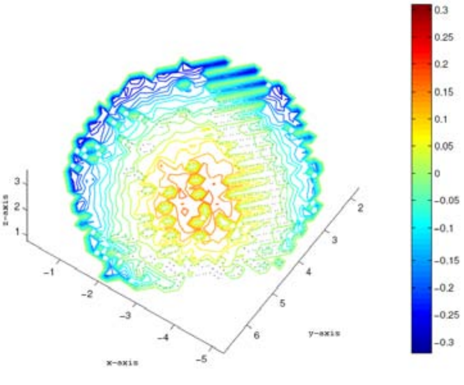

Fig. 7: Isolines for the control of the approximation by planes: here one surface part (cf. Fig. 5) is depicted where – due to the curvature of the object surface – the largest deviations can be found in the middle and near the boundary.

to the voxel structure. If only few neighbouring voxel barycentres can be found, this voxel is classified as boundary voxel (cf. Fig. 6). As the barycentres do not represent the optimal edge or corner coordinates these are calculated by intersection of the assigned (adjacent) planes. The topology information that is derived from the edge and corner voxels can be summarized in a graph to be used in a further 3D reconstruction.

3.5 *Extraction of Details – Boundaries and Isolines*

To extract more detailed information – on the one hand the boundaries of surface parts without neighbouring surfaces, on the other hand the deviations from the extracted planes – the original measurement points are attached and transformed to their corresponding plane. In a first step the minimal enclosing rectangle is determined for each plane (cf. Fig. 8 left). For the points inside this rectangle a fine structured new boundary line is determined (cf. Fig. 8 middle) based on a contour tracking algorithm after rasterisation of the transformed points. By means of the distances between the original points and the adjusted plane isolines can be calculated which are used to inspect the approximation – especially in cases of more complex or curved surfaces (cf. Fig. 7) – as well as for the extraction of finer structures like cornices etc., i. e., specific details of the surface (cf. Fig. 8 right).

4 Examples

The IPF-algorithm being developed for practical use has been applied to several real data sets from which two results are presented in the following. The measurements have been carried out by the INSA (Institut National des Sciences Appliquées), Strasbourg (F), with the terrestrial laser scanner TRIMBLE GX in the year 2006. The point clouds of different scan positions have already been registered by using markers.

4.1 *Castle of Andlau*

The castle of Andlau is situated in the Vosges Mountains near Strasbourg in the Alsace region in north-eastern France. From the medieval building the fortification walls and towers still remain. Because of the wooded downward slopes around the castle many scan position are necessary to record the whole structures of the building. Fig. 9 shows the scanned point cloud of one tower, whereas Fig. 10 represents the voxel centres of gravity using a voxel grid length of 30 cm. The algorithm reconstructs the walls as large plane surfaces (cf. Fig. 11). The curved – almost cylindrical

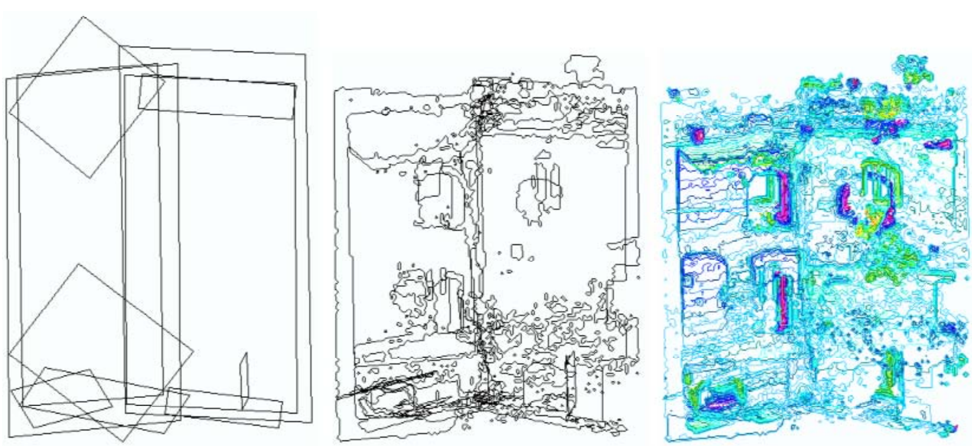

Fig. 8: Minimal enclosing rectangles (left), detailed boundaries (middle) and isolines (right) of a scanned courtyard corner in the castle of Andlau (cf. Sect. 4.1).

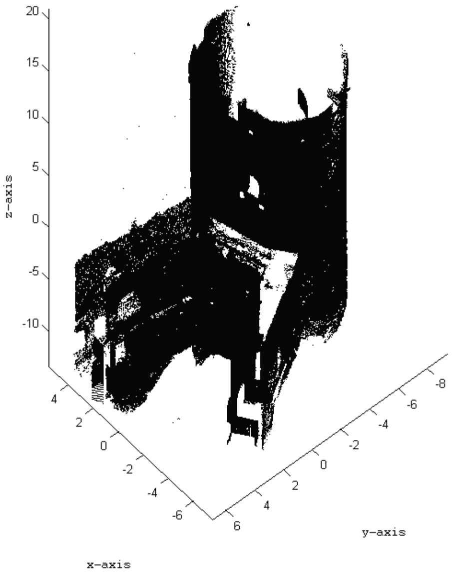

Fig. 9: Andlau castle (subset) – original point cloud.

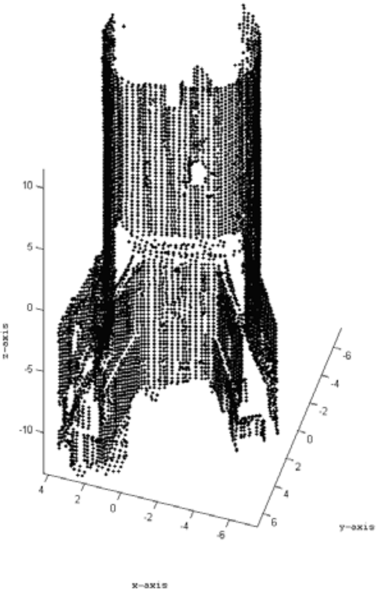

Fig. 10: Andlau castle (subset) – voxel centres of gravity.

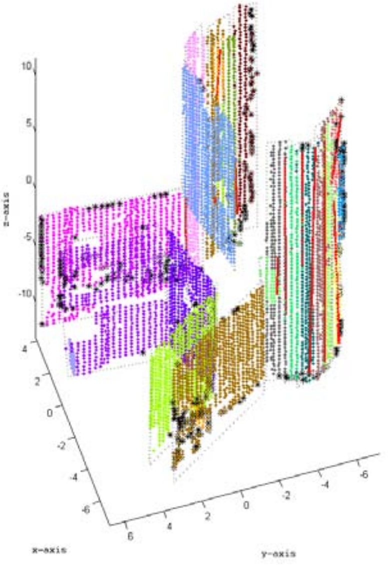

Fig. 11: Andlau castle (subset) – segmented voxel centres of gravity of the extracted plane surfaces (in different colours).

Fig. 12: Andlau castle (subset) – minimal enclosing rectangles of the segmented planes.

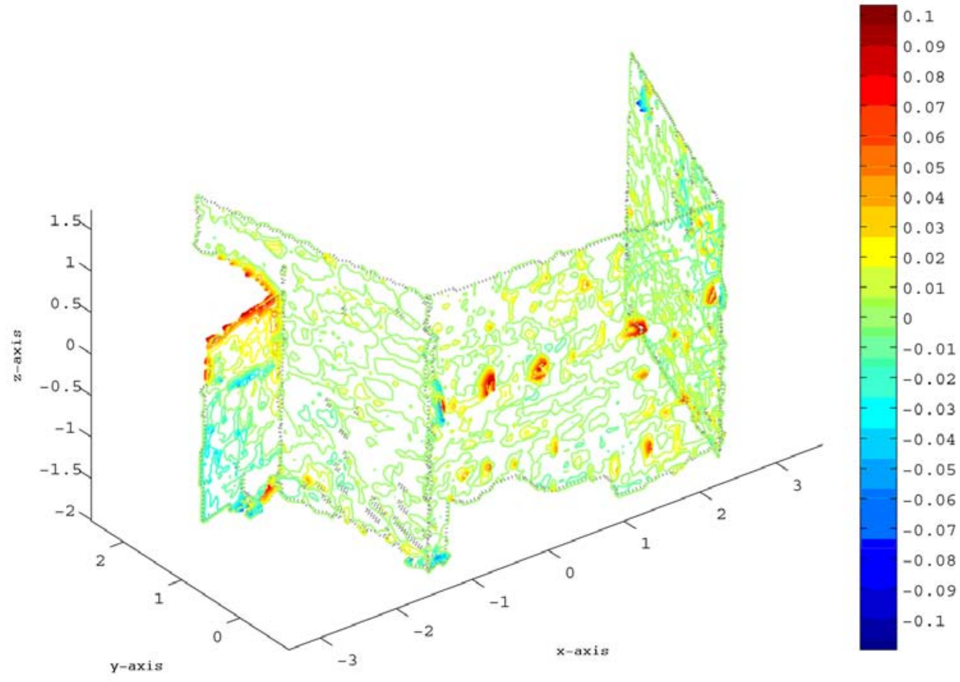

Fig. 13: Andlau castle (subset) – isolines illustrating the height above the adjusted plane, fine wall structures like four holes or bigger stones can easily be recognized.

– surface of the tower is approximated by narrow stripes. The representation in a CAD system (cf. Fig. 12) shows the minimal enclosing rectangles as rough approximation of the boundaries. Much more detailed information can be derived from the isolines (cf. Fig. 13) which depict the fine structures of the wall, e. g., ancient holes for beams of wood. In addition the isolines visualize the quality of the approximation, as mostly lines of low height above the adjusted plane are found and no trend is recognizable.

4.2 *INSA Building*

The INSA building in Strasbourg (F) is a modern school building. In contrast to the previous

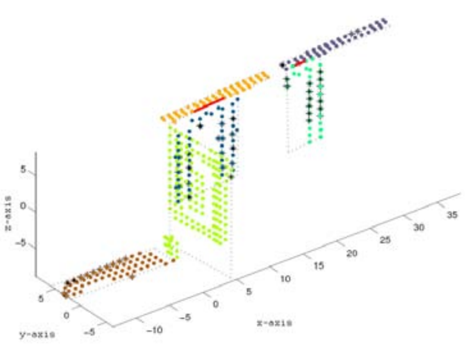

Fig. 14: INSA building (subset) – voxel centres of gravity of the extracted plane surfaces.

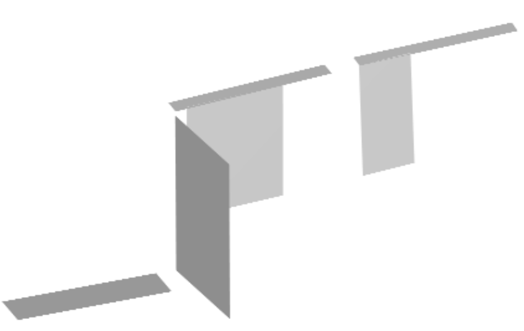

Fig. 15: INSA building (subset) – minimal enclosing rectangles of the segmented planes.

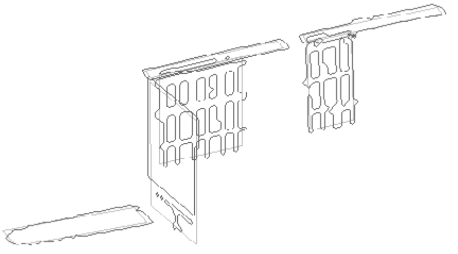

Fig. 16: INSA building (subset) – minimal enclosing rectangles and boundary lines.

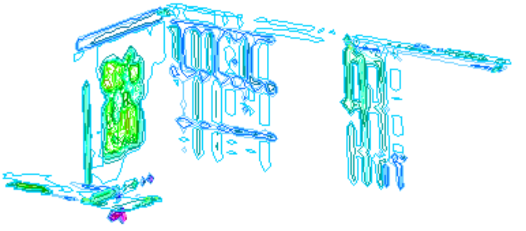

Fig. 17: INSA building (subset) – isolines depicting the minor structures like the relief on the left facade.

example only rectangular structures are found on the facades with exception of a large relief located in the middle of a wall. The original point cloud includes many outliers. But after the first step (cf. Section 3.1) only voxel centres near the building remain. The robustness concerning noise is illustrated in Fig. 14 and Fig. 15, because the algorithm only extracts the large plane surfaces: three walls, two roof surfaces and one floor in the interior of the building. Whereas Fig. 15 gives a rough approximation of the boundaries, the lines in Fig. 16 especially draw the window structures in a fine resolution. The isolines in Fig. 17 show again the quality of the plane estimation. While the relief is modelled in an adequate way by the isolines, no large deviation or trend can be recognized on the other facades.

5 Conclusions

An advanced approach for the extraction of plane surface elements was presented. It is based on main normal vectors of voxel barycentres which lead to the required planes by means of a region growing algorithm. First experiences have shown satisfying results and the method has proved to be robust concerning noise and outliers. The advantages of this approach are the high degree of data reduction and the generation of topological relations between the extracted primitives. Furthermore it can be extended to primitives of higher order, e. g., cylindrical or spherical surfaces. One disadvantage may be a certain generalisation effect due to the voxel structure. However, if the deviations of the laser points from the extracted planes (e. g., as isolines) are included much more details can be modelled.

In the future this method will be applied to additional buildings of different structures as well as to other objects, especially industrial products where its suitability has to be verified. The generation of topology has to be improved for complex or uncompleted object parts where the method obtains fragmentary results. Moreover, the neighbourhood information about the extracted surface primitives has to be extended to the whole object, e. g., in a complete neighbourhood graph, to obtain a higher level of automation.

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Addresses of the Authors:

Dipl.-Ing. Andreas Schmitt, Hasenweg 30, D-76779 Scheibenhardt, Tel. & Fax: +49-7277-207, e-mail: andreas.schmitt@dlr.de

Dr.-Ing. Thomas Vögtle, Universität Karlsruhe (TH), Institut für Photogrammetrie und Fernerkundung, Englerstraße 7, D-76131 Karlsruhe, Tel.: +49-721-608-3675, Fax: +49-721-608-8450, e-mail: thomas.voegtle@ipf.uni-karlsruhe.de

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