Using BIM-Elements as Features for the Transformation of Local Point Clouds Created with Structure from Motion

Tim KAISER, Enrico ROMANSCHEK and Christian CLEMEN, Germany

Keywords: BIM, Structure from Motion, Registration

SUMMARY

In order to use image-based point clouds that were automatically created with Structure from Motion (SfM) methods in combination with a Building Information Model (BIM) the point cloud must be transformed into the building coordinate system. This can be achieved with a classical seven parameter Helmert Transformation. Usually control points i.e. points that have known coordinates in both the point cloud and the building model are used for the estimation of the transformation parameters. In this paper we present a novel, more automated approach to calculate the parameters. In the first step 3D lines structures are extracted from the input image collection and then matched to the planes originating from the BIM model representing the walls, floors and ceilings. Besides of finding a suitable functional model for the observation equations and the adjustment calculation a RANSAC-based algorithm to determine a correct line plane match was developed. For evaluating the concept synthetic data sets have been used. The use-case of the proposed concept is targeting for example craftsmen who want to create point clouds of objects within a limited area of a construction site or a specific room inside the building and want to visualize them for the damage documentation, construction progress monitoring or updating the used BIM model to the actual state.

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1 INTRODUCTION

A BIM-Model depicts a complete digital representation of a building. The model is used as the extensive information source during the complete life cycle of the real world building beginning with the planning and construction, continuing with the operation and eventually stops with the demolition. During these different phases, it will be possible and almost inevitable that deviations between the as-build and the originally as-planned state will occur. Deviations can be as early as in the building phase. This means that the original created BIM-Modell needs to be updated frequently to represent the actual state of the building.

With the advent of modern computer vision algorithms and increasing computation power in consumer-grade PCs it became possible to reconstruct an object from an unordered collection of images in a more or less automated way. These so-called Structure from Motion (SfM) techniques have been proven useful in various different fields and technologies among other things due to their relatively low-cost nature. For example can surveyors use drone images for various mapping purposes, engineering surveying etc. The principal output of this so-called structure from motion technique are point clouds.

With the construction sector in mind, such point clouds can contain the required geometric information for updating the building model for getting the actual as-built state. Especially using local points of closed rooms inside a building could provide a range of possible applications. They could be used for the measurement, modeling and documentation of subsequently build in structures in the room (e.g. added radiators or cable channels). Besides of that little damages like cracks could be registered and located accurately. So overall using the extracted building information from the BIM-Model in conjunction with the local point cloud enables a comparison of the as-planned and the as-built state as well as updating the as-built model.

However, there is the challenge of having two different coordinate systems when combining the two data sources. During the creation of the SfM point cloud an arbitrary coordinate system is used. For a usage within the presented use case, the point cloud must be transformed into the building coordinate system based on a classical seven parameter Helmert-Transformation. This usually requires the manual measurement of ground control points with known coordinates in both systems. However, this task is time-consuming, error-prone and repetitive for big data sets.

Due to these reasons, our presented approach does not depend on a manual measurement of points since it rather uses geometric relationships between specific BIM-objects and extracted line structures from the captured images to compute the transformation parameters. This approach enables an automatic room-based transformation of the local point cloud into the building coordinate system for further analysis.

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2 RELATED WORK

In recent years multiple case studies (e.g. Tuttas et al. 2017; Golparvar-Fard et al. 2015) were performed using BIM-models and photogrammetric acquired point clouds for the progress monitoring of a construction site. By comparing the as-built with the as-planned state deviations can be noted early in construction stages so that it is possible to avoid further mistakes which could lead to delays or increased costs. However, the mentioned papers cover a complete construction site and not only a single room like our system intends to do. Besides of that it is also required to transform the acquired point clouds into the building coordinate system for the comparison. This is achieved by measuring Ground Control Points (GCP) for calculating the transformation parameters.

For establishing a more automatic registration process of a complete point cloud to a given BIM-model Kim et al. (2013) waived to use GCPs. They used a combination of a Principal Component Analysis and an Iterative Closest Point Algorithm to perform a successful registration between the point cloud and the building model. The achieved results are depending on certain circumstances though, so that further research has to be done for a universal application of this method.

In addition to an image based reconstruction terrestrial terrestrial laser scanners are often used for the generation of building point clouds. However, it is still necessary to perform a transformation of the point cloud into the building coordinate system. The only difference is that point clouds from laser scanners are up to scale so that it is not required to estimate the scale factor. Due to the high point density in such point clouds plane-based transformation methods are often used. Planes are searched in the scanned point cloud and are related to extracted planes from the building model. The challenging step is the correct matching of corresponding planes in the point cloud and in the model. This often requires manual involvement (Bosché 2012).

2.1 Building Information Modeling (BIM) and Extraction of Plane Parameters

One of the fundamental ideas of Building Information Modeling is to use a complete digital model of a building through all phases of the building's lifecycle, aiming for example at an optimized collaboration between different crafts, prevention of information loss or redundant data storage. (Borrmann et al. 2015). The major advantage of a BIM-Model is that it not only contains the geometric representation of the building (like in CAD) but rather enriches the geometry with a multitude of semantic information. Such a model consists of several objects like walls, doors or windows that are all linked to the other building parts. In the CAD world a wall just consists of its limiting set of lines whereas in BIM a wall is an object with specified attributes and relations to other objects (Clemen and Gründig 2006). To sum it up, BIM provides a much deeper semantic integration as CAD and especially a topologically correct representation of the building. Due to these characteristics of such a model, it becomes possible to select all affected walls of the room for example by specifying the according room number.

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If the correct room is selected it is necessary to retrieve the plane parameters as input data for the calculation of the Helmert-Transformation since no additional markers or control points should be measured. Due to the mentioned rich semantic information of the building model this can be more challenging than expected. A wall for example can consist of several layers such as the insulation or the plaster. This can also have an impact on the resulting plane parameters since one of these describes the distance of the resulting plane to the origin.
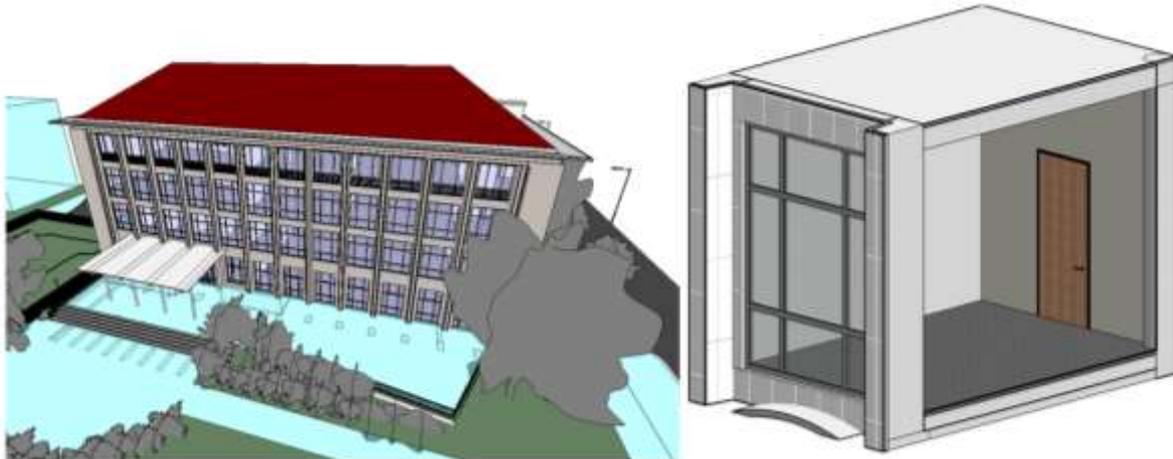

Fig. 1: Sample building model HTW Dresden (left) and selected room of model (right)

In the following section we want to describe a possible workflow for extracting the relevant information from the main components (i.e. the walls, floor, and ceiling) of the building model. The proposed concept assumes that building floors and ceilings are horizontal and walls are vertical with respect to the building coordinate system. Due to the highly dynamic changes in BIM authoring tools and data formats the algorithm is explained in a general form and has to be adapted to the specific tools and data. The basic output of the algorithm is a list of tuples that consist of the normal vector of the plane and a point located on the plane for every plane forming the room. This plane parametrization is equal to the Hesse normal form.

The first step is to select the room from the building model as a separate object (Fig. 1). This room belongs to a story that is used for deriving the floor and ceiling that in turn enable getting the upper and lower plane of the room.
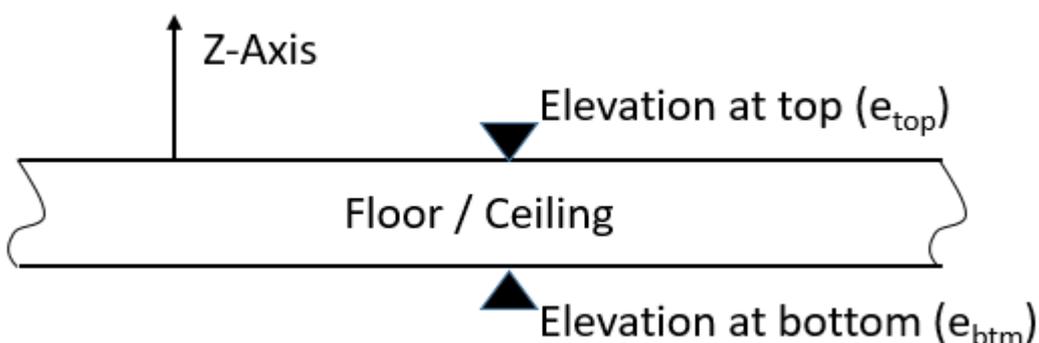

Fig. 2: Sideview of a Floor or Ceiling element. Planes from the object (floor/ceiling) must be carefully selected by any algorithm

The normal of the room's floor plane is the Z-Axis of the building coordinate system (Fig. 2). For a point located on the corresponding plane the elevation at top is multiplied with the Z-Axis. Similar to the lower plane the ceiling's normal vector is the negative Z-Axis and for getting a plane point the elevation at bottom is multiplied with the Z-Axis.

$$P_{top} = \{\hat{z}, e_{btm\ Ceiling}\hat{z}\}$$
$$P_{btm} = \{-\hat{z}, e_{top\ Floor}\ \hat{z}\}$$

For retrieving the remaining planes, a consecutive list of the enclosing wall segments is needed. Every wall segment is defined by an axis (through the middle of the wall) between the starting point A and the end point B and the overall thickness t of the wall segment (Fig. 3). It must be ensured that the directions of the axes point counter clockwise around the room.
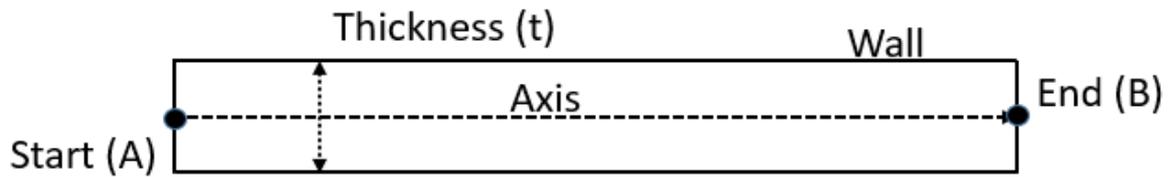

Fig. 3: Topview of a Wall element. The wall is geometrically represented as parametric object.

The actual parameters are calculated as follows:

$$\vec{n} = \hat{z} \times (B - A)$$
$$\hat{n} = \frac{\vec{n}}{|\vec{n}|}$$
$$P_{Wall} = \{\hat{n}, A + \frac{t}{2}\hat{n}\}$$

2.2 Structure from Motion and Extraction of 3D-Lines

The term Structure from Motion (SfM) summarizes a row of processes and techniques that are performed for an image-based 3D reconstruction of an object (for a deeper insight see for example (Westoby et al. 2012)). After having captured the images the first step usually involves to extract keypoints or tie points from the input images using an established feature detector such as SIFT or SURF. For reconstructing an object using SfM it is important to acquire overlapping images so that the same keypoints can be tracked over multiple images. Next, matched keypoints are used for the initial computation of the camera pose and the scene geometry. This step is followed up by bundle block adjustment that finally delivers the interior and exterior orientation as well as the object coordinates in form of a point cloud.

It is important to note that the SfM process only provides 3D coordinates for the matched keypoints. The resulting point cloud only contains the matched keypoints from the described procedure and therefore is sometimes called a sparse point cloud. In order to get a more dense

point cloud with more points different multi-view stereo algorithms (MVS) are applied. These algorithms need the interior and exterior orientation information generated in the SfM stage.

Extraction of 3D-Lines
As stated in the introduction line features defined in the point cloud coordinate system are used to calculate the transformation parameters. To extract the lines the software tool Line3D++ (Hofer et al. 2017) is used. The tool first detects 2-dimensional line segments in every image (Fig. 4). It then matches the possible candidates across multiple other images and uses epipolar geometry constraints to get the three-dimensional start and end point coordinates of the straight line segments (Fig. 5). For a detailed in deep explanation of the algorithm, we refer to the corresponding paper.

Fig. 4: Possible matching candidates for the extraction of 3D-Lines

In addition to the images, Line3D++ needs several other input information to work. This mainly concerns the interior and exterior orientation. The camera parameters are used for undistorting the images whereas the exterior orientation is required to better match the two-dimensional lines. To get these information a SfM must be run beforehand and the results have to provided to the tool. Line3D++ therefore supports various input data formats from different open source SfM pipelines such as VisualSFM, openMVG or Colmap.

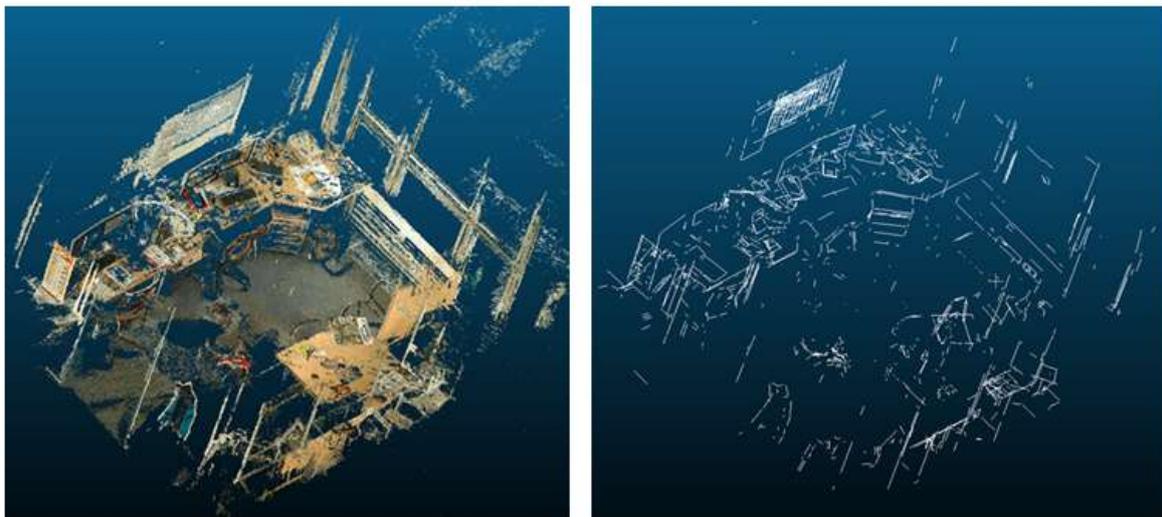*Fig. 5: Generated dense point cloud of a room (left) and extracted 3D line structures (right)*

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3   PROPOSED CONCEPT AND CURRENT IMPLEMENTATION

The standard approach for transforming local point clouds into a global coordinate system is to calculate the transformation parameters with an adjustment calculation using ground control points. Finding and setting up such GCPs can become a challenging task. Due to the rapidly changing nature of a construction site or a building in general, GCP locations must be set up at a location where they are durable and are visible from a wide point of view in every construction and lifecycle phase. It has to be taken care of this when establishing the GCPs on the construction site. That means that expertise knowledge is required for the installment of the GCPs. Since a BIM-model of the building is already given in our specific use-case we want to renounce from using GCPs in favor of a more automated workflow.

3.1   General Workflow of Concept

The workflow (Fig. 6) starts with the capturing of the images of the corresponding room. An arbitrary SfM pipeline is run afterwards for generating the point cloud and getting the interior and exterior orientation of the images. This information is then used for also extracting the 3D-Line structures from the images using Line3D++. This step concludes the data preprocessing on the photogrammetric side.

The affected room is selected from the given BIM-model by specifying for example the room number. The final step in the data capturing phase is to get the plane parameters from the room defining walls. Having gathered both the line and plane data the assignment of these two can be done. Finally this information is used for the calculation of the transformation parameters.
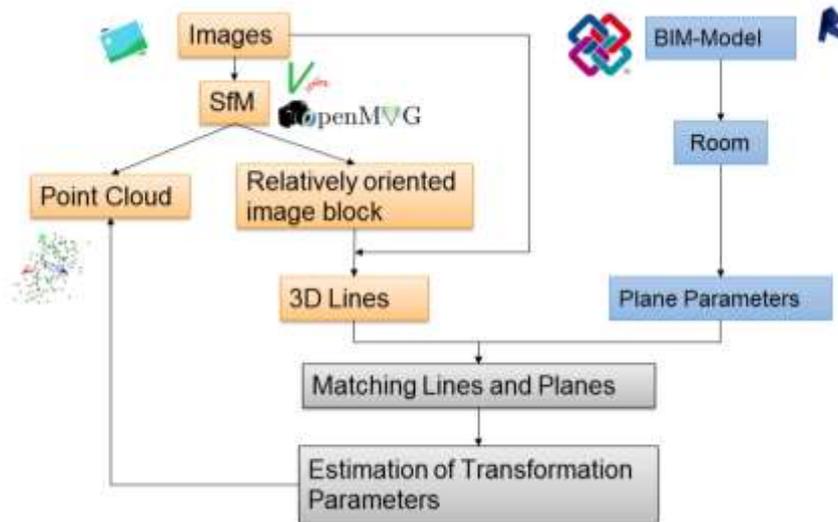

Fig. 6: General workflow of the proposed concept

3.2   Estimation Algorithm and Line Plane Assignment

The following section describes the process for aligning the generated point cloud and the building model. A classical least squares method is applied for estimating the transformation

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parameters. In order to get the point cloud into the building coordinate system a classical Helmert Transformation is used requiring to know the following seven parameters:

- Three rotations around the coordinate axes (equal to the nine elements of the corresponding rotation matrix R)
- Three components of the translation vector $\vec{t}$
- A scale parameter m

3.2.1   Observation Equations

For solving the adjustment problem, geometric relationships between the extracted lines and the room planes are used as observation equations. The used lines are parameterized by their three dimensional start and end point coordinates. The BIM-model allows to extract plane parameters that can be converted in the coordinate form meaning that four parameters are used to describe the plane in the form:

$$ax + by + cz = d.$$

For lines that are directly located on a wall of the room the rotated direction vector $\vec{u}$ must be perpendicular to the normal vector $\vec{n} = [a\ b\ c]^T$ of the wall plane in the common coordinate system. This means that the scalar product between these two vectors must be zero. Furthermore must the start and end points of the rotated, translated and scaled line be lying in the corresponding plane. Similar to Clemen and Gielsdorf (2008) the two constraints are defined by the following two (pseudo-)observation equations:

$$l + v = \ <R * \vec{u},\ \vec{n}> = 0 + v$$

$$l + v = m *\ <\left(R * \vec{s} + \vec{t}\right),\ \vec{n}> - \mathrm{d} = 0 + v$$

In addition, it is necessary to introduce restrictions for getting a valid rotation matrix. One of the characteristics of a rotation matrix is that it is an orthonormal basis. Therefore, the three column vectors of the matrix must be of length 1 that is reached with the following restrictions:

$$w_1 = \ r_{11}{}^2 r_{12}{}^2 r_{13}{}^2 - 1 = 0$$
$$w_2 = \ r_{21}{}^2 r_{22}{}^2 r_{23}{}^2 - 1 = 0$$
$$w_3 = \ r_{31}{}^2 r_{32}{}^2 r_{33}{}^2 - 1 = 0$$

The column vectors must also be orthogonal to each other that is achieved using the restrictions:

$$w_4 = \ r_{11} r_{12} + r_{21} r_{22} + r_{31} r_{32} = 0$$
$$w_5 = \ r_{12} r_{13} + r_{22} r_{23} + r_{32} r_{33} = 0$$
$$w_6 = \ r_{11} r_{13} + r_{21} r_{23} + r_{31} r_{33} = 0$$

The transformation parameters are estimated using the following Gauss-Markov model and a least squares approach. Currently all observations get the same weight and the weight matrix is substituted by the identity matrix resulting in the presented system of equations:

$$\begin{bmatrix} A^T A & B \\ B^T & 0 \end{bmatrix} * \begin{bmatrix} \hat{x} \\ k \end{bmatrix} = \begin{bmatrix} A^T l \\ b \end{bmatrix}$$

With:
- $\hat{x}$ = Transformation Parameters
- B = Linearized Restriction Equations
- k = Lagrange Correlates
- b = Contradiction Vector
- A = Design Matrix
- l = Observations

3.2.2 Critical point: assignment of lines to planes

The above-explained observation equations clearly show that it is necessary to know which line is located on which plane for the adjustment calculation. However, there is no linking information between the lines and planes available. This unknown assignment is the crucial point for the complete transformation process.

Without further information, all theoretical combinations of lines and planes could be possible. If for example a total of just 8 planes and 19 lines are given a theoretical total of

$$8^{19} = 144115188075855872$$

different combinations would be possible. For solving this assignment problem with a reasonable cost it is necessary to reduce the big number of possibilities since the usage of a brute force approach is not feasible with this amount of data.

By applying a filtering step, "invalid" combinations are sorted out before getting into the adjustment calculation. The minimal configuration (that is the minimum required number of observations for the solution of the equation system) consists of four non-coplanar line plane assignments. We therefore calculate the triple product for each possible combination of three lines. In the Euclidean space the triple represents the volume of the parallelepiped defined by the three vectors. Only the combinations with a big volume are kept as the assumption is that the bigger the spanned volume the more orthogonal the vectors are located to each other. This in turn would mean that they are on different planes supporting the demand for four non-coplanar lines. This filtering step is also performed for the planes using the respective normal vectors.

After the filtering step the actual assignment procedure continues using an approach inspired by the RANSAC algorithm (Fischler and Bolles 1981). The basic idea of the RANSAC algorithm is to randomly pick the minimal configuration from the input data, then solve the optimization problem using the minimal configuration. Afterwards the full set of available data is used for the validation of the calculated model parameters. This is done for several iterations until a satisfying solution is found.

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The implemented approach randomly selects one of the filtered line triples and assigns the triple to one of the plane triples. For completing the minimal configuration a fourth non coplanar line is added. Since no information is available which line belongs to which plane all planes have to be considered that are not yet included in the randomly picked plane triple. With the complete minimal configuration the adjustment calculation is run. The calculated parameters are used for transforming the lines of the minimal configuration into the building coordinate system. Afterwards the summed distance between the midpoints of the lines and the assigned plane is calculated and saved. This procedure is repeated for a defined number of iterations.

After completing all iterations, the transformation parameters of the combination with the smallest distance sum is chosen. They are used to transform the complete line data set into the building coordinate system. For every line, the plane with the smallest distance is selected afterwards. If the distance is below a defined threshold (that is set for eliminating outliers) the line is assigned to the corresponding plane. All lines that were assigned to a plane are consequently used for the final estimation of the seven parameters. See the following flow chart (Fig. 7) for a summary of the process. Currently the described algorithm is implemented in the software package GNU Octave.
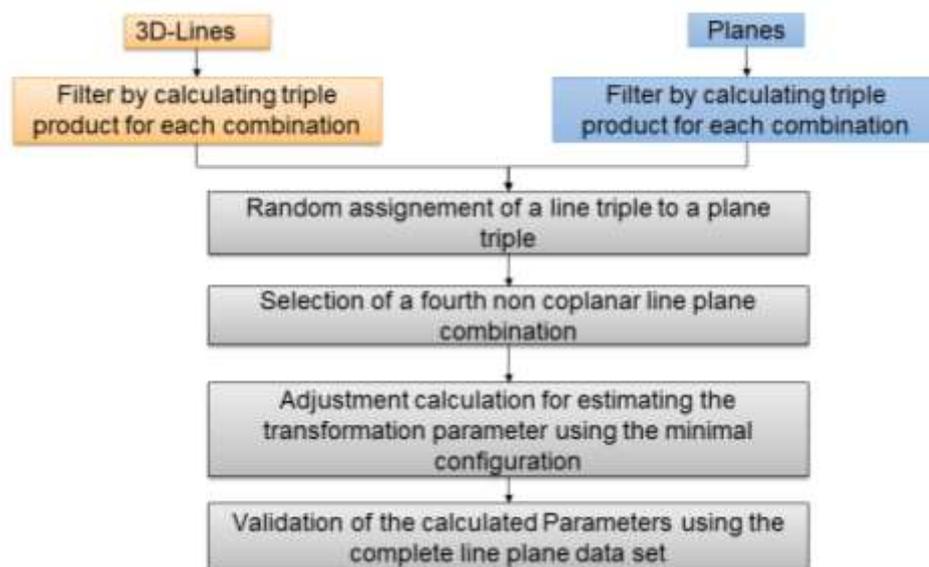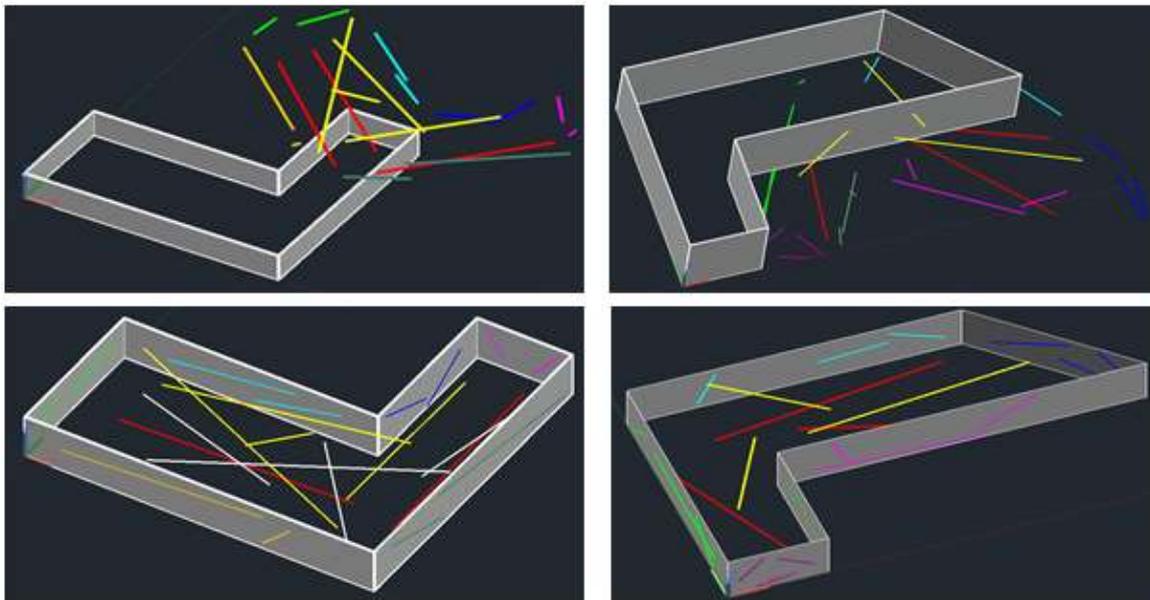

Fig. 7:Basic workflow for the transformation parameter estimation

4   VALIDATION OF THE PRESENTED APPROACH

For a quick validation of the transformation estimation process we generated a set of synthetic test datasets. Multiple rooms with different numbers of planes were created using a CAD Software. Lines were placed on all planes respectively walls, the floor and the ceiling. We could successfully transform the lines into the building coordinate system as shown in Fig. 8.

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In order to have a more realistic data source we randomly added noise to the lines that originally are placed perfectly into the planes. For the correct application of the transformation process it is also very important that it is robust to outliers. In this case outliers are such lines that are detected by Line3D++ but originally are not placed on a wall but for example in the middle of the room or on a tabletop where no plane parameters are known. For simulating this case, we intentionally added fake lines to the data set. Experiments with this data have shown that for a successful parameter estimation up to 13% outliers (three fake lines and 19 correct lines) can be contained in the input data.

Fig. 8: Sample datasets used for the validation of the concept

5   SUMMARY AND FUTURE PROSPECTS

In this paper we presented a novel concept for the automatic transformation of locally created point cloud into a coordinate system of a building model. By using additional information from the given building model in conjunction with extracted 3D line data it becomes possible to correctly register the point cloud without having to measure additional Ground Control Points. The proposed system does not require special hard- or software and therefore could be used by a wide target audience.

The next step will be to evaluate the implemented workflow with real data. It will be interesting to see if the implemented algorithm is robust enough in the current state to deal with a potential high number of outliers. In addition, it is important to investigate the accuracy of the transformation.

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BIOGRAPHICAL NOTES

Tim Kaiser, born 1992. Graduated in 2017 as a M.Eng. in Geomatics/Management from the HTW Dresden, University of Applied Sciences. Since then he is a PhD Student at the Faculty of Geoinformation and Technical University Dresden (Prof. Hans-Gert Maas)

Enrico Romanschek, born 1976. Has worked since 1995 as cadastral and engineering surveyor and has started to study in 2011, he graduated in 2016 as a M.Eng. in Geomatics/Management from the HTW Dresden, University of Applied Sciences. He then worked as research associate for the BMWi/ZIM-Project "TLS2BIM". Since 2018 he is a PhD Student at the Faculty of Geoinformation and Technical University of Berlin (Prof. Wolfgang Huhnt)

Christian Clemen, born 1976. Graduated in 2004 as a Dipl.-Ing. in Surveying from the Technical University of Berlin. From 2004 to 2010 he was an Assistant at the Department of Geodesy and Geoinformation, Technical University of Berlin. He then worked as a GNSS software engineer for Alberding GmbH, Wildau. Since 2013 he has been a full professor at the HTW Dresden, University of Applied Sciences. Christian Clemen is member of the Joint ISO/TC 59/SC 13 - ISO/TC 211 WG: GIS-BIM interoperability. Within FIG he is national delegate for commission 10 and chairing the JWG BIM.

CONTACT

Tim Kaiser
PhD student, Faculty of Geoinformation
HTW Dresden, University of Applied Sciences
Friedrich-List-Platz 1
D-01069 Dresden, Germany
E-Mail: tim.kaiser@htw-dresden.de

Enrico Romanschek
PhD student, Faculty of Geoinformation
HTW Dresden, University of Applied Sciences
Friedrich-List-Platz 1
D-01069 Dresden, Germany
E-Mail: enrico.romanschek@htw-dresden.de

Prof. Dr.-Ing. Christian Clemen
Chair of CAD and Virtual Reality, Faculty of Geoinformation
HTW Dresden, University of Applied Sciences
Friedrich-List-Platz 1
D-01069 Dresden, Germany
E-Mail: christian.clemen@htw-dresden.de
Web site: http://www.htw-dresden.de/geo

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