A first step towards automatic construction progress monitoring

Authors: Noaman Akbar SHEIK, Greet DERUYTER, Alain De WULF, Peter VEELAERT (Belgium)

Key words: construction progress monitoring, BIM, scan, registration, point cloud

SUMMARY

Monitoring the progress of construction projects is important for early detection of structural defects, just-in-time delivery of construction materials, planning of activities, efficient deployment of workers, etc. Especially for large projects, the need for semi-automated progress monitoring is emerging. On the one hand, the 3D data acquisition of the as-built environment has become rather simple by means of advanced techniques such as laser scanning. On the other hand, also the design process underwent a revolution as designing moved from CAD to BIM.

Notwithstanding both evolutions, there is still a missing link, because often the as-built point clouds resulting from laser scanning and the as-planned BIM model are created in different reference systems. Hence, the as-built model has to be integrated with the as planned manually, in order to make their comparison possible. This integration involves a process called registration, during which the as-built model is transformed into the same reference system as the BIM, thus making the assessment of the construction progress possible.

In the research at hand, two novel methods were developed to automate the registration process. The purpose of this paper is not to explain the methodology in detail, but to demonstrate the results for different scenario's and cases.

It can be concluded that both methods have good results, even if the building is only partially finished and clutter (e.g. construction materials and machinery) leading to occlusions in the point clouds is present, provided some boundary conditions are met.

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1. INTRODUCTION

Accurate progress monitoring of under-construction buildings is a critical factor for successful project management [1-7]. It saves time and cost of the project by timely detecting the deviation and non-conformity from the project schedule and design [8-10]. The current practices of construction progress monitoring heavily depend on manual measurements, which are not only time consuming, but also may lead to missing or error-prone information, hence, demand accurate and automated solutions [11-13]. Recently, numerous studies adopted a model-based assessment to perform automated progress monitoring in which the three dimensional (3D) scan model of the existing building is compared to the corresponding BIM design model [5]. The comparison, also known as ’Scan-vs-BIM’, results in the structural differences between both models which are then interpreted to provide progress information. However, effective progress monitoring through ’Scan-vs-BIM’ requires the accurate geometrical alignment of both models through a registration step [14].

Registration is an extensively studied research focused primarily on the alignment of different scans of the same scene instead of on the alignment of BIM with its scan [14]. Generally, the registration of two models is performed in a coarse-to-fine scheme in which a rough alignment is performed through a coarse registration that is later refined with a fine registration. The direct application of fine registration, mostly performed with iterative closest point (ICP) algorithms [15-18], may fail as it requires the initial rough alignment of both models. Although, various coarse registration solutions for different applications and scenarios are proposed and they may perform well with the simple point cloud, their success is limited when applied to large or complex point clouds of buildings [19]. In coarse registration, the extraction of geometric features followed by the identification of their match to compute the transformation, are critical steps. The most robust techniques utilize plane features to identify matching pairs in both models [20,21], however, they still face many challenges including the lack of discriminatory features and distinct invariants to identify matching features.

Numerous studies proposed automated methods for different environments and applications, yet, their success is limited to simple point clouds or certain scenarios, hence, they may fail in case of large or complex building scans [19]. Similarly, clutter present at the construction site during scanning results in noise and occlusions that may restrict the effectiveness of the registration techniques. Furthermore, there is limited research focused on the alignment of incomplete building scans with their BIM model, hence, the registration of building models for progress monitoring still remains a challenge. Therefore, the current research addresses the registration problem in the context of progress monitoring. This paper demonstrates the results of two novel methods to perform the registration of building scans with their corresponding BIM model and addresses the difficulties by extracting features from plane segments and process them through a unique scheme to identify their matching pairs.

2. RELATED WORK

Registration can be defined as the alignment of various models or scenes through their matching geometrical information by calculating the rotation and translation parameters. Registration can be divided into coarse and fine registration in which the latter can accurately align the models, however, it requires some good initial alignment that is achieved through the coarse registration, hence, a coarse-to-fine registration strategy is applied [22]. The fine registration is already well-established due to its popular techniques including the ICP algorithm [15] and its variants [23-25]. However, coarse registration is still undergoing numerous challenges and many studies have attempted to address those challenges.

Generally, the coarse registration performs the registration based on the geometric features present in the models. This involves the extraction of features from models and then identifying the matching features to compute the transformation. The extraction of geometric features includes choosing key points or specific primitives from their geometry, instead of using the complete model to reduce computation, and increase the matching identification [26].

According to the features types, coarse registration can be categorized into point-based or primitive-based approaches.

The point-based approaches such as scale-invariant feature transform (SIFT) key points [27,28], virtual intersection points [29], FPFH key points [30], speeded up robust features (SURF) key points [31], and semantic feature points [32,33] to register point clouds are sensitive to noise and varying point density. Furthermore, their efficiency is also reduced in large datasets [34].

In comparison to points, primitive-based approaches utilize lines, planes, or curved surfaces as geometric features and are proven to be more robust in identifying matching features [26]. Planar surfaces present in the models are also employed in many studies [14,20,34-39]. These planar surfaces are extracted from point clouds using segmentation techniques such as Random sample consensus (RANSAC) segmentation [40-42], region growing [43], voxel-based growing[34], Hough transform [44], and dynamic clustering [39]. These plane-based techniques perform well in urban infrastructures including buildings enriched with significant planar features [22]. However, the quality of the extracted plane segments influences the efficiency of plane-based techniques. Furthermore, the inaccuracy in normal values of plane segments can lead to the identification of false matching planes [26]. To accurately identify matching plane segments, discriminative primitives, also defined as descriptors, are used. A lack of distinct and reliable descriptors may hinder the matching process. Consequently, some studies prefer to manually identify the matching planes [45], however, recent and current research aims to address this problem efficiently in an automated way. Some studies utilize the geometric information acquired from a set of three planes. For example, Dol and Brenner [35] performed the search using the tripe product of plane normal to find their matching pairs. The search process terminated with the acceptable outcome where the combinatory complexity was reduced using several geometrical constraints including the area, mean intensity values, and bounding length, however, the experimental details were not published [21]. Similarly, Brenner, et al. [46] used the angles between the three planes for matching. Theiler and Schindler [29] addressed the matching problem by extracting the virtual tie points obtained from the set of three planes using the descriptors in which the distance within the tie points was used as the matching invariant. To reduce the combinatory complexity, candidates were limited to using a specific threshold. However, this method didn’t address the additional tie points from the non-intersecting planes at symmetrical distances. Similarly, the utilization of only distance constraints may not be reliable to identify matching pairs. Furthermore, the success rate was also found to be sensitive to high noise and occlusion. Xu et al. [34], addressed the matching problem through a coordinate frame computed from the normal values of three planes in a RANSAC-based

strategy. In each iteration, transformation parameters obtained from the corresponding coordinate frame of planes were assessed according to the number of coplanar patches. In the end, transformation with the highest coplanar patches was finalized. The limitation of this method is that models with many parallel planes may end up with incorrect transformation parameters due to the adoption of only coplanar criteria. Furthermore, Li et al. [39] proposed a registration method with two strategies to identify the set of three matching planes intersecting at a point, based on their relative angles. The first strategy identifies matches between sets of planes having different relative angles with each other. If the relative angles are not different, the method utilizes the second strategy that finds matches between sets having at-least one perpendicular relative angle. This method may also fail if there are too many planes because the utilization of only angle constraint makes it unreliable. None of the mentioned methods and studies were used in the context of construction progress monitoring where the scan model is aligned with the BIM model.
In studies addressing the Scan-vs-BIM problem, Kim, et al. [48] used a coarse-to-fine strategy for registration of the as-built point cloud with the CAD converted as-planned point cloud. The coarse registration employed the Principal Component Analysis (PCA) [49] which involves the determination of the rotation based on the principal components of the model, whereas the translation is calculated from the model centroids. The real-life scan model includes noise and occlusion, therefore, the practicality of this method is limited as the method assumes that both models have the same matching centroid and the same direction of principal components. The two assumptions are valid if both models are duplicates of each other. Even though the aforementioned studies offer many solutions, however, the registration of the building model as Scan-vs-BIM is still a challenge mainly due to the lack of discriminatory features and distinct invariants for matching detection.

3. METHODOLOGY

Buildings structures often have orthogonal geometries with evident plane segments, such as roofs or walls, and corner points. The proposed methods extract this geometrical information from the corresponding building models and then identify their matching pairs to compute the transformation parameters. To find the transformation, the first method directly utilizes the plane segments through a minimization process, while the second method employs the corner points as points of interest, based on various geometric invariants. The corner points are also developed as the results of the intersection of three plane segments, therefore, the extraction of plane segments is needed in both methods. An example of segmented plane segments from a model is shown in ***Figure 1***. The workflow to extract the plane segments from the scan and IFC-based BIM model of the building is shown in ***Figure 2a*** and ***Figure 2b*** respectively. A brief explanation of the workflow of both methods is explained in the next paragraphs.

The overall workflow of the first (plane-based) method is shown in ***Figure 3***. First, in both models, the extracted plane segments are grouped based on their orientation, which results in clusters of parallel plane segments. Then, the directions of the plane clusters from both models are further processed to find the possible rotation matrices. Accordingly, the directions from all possible combinations of at least three clusters from both models are compared. The rotation matrices that align the corresponding cluster directions from both models are computed followed by the calculation of the respective translation vectors for each of the computed rotation matrices. Finally, the determined transformations are evaluated to identify the most likely set of transformation parameters, by a proposed computational framework that measures the likelihood of matching by means of a minimization process. The directional assessment confirms the potential matching plane segments are parallel to each other, whereas the translational assessment ensures the minimum translation between matching plane segments using the centroid values. As the method also enables the identification of matching plane segments, the accurate translation is computed from the best-matched plane segments to further refine the translation parameter. Finally, by applying the transformations parameters, the as-built model of the incomplete building is registered to its as-planned model, which makes it possible to use the proposed method for the comparison of under-construction buildings with their design, which is a necessity for effective progress monitoring. Also, the identification of the matching planes, which represent the building's structural components, between both models allows for the individual inspection of building components, needed for progress monitoring.

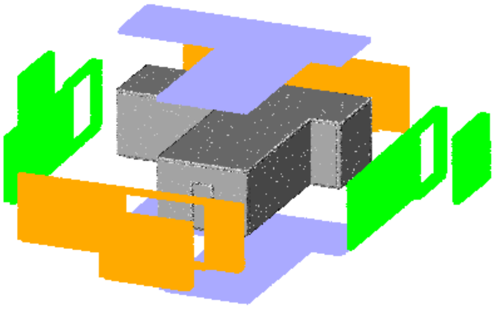


Figure 1. Visualization of plane segments extracted from the model.

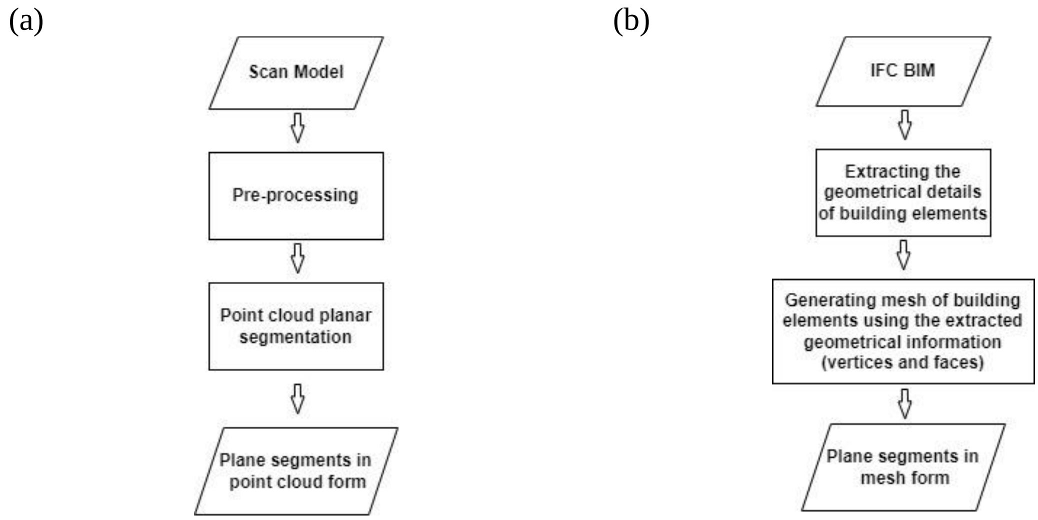


Figure 2. Flow chart for extracting the plane segments from (a) Scan, and (b) BIM model.

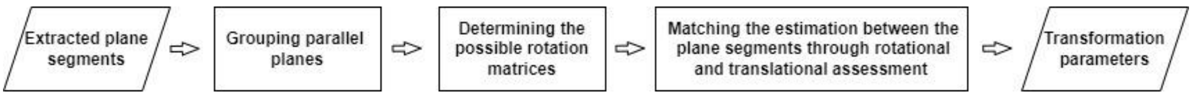


Figure 3. The overall methodology of the plane-based method.

The second method, as shown in ***Figure 4***, consists of three major steps. The first step finds the corner points in the models from all possible combinations of intersecting plane segments. The potential matching points are identified based on (1) the property that if a pair of two corner points from both models are matching, the distance between the two points is the same in both models, (2) the angles between the intersecting plane segments of both matching points should be the same, and (3) the rotation, as well as the translation obtained from both matching points, should also be the same. Normally, a large model can result in a high number of plane segments ultimately leading to huge numbers of corner points, which can result in extremely high computation times. Therefore, a random selection of corner points through RANSAC is performed. After the identification of potential matching points, first duplicate points are removed after which the remaining points are clustered according to similar transformation parameters. Then, the most likely transformation is recognized based on the property that the correct transformation aligns all matching corner points. Therefore, the cluster for which the transformation results in the highest number of aligned corner points is considered to be the correct one. In the last step, the most optimal transformation is selected as the one that yields the minimal error to align all the matching corner points into each other. In addition, plane segments can also be detected by identifying the corresponding intersecting planes of matched corner points. hence, this method also enables the registration of scans of partially completed buildings with their BIM model.

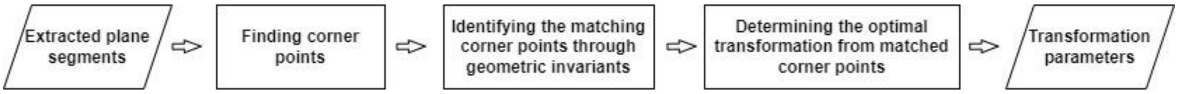


Figure 4. The overall methodology of the corner point-based method.

4. RESULTS AND DISCUSSION

Both methods were tested on a range of simulated and real-life datasets. The two simulated datasets (A1, A2) were artificially developed to assess the proposed methods without effects of noise or outliers. BIM models, representing single floor buildings with an equal number of nine plane segments (***Figure 5***), were converted into point clouds which then served as scanned models. These artificial scan models were then subjected to random transformations.

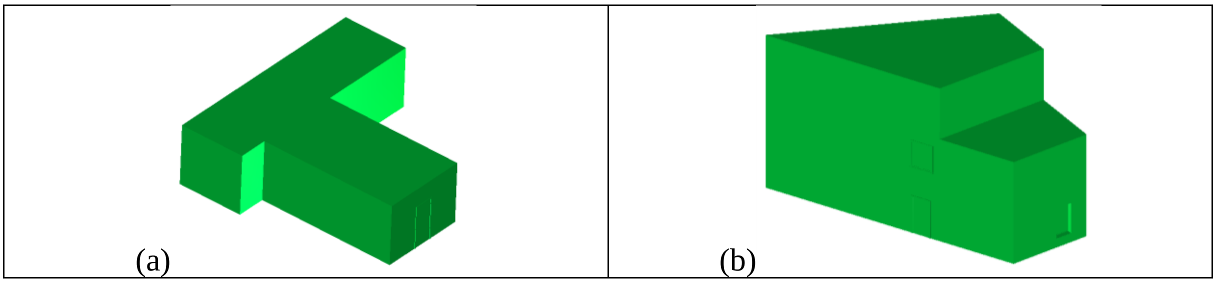


Figure 5. simulated 3D models developed for (a) dataset A1 and, (b) A2.

The two real-life datasets (B1, B2) include a conference room and a large educational building for which the scan models were acquired through laser scanning, while their respective BIM models were manually prepared. The point clouds of dataset B1and B2 contain 79,537,667 and 64,773,370 points respectively and are shown in ***Figure 6*** along with their BIM models.

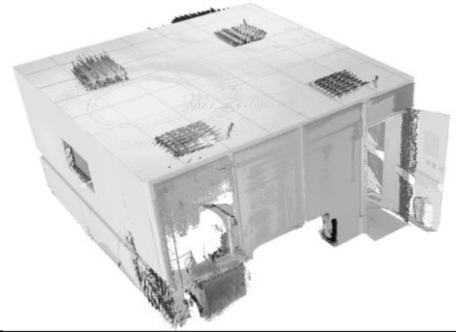
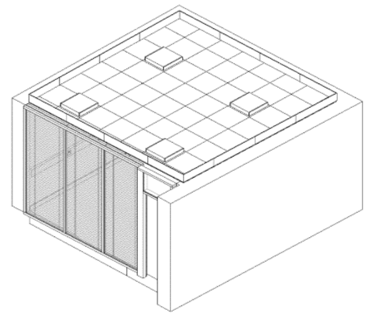
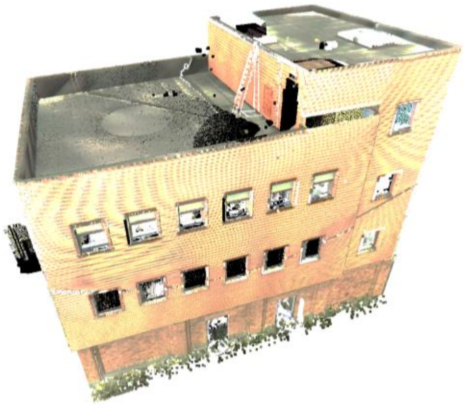
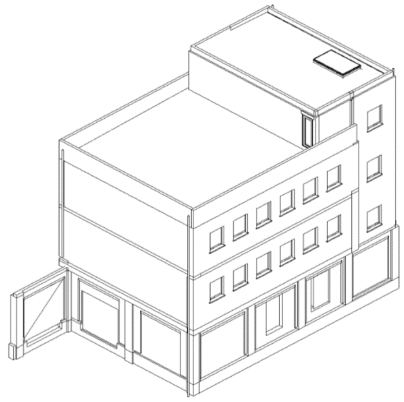
	Scan model	BIM Model
(a)		
(b)		

Figure 6. visualization of the point clouds and BIM models for datasets (a) B1, and (b) B2

During the testing, the as-built point clouds were down-sampled with a voxel size of 0.2m. The plane extraction was performed by means of RANSAC segmentation using 1000 iterations. Similarly, a suitable tolerance value was also set to verify the geometrical invariants according to the errors in the point cloud. Although the real-life point clouds were both distorted by the occurrence of noise and occlusions, the results show that both methods performed the registration successfully. The registered models of all the datasets are visualized in ***Figure 7***.

The registration accuracy of both methods was evaluated through a comparison of point clouds with their corresponding BIM models (ground-truth). To assess the registration accuracy, the average values off 100 separate transformations - based on the same the plane segments - were considered. Using the same plane segments in each transformation, rules out deviating initial parameters as a result of using RANSAC, which would hinder the fair comparison of the transformation itself in both methods. To evaluate the results, the rotation and translation errors, along with the root mean square error (RMSE) were assessed. The evaluation results (*Table 1*), demonstrate good accuracies for both methods in simulated as well as in real live situations, however the corner point-based method performs significantly better for all considered parameters. The explanation is to be found in the fact that the plane-based method directly utilizes the centroid of the plane segments, which can be affected by the presence of noise or occlusions. In the corner point-based method, on the other hand, the accuracy of the calculation of the intersections of plane segments using their normal values, is not significantly affected by the presence of noise or occlusions.

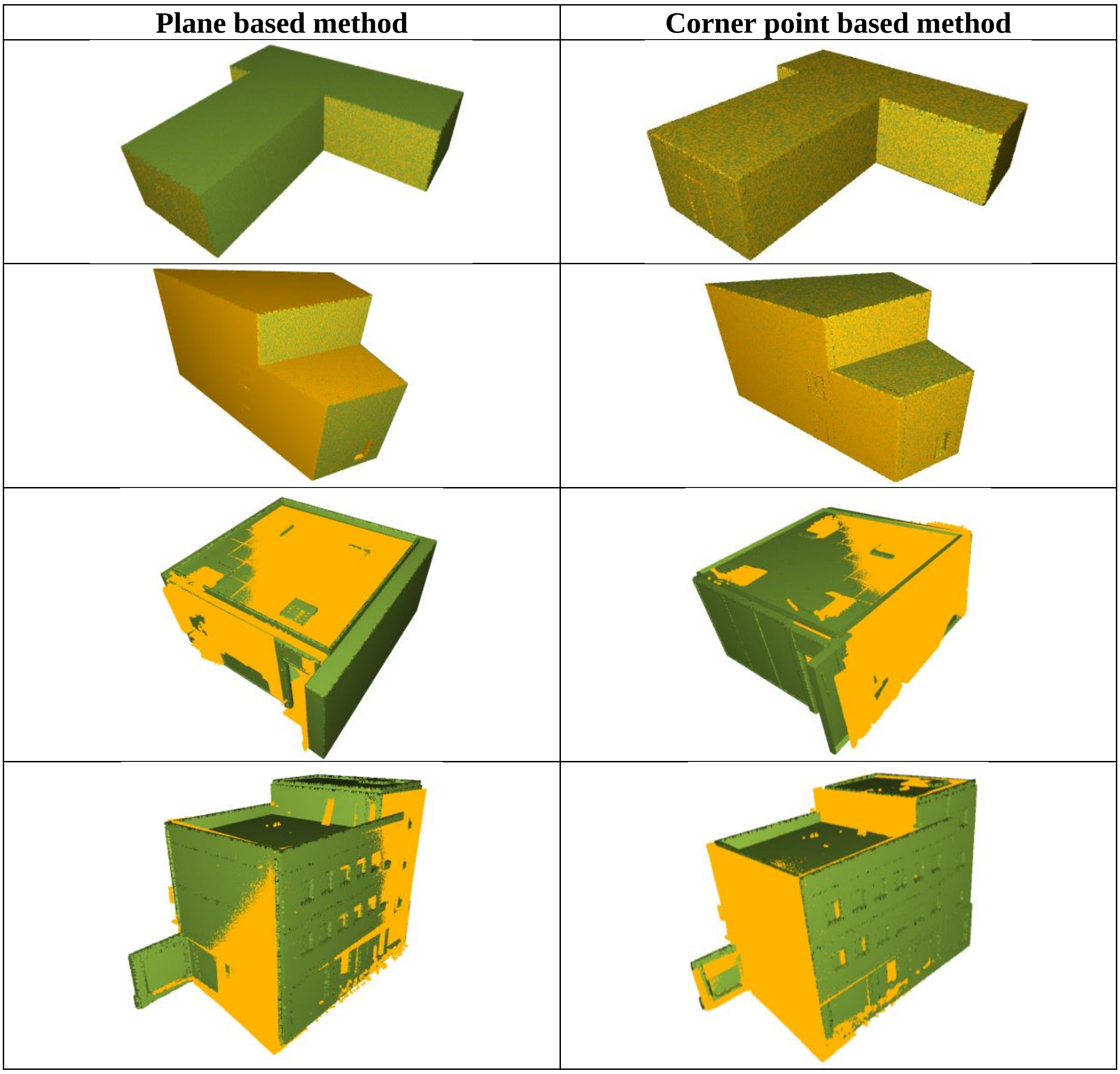


Figure 7. Visualization of registered models of all the datasets processed through (a) Plane based method and, (b) Corner point-based method.

Table 1. Registration accuracy results of both methods according to each dataset

	Plane based method			**Corner point based method**		
Datasets	**RMSE (mm)**	ϵ_R **(°)**	ϵ_t **(mm)**	**RMSE (mm)**	ϵ_R **(°)**	ϵ_t **(mm)**
A 1	7.186	0.007	29.164	7.519	0.002	4.036
A 2	8.792	0.005	35.385	8.485	0.003	7.821
B 1	18.119	0.027	94.267	15.884	0.015	37.649
B 2	17.781	0.021	107.142	16.139	0.009	39.725

Further testing, however, also revealed that to obtain good results, some initial conditions have to be met.

The plane-based method requires two conditions: (1) the scan model needs at least three plane segments in distinct directions for the correct calculation of the rotation matrix, and (2) the size of most plane segments in the scan model should correspond to their matching plane segments for the minimization process to work correctly. This is illustrated in ***Figure 8***, where the simulated dataset of the partially built model contains only plane segments in two distinct directions leading to incorrectly computed transformation parameters.

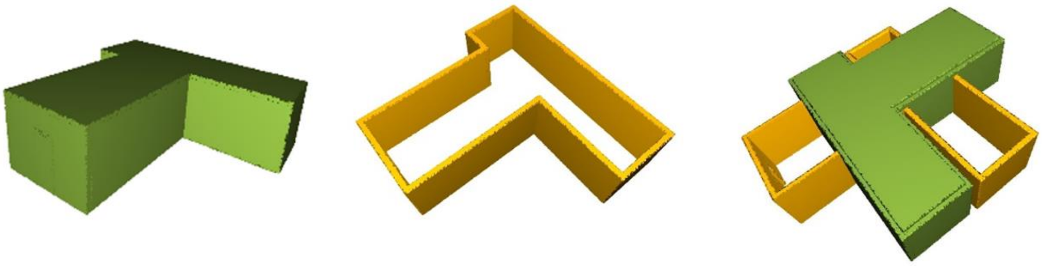


Figure 8. Visualization of unsuccessful registration of dataset with partially built scan model using the plane-based method

In contrast, the simulated dataset of the partially built model in ***Figure 9*** contains less segments, but having three distinct directions, this does not hinder the registration process.

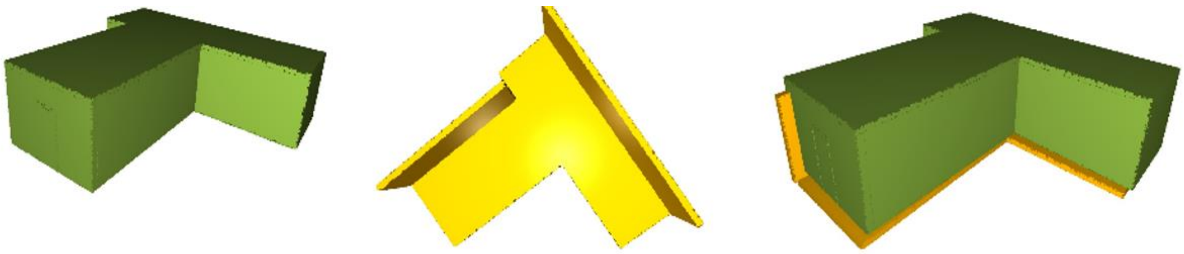


Figure 9. Visualization of the successful registration of dataset with partially built scan model using the plane-based method

As compared to the plane-based method, the corner point-based method requires at least two corner points in the scan model, otherwise, the method will fail. Although the extraction of a corner points already requires the presence of three plane segments in distinct directions, the registration still fails if there is only one corner point, because the need for at least one pair of corner points from both models during processing to confirm the geometric invariants. Furthermore, at least one corner point, in terms of its position with others, should be non-symmetric as well. ***Figure 10*** demonstrates that if all the corner points extracted from the dataset (***Figure 10a***) of partially built building model are positioned symmetrically, then an incorrect transformation (***Figure 10b***) can be computed based on the correspondence to non-matching points (***Figure 10c***). Therefore, this method demands the presence of at least one asymmetric position of corner point among the other symmetric points to accurately identify the correct transformation.

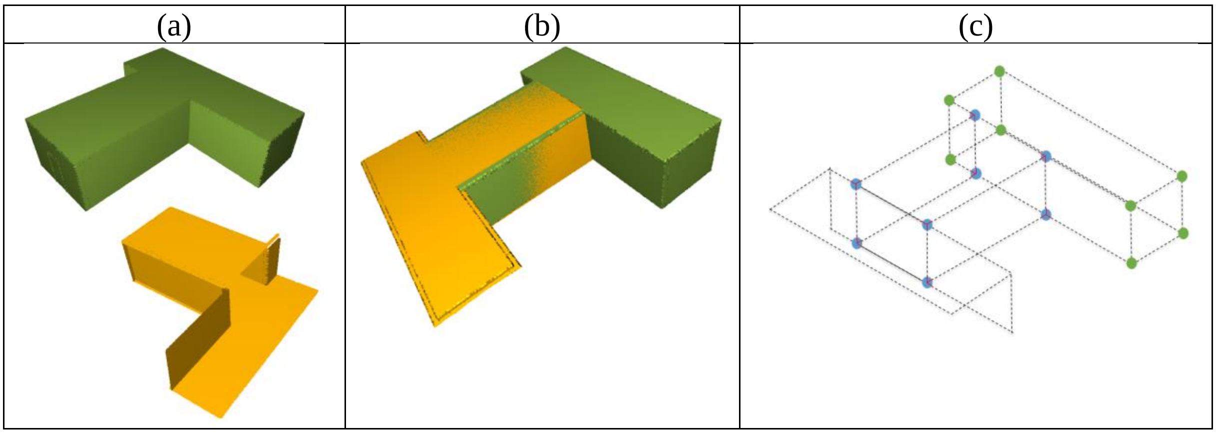


Figure 10. Visualization of (a) Models before registration, (b) Incorrectly registered models and, (c) Corner points of Incorrectly registered models

Although the corner point-based method is relatively more accurate, the plane-based method is more suitable for datasets with scan models having a low amount of structural components already constructed.

5. CONCLUSION

The accurate registration of a scan model with its BIM model is critical for construction progress monitoring using the model-based assessment. The current paper details the literature to study the registration problem and then briefly explains two novel methods to register the scan and BIM models in terms of construction progress monitoring. Buildings often have orthogonal geometries with dominant plane segments. Based on that, both new proposed methods identify the matching features from the models to compute the transformations. After extracting the plane segments, the first method directly utilizes the plane segments of the building as matching features while the second method finds the corner points obtained from the intersection of plane segments.

Both methods were extensively tested and validated successfully on simulated and real-life datasets. The dependence of both methods on plane structures of the building makes them less sensitive to noise and outliers, thus enhancing the overall reliability. Furthermore, both methods also proved their ability to register partially built scan models, which is a big step forward in automated construction progress monitoring, provided a minimal number of three planes with distinct directions is already constructed. The corner point-based method proved to be more accurate as compared to the plane-based method, however, the latter requires the presence of fewer matching plane segments for registration of datasets with partially built scans. Along with the transformation parameters, these methods also enable the identification of the matching planes between both models. These planes represent the building's structural components and their identification is a prerequisite for the individual inspection in progress monitoring. This distinction enables the application of the proposed method in under-construction buildings, which is a necessity for effective progress monitoring.

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CONTACTS

Noaman SHEIK, Greet DERUYTER, Alain De WULF, Peter VEELAERT
Ghent University
Sint-Pietersnieuwstraat 41, Technicum blok 2,
9000 Gent
Belgium
Phone:+32 09 3313261
noamanakbar.sheik@ugent.be, greet.deruyter@ugent.be, alain.dewulf@ugent.be, peter.veelaert@ugent.be
Website: Ugent.be