EVALUATING GEOMETRY OF AN INDOOR SCENARIO WITH OCCLUSIONS BASED ON TOTAL STATION MEASUREMENTS OF WALL ELEMENTS

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ABSTRACT:

Scan2BIM approaches, i.e. the automated reconstruction of building models from point cloud data, is typically evaluated against the same point clouds which are used as input for the reconstruction process. In doing so, the point clouds are often used as ground truth without considering their own inaccuracies. Thus, in this research, we investigate the manual creation of an accurate ground truth, with a process which takes into account the measurement accuracy as well as the modeling accuracy. Therefore we created a ground truth to an existing laser scan data with a total station, based on the assumption that a total station generally measures points more reliably. In addition, a manual selection and classification of points on the wall surfaces during the measurement, serves a reliable detection of the walls via plane fitting. This allows for the creation of a more reliable ground truth, which is determined by the intersection of the planes from corners and edges. The ground truth is aligned parallel to the axes of a local coordinate system. From MLS and TLS point clouds of the same building area, walls are manually classified and corners and edges are determined in a similar way to the total station. These TLS and MLS corners are registered to this ground truth using least squares optimisation at the vertices. The transformation thus determined is used to transform the laser scanning point clouds as well. The resulting errors in the corners and the whole point cloud are evaluated. We conclude that the standard deviation of wall surfaces alone isn't sufficient to determine the quality of the reconstructed building model. Despite low measurement noise in single wall surfaces, deviations in the reconstructed room model may arise.

1. MOTIVATION

The digitization of buildings in the form of Building Information Modeling (BIM) models plays a major role in efficient building management. For this purpose, existing buildings can be measured for example by laser scanning. Building models are created from these three-dimensional point clouds. To development efficient methods to automate this process, the availability of data from buildings that include both point clouds and accurate ground truth is necessary. A ground truth is generally created manually by modeling buildings based on their point clouds. These models typically do not include a direct statement of ground truth accuracy, especially with respect to individual building elements and geometric accuracy. In a real-world scenario, many challenges arise with respect to the definition of building elements and the achievable accuracy of building models. Furthermore, when using different measurement systems, the accurate registration of the individual data sets with respect to ground truth is of crucial importance. Therefore, the aim of this research is to investigate the creation of an accurate ground truth of an indoor space and to focus on the measurement accuracy and the modeling accuracy in this process. To achieve high accuracy, a total station is used to whose data a Mobile Laser Scanning (MLS) and a Terrestrial Laser Scanning (TLS) point cloud are registered. The quality of the wall surface detection and the registration are assessed.

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2. RELATED WORK

Scan2BIM, i.e. the automatic reconstruction of generalized and abstracted models of buildings from point clouds is still an active field of research (Kang et al., 2020; Pintore et al., 2020). Different approaches range from detecting local plane patches (Nikoohemat et al., 2020b), line segments or corners (Schmidt et al., 2023a) locally and assembling them to room entities to the global detection of planes and their subsequent intersection to cell complices in 2D (Tran and Khoshelham, 2020) or 3D (Coudron et al., 2018). Other approaches hybridly incorporate elements of both strategies (Ochmann et al., 2019) - plane patch assembly and global plane intersection, reconstruct building environments in a discretized voxel representation (Hübner et al., 2021), incorporate the trajectory of a mobile indoor mapping system as an additional source of information (Lim and Doh, 2021) or fit parametrized CAD models of building components into the point cloud (Xue et al., 2019).

A frequently used metric for the evaluation of Scan2BIM approaches has been proposed by Khoshelham et al. (2018). This metric comprised of completeness, correctness and accuracy parametrized by a buffer distance as search radius has been utilized e.g. in the ISPRS benchmark on indoor modelling (Khoshelham et al., 2021). A discrete version of this metric suitable for voxel data has been proposed in (Hübner et al., 2022). However, this metric relies on the availability of reference geometry, either in the form of a point cloud (Anil et al., 2013; Bonduel et al., 2017; Chen et al., 2018; Assali et al., 2019) or a manually created building model (Khoshelham et al., 2018) which, in turn, is derived from a point cloud or manual in-situ measurements.

Thus, Scan2BIM approaches are typically evaluated against the same point clouds they are using as input data or against building models manually constructed based on the same point clouds. In doing so, the point clouds are often considered as ground truth without considering their own inaccuracies. However, when deviations of the derived models from the actual physical building are of interest, the actual accuracy of the point clouds cannot be ignored. This concept is reflected in the guidelines of the US Institute of Building Documentation where a distinction between measured accuracy for the underlying point cloud and represented accuracy for the derived building model is drawn (US Institute of Building Documentation (USIBD), 2016).

Concerning measured accuracy, a large number of works deal with characterizing the measurement quality of indoor mapping systems ranging from static setups with terrestrial laser scanners (Soudarissanane et al., 2011; Calders et al., 2017; Lichti et al., 2022) and mobile laser scanning systems (Lehtola et al., 2017; Tucci et al., 2018; Salgues et al., 2020) over range cameras (Khoshelham and Oude Elberink, 2012; Hou et al., 2023) to even augmented reality entertainment hardware (Hübner et al., 2020) and smartphones (Díaz-Vilariño et al., 2022) which can be used for mapping indoor environments as well.

Other works on evaluation methodology focus on assessing the quality of indoor mapping point clouds (Karam et al., 2018) or reconstructed building models (Nikoohemat et al., 2020a) in the absence of reference data, e.g. by relying topological and geometric consistency constraints or on assumptions about the planarity and orthogonality of room surfaces.

3. METHOD

This chapter describes the steps to create a ground truth (sec. 3.1) with the laser scanning point cloud segmentation and classification (sec. 3.2). Followed by the plane detection and the corner extraction (sec. 3.3). The last section describes our approach for point cloud registration based on corners (sec. 3.4).

3.1 Creating a ground truth

The ground truth is created semi-automatically from measurements with a total station. It is defined by the 8 main corners of a rectangular room. Depending on the room it is not possible to measure the corners directly, because they might be completely hidden or not visible from the position of the measurement system. To measure these model corners despite occlusions, planes are fitted to the walls, ceiling and floor. These planes are intersected to calculate the corner points. They define the ground truth, which is used to evaluate the determination of walls, corners and edges in an indoor scenario using TLS and MLS.

3.2 MLS and TLS wall segmentation and classification

The point clouds from MLS and TLS are preprocessed semi-automatically. In order to filter erroneous points and to classify the points in relation to the surface, the point clouds are manually cropped. Noisy areas and the edges of surfaces are visually assessed and cropped for this purpose. Additionally, an automatic filtering is carried out using the intensity of the laser measurement and planarity of surfaces. Since areas with low intensity are potentially less accurate. The filtered point clouds are manually classified as wall, ceiling and floor.

3.3 Plane detection

For the detection of planes in the point cloud, we use M-Estimator Sample Consensus (MSAC) Torr and Zisserman (2000), an extension of Random Sample Consensus (RANSAC) Fischler and Bolles (1981) on every surface of the room. RANSAC selects three points in the point cloud randomly and counts the inlier points within a threshold. Therefore, the plane lies exactly on at least three points. To avoid this condition, compensating planes based on singular value decomposition were fitted to the inlier points. The use of inliers ensures that gross outliers do not affect the plane.

3.4 Point cloud registration

For the rough registration of the respective laser point clouds to the point cloud from the total station, the wall (W1) of the MLS and TLS are rotated and translated parallel to the x-Axis. The corner of the intersection between W1, W4 and the floor is set to the origin of the coordinate system.

With this rough registration between laser scanning and total station as basis, the least squares method is used on the corner points to ensure an accurate registration at the corners of the MLS and TLS points relative to the total station points. The sum of the least squares from the distances between the vertices from the laser scanner data is iteratively reduced relative to the total station data. The resulting optimal transformation is used to register the original point cloud from MLS and TLS onto the total station ground truth model.

4. EXPERIMENTS

This chapter describes the acquisition and processing of point clouds of an indoor environment (sec. 4.1) and the implemented point cloud filtering and classification (sec. 4.2). Furthermore the creation of the ground truth model (sec. 4.3) and the evaluation of the quality assessment of the planes and ground truth model (sec. 4.4) are described.

4.1 Data collection

This research focuses on data quality. Therefore, one room was examined in detail. For the creation of a ground truth, we measured a conference room at the ground floor of a university building with a total station (fig. 1). A single instrument standpoint was used, to measure the surfaces semi-automatically. To avoid occlusions we removed the furniture from the room for the acquisition. With the total station, flat areas on the walls were measured manually as a polygon. Within this polygons, points were automatically measured in a regular grid (fig. 2). To ensure multiple points per surface, a grid resolution of $0.5\,\mathrm{m}$ was selected for large surfaces and $0.1\,\mathrm{m}$ for smaller surfaces. Since the surface areas of the window front are very small, it is not automatically measurable and points were selected manually as regularly as possible (Fig. 3).

During the measurement process, the points were manually classified depending on the wall, floor or ceiling they are located on (Fig. 1). Additionally, the data sets from Schmidt et al. (2023b) were used, containing the same conference room, surveyed with a mobile laser scanner and a terrestrial laser scanner. These data sets were registered to the ground truth from the total station via the method described in chapter 3.4.

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Figure 1. Representation of the room with the walls (W1, W2, W3, W4), ceiling (C) and floor (F)

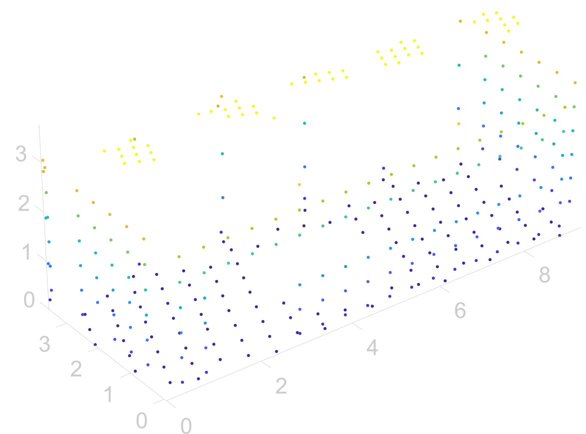

Figure 2. Point cloud of the conference room acquired with the total station, the color represents the height from blue to yellow

4.2 Laser point cloud filtering and classification

The laser scanning point clouds have been filtered manually. Flat wall surfaces were cut out while using the intensity as a guide. A point cloud has been created for each wall, and classified depending on whether it belongs to W1 - W4, F or C.

Alternatively, automatic filtering using intensity and planarity has been used. Planarity has been calculated with a $2\,\mathrm{cm}$ radius, to not filter out smaller surfaces for example on the window front W2. The lower threshold for planarity was set to 0.2 and for intensity to 0.015 This was determined empirically and was necessary to avoid filtering out too much of the area at the window front W2.

Figure 3. Structure of the window front (W2), total station measurement on the bars (red)

4.3 Ground truth model creation

The ground truth model is defined over 8 corners, therefore the intersection points of the 6 primary surfaces in the room are considered, i.e. the surfaces that have the largest surface area. An exception to this is the window front. This consists of metal and glass, which leads to a sparse point distribution and larger errors. The window front was defined using the interior surface area of the beam-like structures between the windows, since the larger glass area cannot be measured using laser-based methods (Fig. 3).

The first step of the plane detection in this scenario uses MSAC with an inlier threshold of $5\,\mathrm{mm}$. All measuring systems have a distance measuring accuracy of about $2\,\mathrm{mm}$. The inlier threshold was chosen as $5\,\mathrm{mm}$ to allow for small measurement errors while avoiding gross measurement errors. By using MSAC, planes lie on 3 points selected randomly from the whole point cloud. Compensating planes are determined from the MSAC inliers in a second step, in order to determine optimal planes.

4.4 Evaluation

To evaluate the quality of the plane determination, the absolute distance of the points classified as belonging to a plane is calculated. From this, the standard deviation per plane is determined. We compare the standard deviation for the manually filtered point clouds and the standard deviation of only the inliers used for the compensating plane. Here it should be noted that for the inliers the maximum possible distance between a point and a plane is 5 mm.

The accuracy of the registration between total station, TLS and MLS is evaluated by the Root Mean Squared Error (RMSE) at the corners of the room. In addition, the mean distance and standard deviation between the point clouds are calculated. We compare the results of our transformation approach via edges with the use of ICP Besl and McKay (1992) for the transformation between the filtered point clouds and the total station point cloud.

5. RESULTS

This chapter shows the standard deviation of the distance between points and planes (sec. 5.1) and the RMSE at the corners after registration (sec. 5.2). As well as the point cloud distances after registration of the filtered point clouds using ICP (sec. 5.3).

5.1 Standard deviation distance between points and planes

Std.	Total station		TLS		MLS	
[mm]	all	inliers	all	inliers	all	inliers
W1	1.9	0.8	1.2	1.0	1.1	1.0
W2	16.3	0.9	10.0	1.4	7.4	1.4
W3	0.9	0.9	1.6	0.7	1.8	1.0
W4	1.8	0.9	1.1	0.9	1.4	1.1
F	1.1	1.1	1.0	0.9	1.3	1.1
C	3.4	0.9	3.8	0.5	2.2	1.2
mean	4.2	0.9	3.1	0.9	2.5	1.1

Table 1. Standard deviation of the planes compared to all points of a wall and only inliers

Comparing the standard deviations of the planes using the complete and filtered point cloud, the walls are between 1 and 4 mm, excluding the window front W2. The high standard deviations of W2 (tab. 1) show the difficulty to measure it with good quality using all three measurement systems. The standard deviation of the distances at the ceiling of MLS compared to TLS as well as to the total station are smaller almost by a factor of two. Using only the inliers from MSAC to calculate the standard deviation shows little difference between the measurement methods with a tendency for minimally larger values for MLS compared to TLS and the total station.

5.2 RMSE at the corners

RMSE [mm]	acquisition	
filtered PCL	TLS	MLS
manually	12.9 – 16.1	26.1 – 31.1
only W2 man.	13.5 – 15.9	30.5 – 34.7
unfiltered	13.1 – 15.5	57.7 – 65.0
automatic	14.1– 17.1	61.2 – 63.0

Table 2. RMSE at the corners (least squares) after transformation between ground truth and laser point clouds with different filtering methods

The RMSE at the corners after registration (chapter 4.2) is at 1.3 to 1.6 cm for TLS and between 2.6 and 3.1 cm for MLS (tab. 2). For the TLS almost no difference can be seen due to filtering of the point cloud in this example. For MLS the RMSE is the smallest with manual filtering, with little differences when only filtering W2. No filtering increases the RMSE by the factor of 2 to 6 cm for MLS.

5.3 Point cloud distances after ICP registration

Distance [mm]	PCL 1	PCL 2	mean	std.
Least squares (corners)	TS	MLS	5.3	4.6
	TS	TLS	2.8	3.1
	MLS	TLS	5.1	4.4
ICP (PCL)	TS	MLS	40.1	29.6
	TS	TLS	39.4	27.2
	MLS	TLS	38.0	29.2

Table 3. Standard deviation (std.) of distance between point clouds (PCL) after registration to total station (TS) with least squares at corners and ICP with point clouds

Using the ICP for registration on the complete and manually filtered point cloud, the standard deviation is at 3 cm. In comparison least squares optimization on the corners of the room shows a standard deviation of 3 to 5 mm (tab. 3).

6. DISCUSSION

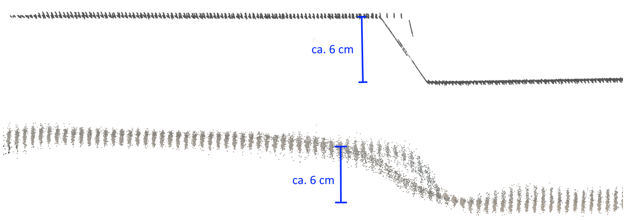

Figure 4. Right angle wall offset on wall W3 and laser measurement with TLS (top) and MLS (bottom)

Figure 5. Right angle wall offset on wall W3

In general, the differences in the standard deviations of the planes between the different measurement systems are very small, especially when only considering the inliers selected by MSAC. The standard deviation over all points allows to estimate the quality of the point cloud per wall, but also depends on the filtering of the point clouds. The standard deviation of

Figure 6. Ceiling (C) with panels and beam structure

the inliers cannot be used to determine the accuracy of the fitted plane in individual walls due to the small differences. The differences in the standard deviation of the plane at the ceiling between MLS compared to TLS and the total station suggest that the nearly complete coverage of the ceiling has a impact on the accurate determination of the plane of the ceiling in this scenario. The almost infinite viewing angles with MLS-system seem to be more important than the better measurement accuracy which the other systems provide.

The registration method was chosen to reduce the errors at the corners which represent the ground truth. The results lead to the conclusion that an accuracy below 1 cm is difficult to achieve. Since the differences between the point clouds after registration with our method are between 3 to 5 mm, it is seen as more accurate than using ICP with the complete manually filtered point clouds. But it is not possible to distinguish between errors caused by the transformation and errors caused by the determination of corners and edges in our evaluation.

The differences between manual filtering and no filtering are very small for TLS. For MLS the differences for W1, W3, W4, C and F are small, but very large for W2. So, we conclude that a manual filtering of surfaces which are difficult to measure is very important for MLS. But the filtering has little influence in this scenario for TLS and most surfaces in MLS. The implemented automatic filtering didn't lead to any benefits in accuracy for MLS and TLS.

Measurement errors and post-processing of the point clouds lead to rectangular edges not being detected as such (fig. 4). In addition, W3 shows a slight offset of 6 cm in the area of one corner. Since the used approach defines only the plane of the dominant wall, the corner points of the ground truth do not match the actual corner points (fig. 5). Depending on the definition of the corner, corners are hardly measurable with laser scanning. Accordingly, a ground truth, which must be created under certain assumptions, may not agree with an automatic detection of the spatial geometry at such locations. Similar problems exist on the ceiling, which consists of individual elements that together form a surface interrupted by beam-like structures (fig. 6). At this point, the definition of a corner between a ceiling and a wall from the point of view of building science differs from a corner created from the intersection of planes. A ground truth has to be very detailed here, which is complicated by occlusions, in order to meet all conceivable requirements, for example for the capture of BIM models.

7. CONCLUSION

We created a ground truth consisting of corners, edges and planes for laser scanning point clouds. We used a total station and focused on accuracy.

To determine the quality of the model of a single wall the standard deviation isn't sufficient in this scenario. The difference in standard deviation between the measurement systems is small (tab. 1), while the errors of the generated ground truth at the corners of the room show large differences (tab. 3). Therefore, no absolute statement can be made about the accuracy of the ground truth model. However, by reducing influencing factors such as erroneous measurements and misclassified points by means of total station measurement, the reliability can be increased.

For the correct determination of the walls with this method manual filtering is necessary with laser scanning, depending on the acquired surface. Additionally, the planes which represent a wall have to be defined manually in some cases to create the ground truth, because depending on the wall structure, for example at the window front, the definition of a plane is not unique. Alternatively, every detail must be captured for a wall, or the outermost surface. If this is a glass surface, a ground truth can only be modeled manually, because it is not measurable with laser measurements.

To transform between the ground truth and the laser scanning point clouds, the chosen transformation approach, using least squares over the corners is very suitable for registering building point clouds from different sensors in this setting. This is shown by the small point cloud distances compared to ICP (tab. 3).

Since the registration of the ground truth introduces errors, which can be avoided by creating a ground truth directly from a point cloud using only one measurement system. Additionally this reduces the effort for the measurement, which is generally the highest with total station measurement and lowest with MLS. TLS is in between, depending on the number of acquisition positions.

This research presents a workflow in creating an accurate ground truth, focusing on corners, with a total station for laser scanning point clouds. We show good accuracy using least squares for the corners of a room.

8. OUTLOOK

To avoid time consuming manual point cloud filtering a sufficient method for an automatic filtering is important. The use of geometric point cloud metrics in combination with a semantic segmentation of surfaces could be able to solve this problem. We focused on a simple ground truth and high accuracy of one room, in further research the creation of a more detailed ground truth is necessary, which contains not only one room, but also a whole building. It needs to be investigated whether the approach can also be applied to whole buildings. Especially the registration when passing through doors, can be very challenging for the measurement systems used. Hübner et al. (2019), for instance, have shown in their evaluation of a low-cost indoor mobile mapping system, that large drift effects can occur when passing through doors in poorly textured, unfurnished indoor environment.

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