PLANE-BASED COARSE REGISTRATION OF 3D POINT CLOUDS WITH 4D MODELS

Frédéric Bosché

School of the Built Environment, Heriot-Watt University, Edinburgh, Scotland
bosche@vision.ee.ethz.ch

ABSTRACT: The accurate registration of 3D point clouds with project 3D/4D models is becoming more and more important with the development of BIM and 3D laser scanning, for which the registration in a common coordinate system is critical to project control. While robust solutions for scan-model fine registration already exist, they rely on a fairly accurate prior coarse registration. This paper first shows that, in the context of the AEC/FM industry, the scan-model coarse registration problem presents specific (1) constraints that make fully automated registration very complex and often ill-posed, and (2) advantages that can be leveraged to develop simpler yet effective registration approaches. A semi-automated system is thus proposed that takes those characteristics into account. The system automatically extracts planes from the point cloud and 4D model. The planes are then manually but intuitively matched by the user. Experiments, comparing the proposed system to registration software commonly used in the AEC/FM industry, demonstrate that at least as good registration quality can be achieved by the proposed system, but more simply and faster. It is concluded that, in the AEC/FM context, the proposed plane-based registration system is a compelling alternative to standard point-based registration techniques.

Keywords*: Coarse Registration, Laser Scan, Point Cloud, 3D, 4D, CAD model*

1. INTRODUCTION

Dense laser scanning (or LADAR) is now being slowly but steadily adopted on building sites. One first reason is that many large capital facility owners realize that this technology is actually able to capture, at constantly lower price, the as-built three-dimensional (3D) status of their facilities, which is critical for them to control the quality of the delivered asset and subsequently accurately plan and design maintenance operations and future developments. The US General Services Administration (GSA), one of the world's largest facility owners, is one key investigator of this technology [13]. Secondly, large contractors have identified laser scanning as a technology enabling them to perform critical dimensional quality control accurately, comprehensively and rapidly, thus reducing the risk of late-identified errors that are very costly to correct, and improving the quality of the delivered facilities [6].

Laser scanners produce dense 3D *point clouds*. An important particularity and limitation of laser scanners is that they can only acquire points with line of sight. As a result, in order to acquire comprehensive data from a given scene, multiple scans must generally be acquired from different viewpoints and then accurately registered in a common coordinate system. Furthermore, in the AEC/FM context, the purpose of acquiring laser scans is typically to measure the *as-built 3D status* and compare it with the design (i.e. *as-designed 3D status*). AEC/FM projects are more and more designed using 3D CAD engines (extending to BIM engines), which offers the possibility to directly compare the site laser scanned point clouds with project 3D models by aligning them in a common coordinate system. As a result, there is a strong need for accurate and efficient methods for co-registration of site laser scans (here called as *scan-scan registration*), but also co-registration of site laser scans with project 3D CAD/BIM models (here called *scan-model registration*).

Independently of the data sets to be registered, 3D data registration typically consists in two steps: (1) a coarse registration step to "roughly" align the datasets, followed by, (2) an automated fine registration step to optimally align them. The fine registration of 3D data is a well studied problem with known robust solutions based on the Iterative Closest Point (ICP) algorithm [1][2][14], or the Generalized Procrustes Analysis [7]. Here, we more particularly focus on the problem of the coarse registration of a laser scan with a 3D (CAD) model, for which satisfactory solutions do not necessarily exist, especially in the AEC/FM context.

The coarse registration of two 3D data sets is best achieved by matching corresponding 3D features in the two data sets. This however requires the robust identification of matching features. Currently available and used software packages in the AEC/FM industry typically employ a manual point-based matching approach: the user manually selects and matches pairs of points (at least three pairs are required). This approach is however not always reliable because of the scan point selection stage: it is quite difficult to travel through and visualize point clouds to find and select the points of interest. Inaccurate selections are common.

Other generally fully automated approaches have been suggested in the literature, but mostly outside the AEC/FM context and focusing on the scan-scan registration problem. Their goal is to automatically extract and match salient features from the point cloud and 3D model. Numerous features have been investigated such as points [11][5], lines [10], surfaces [3][8] and also combinations of these [9][12][15].

In particular, the approach in [8] is based on surfaces with homogeneous curvature (e.g. cylindrical and planar surfaces). Surfaces are preferred to points because they are more likely to be visible in multiple scans. However, this approach seems limited to parts with very distinctive surfaces, which significantly simplifies the matching stage.

2. AEC/FM CONTEXT

The AEC/FM context presents some specific advantages that can be leveraged during the registration process, but also some specific constraints that must be dealt with. The following five are particularly identified:

Simple surfaces (advantage): From a geometrical point of view, the built environment tends to be composed of 3D elements with "simple" geometries, whose envelops can be decomposed into a set of planar, cylindrical, spherical and toriodal surfaces. Of those, planar surfaces are by far the most common. As a result, it appears appropriate to use planar surfaces as registration features. Furthermore, these are often clustered into vertical and horizontal planes.

Vertical Axis (advantage): Laser scans are typically acquired with knowledge of the direction of the axis normal to the ground, which typically corresponds to the vertical axis of the project 3D CAD/BIM model.

Self-similarities (constraint): Although buildings are composed of objects with simple surfaces, they also typically present numerous self-similarities resulting from the common use of symmetries in designs.

Noisy data (constraint): Construction laser scans are often acquired in cluttered environments with many objects that are not part of the actual building under focus (e.g. equipment, temporary structures). These objects create occlusions reducing the amount of points acquired from the building of interest, and the points acquired from them represent obstacles to the registration process: (1) they may represent a large portion of the scans, and (2) they contain data from objects composed of planar, cylindrical, etc. surfaces. Cleaning a scan from this data prior to performing registration is far too complex and time consuming to be considered.

Multiple objects (constraint): Compared to the different contexts in which scan-model coarse registration has been investigated (such as in [8]), in the AEC/FM context, a project 3D model is not made of a single object, but hundreds. Additionally, not only do many objects present individual self-similarities, but many objects are also similar (often identical) in shape to each other, and the global model itself presents numerous self-similarities.

In conclusion, previously proposed automated feature-based approaches, such as the one in [8], would likely perform poorly due to the presence of numerous surface self-similarities in the project 3D model and site scans. Additionally, as discussed previously, software packages currently used in the AEC/FM industry for 3D data registration perform coarse registration using 3D point features, which requires tedious user interaction, and may lead to non-optimal (and sometimes erroneous) registrations.

3. PROPOSED APPROACH

Based on the context analysis, a semi-automated plane-based coarse registration system is proposed. It is developed with two assumptions:

- The elements composing the project 3D model are converted into meshes. Such representation is very common in computer science applications because it is simple to handle while able to preserve shape information.
- The model and point cloud are both oriented so that their vertical (Z) axes correspond (with some allowance for small deviation). As a result, the number of unknown registration parameters is reduced from six to four (X, Y and Z translations, and Z rotation).

With these assumptions, the registration process is decomposed into three stages:

1. Automatic extraction of all vertical and horizontal planes present in the model and several major ones in the point cloud.
2. Alignment of the model and point cloud in the X-Y plane (X-Y translation and Z rotation) using two compatible matches of non-parallel planes.
3. Alignment of the model and point cloud along the Z axis (Z translation), using one match of compatible planes.

3.1. Plane Extraction

Horizontal and vertical planar surfaces are extracted from the 3D model by simply iterating through all the faces of the objects that constitute it. If a given face is aligned to any planar surface found until then (i.e. with their normal vectors pointing in a similar direction, and with the face's vertices located in the neighborhood of that surface), then it is assigned to that surface. Otherwise, a new planar surface is created to which that face is assigned.

Compared to previously proposed surface-growing approaches, the planes extracted with this approach may include non-contiguous mesh faces, and more particularly from faces of different objects.

For extracting planar surfaces from a point cloud, a RANSAC [4] algorithm is used. The proposed implementation however differs from a basic RANSAC approach in three ways:

<u>Returning a limited number of planes</u>: Instead for searching for all planes, the search continues only if: (1) less than N_{min} horizontal planes (Z) or less than $2 \times N_{min}$ vertical planes (X-Y) have been found so far; or (2) the list of vertical planes found so far does not contain any pair of planes that are not parallel to each other; or (3) another well-supported plane has been found at the current iteration and less than N_{max} planes have been found so far; or (4) the maximum number of attempts to find good planes A_{max} has not been reached. In the proposed implementation, N_{min}=1, N_{max}=15 and A_{max}=25.

<u>Accepting well-supported planes</u>: During the search of a new plane, once a plane with significant support from the data is found, it is accepted as the best plane before all

RANSAC iterations have been completed. While this significantly accelerates the plane extraction, it may also result in a non-optimal plane being chosen. In order to cope with this risk, four measures are taken including:

1. No such plane is accepted before 25% of the RANSAC iterations, $I_{max,1}$, have been gone through.
2. The threshold for accepting such a plane is set sufficiently high: a plane is accepted if the surface covered by the points supporting it is larger than a threshold $Surf_{min}$ ($Surf_{min}$=2m^2).
3. One iteration of fine registration [2] is applied to each sufficiently supported plane, to cope with well-supported but yet locally suboptimal planes.
4. After planes have been found, the similar ones are combined (i.e. with similar orientation and supporting points close to the other plane).

Testing only relevant point triplets: At each RANSAC iteration, a sub RANSAC loop (with $I_{max,2}$ iterations) is used for searching for point triplets that are within $Dist_{triplet}$ max distance from one another and that form planes that are either vertical or horizontal. Only such a triplet is considered as candidate for further testing, i.e. searching for supporting points in the rest of the data. This choice is made, because (1) we are only interested in vertical and horizontal planes, and (2) points belonging to a common plane are typically gathered in dense clusters corresponding to different objects (as it occurs in the model plane extraction process). This enables significantly reducing the number of necessary RANSAC iterations in the main RANSAC loop, $I_{max,1}$, compared to a standard implementation. In the proposed implementation, $Dist_{triplet}$=300mm. $I_{max,2}$ is set to 288,000, which corresponds to having a 90% chance of finding an acceptable triplet when 2% of the scanned points are estimated to belong to such a triplet. Finally, $I_{max,1}$ is set to 230 (only), which still corresponds to having a 90% chance of finding a plane when one estimates that 1% of the accepted triplets belong to that plane.

3.2. Plane Matching

For matching scan and model planes, the proposed system requires the input of the user. For each matching, the user first selects a pair of planes. In the cases of the second and third matches (i.e. second vertical plane and horizontal plane matches), the system then informs the user on the feasibility of the match given the previous ones. If it is allowed, the user simply confirms the match.

Contrary to point-based approaches, the selection of planes in 3D data is easier because planes are larger features. However, many planes are extracted from the model and scan so that the selection of a specific plane using a typical ray-plane intersection approach may be very tedious. As a result, a different approach is proposed that uses the data supporting the planes.

In the case of selecting a plane extracted from the point cloud, instead of selecting a plane, the user selects a point from the set of points supporting it. This point selection does not suffer from the limitations of the manual point-based matching mentioned earlier, because no specific point has to be selected and the supporting points are generally gathered in large clusters. In addition, in order to easily identify which points correspond to extracted planes, these are colored similarly, while the non-supporting points have their original color. And, when a plane is selected and matched, it and its set of supporting points simultaneously change color enabling the user to see if he or she selected the right plane (see Figure 1).

Similarly, in the case of model plane selection, instead of selecting an actual plane, the user selects an object’s face supporting that plane. Compared to the case of the point cloud, the planes are however not plotted when not selected, because there are generally too many of them (many dozens), which would result in a great scene clutter, and they don’t bring much additional visual information for the selection (see Figure 1).

3. EXPERIMENTS

The proposed coarse registration approach has been implemented in a software package. The central part of the GUI is composed of three 3D viewports. The top viewport shows the current registration state of the loaded point cloud and 3D model. The bottom left viewport shows the 3D model only, and the bottom right the point cloud. These two bottom viewports are used to perform the selections of planes (see Figure 1).

An additional feature of the proposed software package not discussed yet is the possibility to load a construction schedule along with the 3D model, i.e. a 4D model. Based on the date of acquisition of the laser scan to be matched, only the corresponding time-stamped 3D model of the project is used for the registration. This makes the selection of model planes somewhat easier, because the model and point cloud data look more similar.

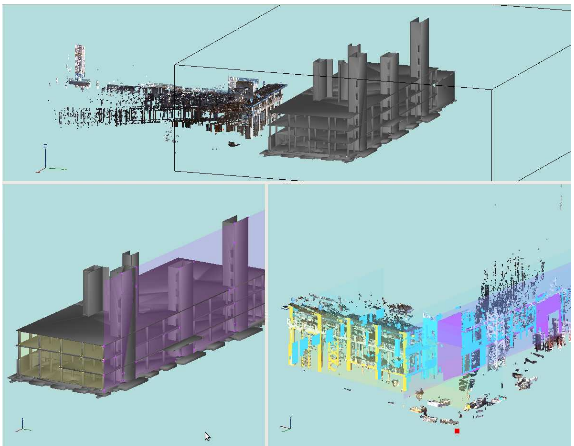

Figure 1: The three 3D widgets composing the GUI of the proposed system. The lower two widgets show a pair of matched planes (purple) and a second pair of selected ones (yellow).

Two persons with previous experience in model-scan registration were then asked to perform 12 scan-model registrations with two commonly used software packages (RealWorks by Trimble, and Geomagic Studio) and the one proposed herein. The data was obtained during the construction of the concrete structure of the Engineering V building at the University of Waterloo (see Acknowledgements). Registration performance was then compared based on two criteria:

Registration Speed (Table 1): Time to perform the coarse registration.

Registration Accuracy (Table 2): Matching quality achieved after a fine registration step is applied to the obtained coarse registration – the ICP-based algorithm as presented in [2] is used. Quality is assessed with: (1) the number of matched points (N. Matches); and (2) the root mean square error of the distances of the points matched to the 3D model (RMSE).

Table 1 shows that both users managed to perform the requested registrations faster with the proposed approach (with similar times for both) than with point-based approaches. The difference is particularly large with Realworks, but this is explained by the fact that, while the coarse registrations performed with Geomagic Studio were systematically done with 3 points only, those done with Realworks were done with at least 5 points, thus requiring more time.

Table 2 then shows that the registrations achieved with the proposed approach were most of the time (66% to 92%) of similar or better quality than those obtained with the point-based approaches. This appears especially clear when one considers both RMSE and N. Matches (92%).

3. CONCLUSION

This paper presented a semi-automated plane-based coarse registration approach with focus on model-scan coarse registration in the context of the AEC/FM industry. While the problem of coarse registration has been well investigated in the past, it has been shown that the AEC/FM context presents specific (1) constraints that make fully automated registration very complex and often ill-posed, and (2) advantages that can be leveraged to develop simpler yet effective registration approaches. Considering those, the system automatically extracts planes from the point cloud and 3D/4D model. The planes are then manually but easily selected and matched by the user. Experiments, comparing the proposed system to commonly used (but also general-purpose) registration software packages demonstrate that at least as good registration quality can be achieved by the proposed system, but more simply and faster. It is concluded that, in the AEC/FM context, the proposed system is a compelling alternative to standard point-based registration techniques.

User	Software	Pre-processing	Processing	Total
1	Geomagic	-	10:51	10:51
	Proposed	2:32	01:02	03:34
2	RealWorks	-	33:29	33:29
	Proposed	02:16	01:56	04:12

Table 1 Mean Pre-processing, processing and total times (mm:ss). Pre-processing refers to the plane extraction stage in the proposed approach.

User	RMSE		N. Matches		RMSE & N. Matches	
	Better	Worse	Better	Worse	Better	Worse
1	17%	8%	50%	17%	17%	8%
2	25%	17%	25%	33%	8%	8%

Table 2 Comparison of registration quality (*RMSE* and *N. Matches*). . *Better*, resp. *Worse*, gives the percentage of times when a better, resp. worse, result was obtained using the proposed approach compared to the point-based one.

ACKNOWLEDGEMENTS

The author would like to thank Prof. Dr. Carl T. Haas and Yelda Turkan from the University of Waterloo, Canada who kindly shared their data (4D model and laser scans) of the Engineering V building of the University of Waterloo.

REFERENCES

[1] Besl, P. J. & McKay, N. D. “A method for registration of 3-D shapes”, *Trans. on Pattern Analysis and Machine Intelligence*, Vol. 14 , pp. 239/256, 1992.

[2] Bosché, F., “Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction”, *Advanced Engineering Informatics*, Vol. 24 , pp. 107–118, 2009.

[3] Dold, C. & Brenner, C. “Registration of terrestrial laser scanning data using planar patches and image data”. *The ISPRS Archives*, Vol. XXXVI, 2006.

[4] Fischler, M. A. & Bolles, R. C., “Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography”, *Graphics and Image Processes*, Vol. 24, pp. 381-395, 1981.

[5] Gelfand, N., Mitra, N. J., Guibasy, L. J. & Pottmann, H., “Robust global registration”, *Eurographics Symposium on Geometry Processing*, 2005.

[6] Goucher, S. & Sheive, B. L., “Refine dimensions: High-definition scanning helps redefine oil refinery fabrication”, *The American Surveyor*, 6, 2009.

[7] Grün, A. & Akca, D., “Least squares 3D surface and curve matching”, *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol. 59 , pp. 151–174, 2005.

[8] Ip, C. Y. & Gupta, S. K., “Retrieving matching CAD models by using partial 3D point clouds”, *Computer-Aided Design & Applications*, Vol. 4 , pp. 629–638, 2007.

[9] Jaw, J. & Chuang, T., “Feature-based registration of terrestrial lidar point clouds”. ISPRS Archives, Vol. XXXVII, pp. 303–308, 2008.

[10] Jaw, J.-J. & Chuang, T.-Y., “Registration of ground-based lidar point clouds by means of 3D line features”. *Journal of the Chinese Institute of Engineers*, Vol. 31 , pp. 1031–1045, 2008.

[11] Johnson, A. E., & Hebert, M., “Surface matching for object recognition in complex three-dimensional scenes”,

Image and Vision Computing, Vol. 16 , pp. 635–651, 1998.
[12] Li, Y. & Wang, Y., “An accurate registration method based on point clouds and redundancy elimination of lidar data”. *ISPRS Archives*, Vol. XXXVII, 2008.
[13] Mauck, B. & Gee, R., “Chicago federal center: Improving scan-to-revit modeling”, *SparView (online)*, Vol. 8(5), 2010.
[14] Rusinkiewicz, S. & Levoy, M., “Efficient variants of the ICP algorithm”, *Proceedings of 3DIM*, pp. 145–152, 2001.
[15] Stamos, I. & Leordeanu, M., “Automated feature-based range registration of urban scenes of large scale”, *Proceedings of CVPR*, Vol. 2, pp. 555–561, 2003.