Towards Automated Retrieval of 3D Designed Data in 3D Sensed Data

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Abstract

Construction productivity, one major project performance indicator, requires the continuous assessment of construction progress over time. Current practices for construction progress assessment are labour intensive, expensive, and generally result in partial and sometimes erroneous information. It is thus difficult to make appropriate and timely management decisions. However, recent three-dimensional (3D) Computer Aided Design (CAD), 3D scanning and global positioning technologies present an opportunity for developing more efficient, robust and automated approaches. After reviewing and analyzing previous works conducted in the field of automated object detection, this paper presents a new approach taking advantage of global positioning technologies for robustly retrieving 3D CAD elements within 3D scanned data. This approach is implemented and experimented in laboratory. Results are conclusive towards further experiments for its application to many different fields including automated construction progress assessment for effortless productivity tracking.

Keywords

3D sensed data, 3D/4D designed data, GPS technologies, automated comparison.

Introduction

Project performance assessment requires comprehensive and efficient construction exploration, and as-built data recording and post-processing for comparison with as-planned data. There are several different project performance indicators. One of them, productivity, requires the continuous assessment of construction progress over time. Current practices for construction progress assessment are labour intensive, expensive, and generally result in partial and sometimes erroneous information. It is thus difficult to make appropriate and timely management decisions (Akinci et al. 2006; Gordon and Akinci 2005; Navon 2007).

Three-dimensional (3D) laser scanners allows for precise and comprehensive acquisition of 3D as-built data. This 3D data can be analyzed with the aim of identifying critical and reliable construction status information. In the specific case of construction progress assessment, laser scanners can be used to automatically acquire 3D data from an asset in construction at any time. This 3D data can be analyzed to identify the presence of 3D project elements and to compute volumes, so that the quantity of work that has been performed up to that specific time can be estimated. This approach directly identifies of in-place quantities, so that it is potentially more robust than other methods that indirectly calculate work progress – i.e. by recording in real-time the rough location of resources for inferring production quantities (Navon 2007; Song et al. 2006). However, this approach can only be beneficial if progress can be estimated with high accuracy and in a timely manner (as these other indirect methods often work in real-time). In other words, industry managers could benefit from such a technology only if it can operate rapidly and even, if possible, automatically (Cheok et al. 2000).

The next section strategically compares different approaches for efficiently and automatically comparing 3D as-built and as-planned data. The third section presents the theoretical implementation of the suggested approach based on point clouds. Finally, the fourth section describes experimental test results obtained in the Centre for Pavement and Transportation Technologies (CPATT) at the University of Waterloo.

3D Scanned and 3D CAD Data Comparison Strategy

General Approaches. The identification of 3D objects within 3D data sets is not a new problem. Previous research, mainly conducted in the field of robotics, focused on two different approaches (Johnson and Hebert 1999). The first and most usual approach consists in segmenting both the scanned data and library-stored images of the searched 3D objects based on specified features, and then identifying best matches, if any, between each pair of segments. The problem with this approach is that natural scenes – scenes dealt with without any prior knowledge – may include any object (searched or not searched), which makes efficient automated segmentation of the scanned data very difficult. Besides, cluttered scenes such as construction sites result in occlusions that alter the similarity between 3D scanned image segments and segments of the searched3D objects (Johnson and Hebert 1999). Previous work in civil engineering automation acknowledges the difficulty of automating this approach to efficiently retrieve objects in construction 3D images (Teizer et al. 2007).

The second approach consists in first identifying specific and distinctive features for each searched object. The presence of an object is then statistically inferred by aligning its distinctive features everywhere in the sensed data and assessing the matching quality at each position. For instance, an approach described in (Johnson and Hebert 1999) efficiently uses spin images of different poses of searched 3D objects to find them in cluttered 3D scenes. The advantage of such an approach is that it can be entirely automated as it does not require any segmentation. It nevertheless presents some limitations. First, when the number of objects (searched or not searched) increases more distinctive features (spin images in (Johnson and Hebert 1999)) have to be found to ensure positive object identification. Additionally, matching has to be assessed at every possible position in the scanned data. As a result, the computational complexity of the algorithm rapidly increases with the number of searched objects as well as the size of the scanned data. In (Johnson and Hebert 1999) the authors nonetheless show that Principal Component Analysis can be used to reduce the searched domain constituted by all the spin images. Aside from this computational complexity, it must be noted that distinctive features (spin images in (Johnson and Hebert 1999)) are pre-calculated without any consideration for possible occlusions so that when these occur the identification performance rapidly decreases.

In conclusion, the first approach should be discarded for automated applications because of its need for efficient segmentation tools. The second approach could be automated. However, it is computationally very complex and not robust with cluttered and occluded scenes. This second approach is nonetheless further investigated with the aim of identifying in the specific context of automated construction progress assessment ways to reduce and possibly remove these limitations.

3D CAD models and (Geo-) Referencing. The Architectural/Engineering/ Construction & Facility Management (AEC-FM) industry has been experiencing a rapid increase in the use of 3D CAD modeling and geo-referencing technologies. These technologies are becoming very comprehensive and reliable so that their use will certainly be generalized in the future. In the context of the investigated problem, these technologies can be used to reduce the complexity of the investigated approach. First, 3D CAD models constitute a spatially-organized library of the project 3D objects. In a 3D CAD model, the objects are expected to have the same relative position (location and orientation) as in reality. Regarding the investigated approach, this means that with 3D CAD models spin images don't have to be calculated for each searched object but for the entire 3D CAD model at once. This tremendously reduces the number of spin images to be calculated. Additionally, using the entire 3D CAD model for calculating spin images allows anticipating occlusions due to other CAD objects. Despite these improvements, the approach complexity is not fully reduced as many spin images still have to be calculated for different orientations of the model and distances to the point of view. This complexity can be reduced by referencing (location and orientation) 3D images and 3D CAD models to each other, which allows the best matching 3D CAD model spin image be known a priori. Geo-referencing technologies such as GPS and digital compasses can be used to perform this referencing.

As a result, 3D CAD models and geo-referencing technologies can be used to tremendously reduce the complexity of the second approach described earlier and partially improve its robustness with respect to occlusions.

3D CAD Format. 3D/4D models present 3D as-planned information in the proprietary 3D CAD engine native format (i.e. DXF, DWG, DGN, etc.). The investigated retrieval problem requires having full access to 3D CAD model data in order to calculate 3D CAD model spin image. So, since native formats are inaccessible, 3D CAD models must be converted into an open-source format. This open-source format must be chosen so that it preserves the accuracy of the 3D information expressed in the native format. In (Bosche and Haas 2006), the authors identify the StereoLithography (STL) format has a good candidate. This format approximates 3D object surfaces by tessellations of triangles. Detailed information about this format can be found in (3D Systems 1989).

Comparison of Referenced 3D CAD Models and 3D Images.

Current Approach. The problem consists now in comparing 3D CAD models in STL format and 3D as-built data in a point-cloud format. This problem is also not new and commercial software packages already present solutions to it. The approach they use is generally based on the following two characteristics:

- The as-built point cloud is referenced to the CAD model orthogonal frame.
- The closeness metric between a cloud point and a CAD object is the distance between the point and its orthogonal projection on the CAD object surface.

This approach has two limitations. First, it is not possible to know a priori on which surface of which object the point should be projected, so that the number of projections to be estimated rapidly increase with the number of CAD object and their surface complexity. The second limitation is that orthogonal projection is not a good measure of closeness as points are generally not acquired with directions perpendicular to surfaces. As a result, with this closeness metric, range measurement uncertainty is discarded, which may lead to misleading conclusions.

Proposed Approach. These limitations lead the authors to the formulation of a new approach that is based on the combination of the following two characteristics:

- The CAD model is referenced to the laser scanner's cylindrical frame.
- The closeness metric between a cloud point and a CAD object surface is the distance between the point and its projection on the CAD object surface along its scanning direction.

Referencing the CAD model to the scanner's cylindrical frame allows calculating for each CAD object surface (triangles when converted into STL format) the minimum pan and tilt values. As illustrated in Figure 1, this allows estimating exactly on which surface each point should be projected prior to actually calculating this projection. Then, as explained previously, the projection of each point along its scanning direction provides a more adequate closeness measure since it can incorporate range acquisition uncertainty and therefore increase the quality of comparison results. This approach can be summarized as the calculation of an *as-planned point cloud* where each as-planned point corresponds to an as-built cloud point (same pan and tilt angles), but for which the range is obtained using the 3D CAD model instead of the real world.

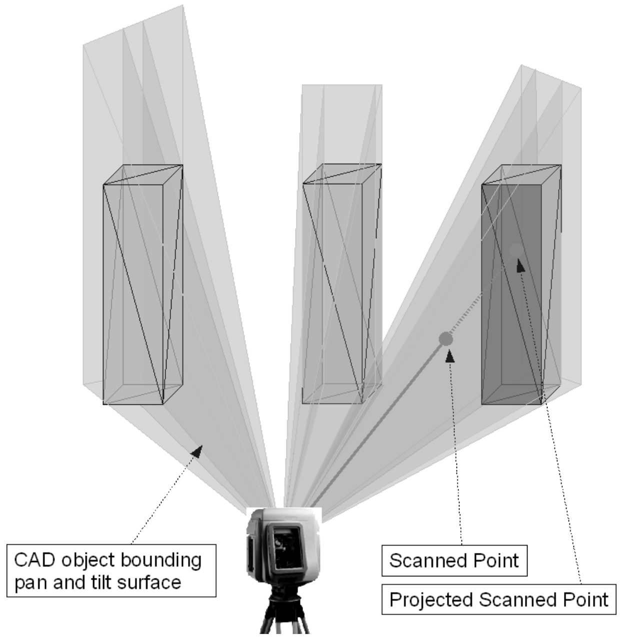

Figure 1: Advantage of combining laser-based referencing and projection along scanning direction

Algorithmic Implementation of the Proposed Approach

The algorithmic implementation of the proposed approach works as follows. First, the 3D CAD model is referenced to the scanner's cylindrical frame so that each object vertex is expressed with a pan, tilt and range value. Then, for each 3D as-built cloud point, a corresponding as-planned point having the same pan and tilt values is calculated. The range value of the as-planned point is calculated by tracing a ray from the laser scanner in the direction defined by the pan and tilt values of the as-built point. The first CAD object surface point intersected by this "ray" is the corresponding as-planned cloud point and its range can be deduced. Further, the CAD object from which this point is obtained can be recorded as an additional feature of this point. As a result, by sorting the as-planned points with respect to this additional feature, an as-planned point cloud can be deduced for each 3D CAD object.

Then, for each CAD object, each as-planned cloud point is compared to its corresponding as-built point. Since both points have the same pan and tilt values, only their ranges are compared. For now (with respect to the results presented in this paper), an as-planned point is considered retrieved is the difference between its range and the one of its corresponding as-built point is lower than a predefined "*Range Threshold*". Once the retrieval of each CAD object as-planned cloud point is calculated, an as-planned cloud retrieval rate (number of retrieved as-planned points divided by the total number of points in the CAD object as-planned point cloud) is deduced. This retrieval rate is compared to a pre-defined *"Retrieval Rate Threshold"* is order to infer the retrieval/identification of the CAD object.

Experimental Results

An indoor experiment has been conducted to test the proposed approach and the corresponding algorithm. A 4D CAD model of the construction of column-slab structure is developed using the 3D CAD engine Bentley® Microstation®. Five 3D CAD models displayed in Figure 2 compose this simulated 4D CAD model. Then the structure is manually built in the laboratory, with as much precision as possible with respect to the model, and scanned using the Trimble® GX3D laser scanner. The characteristics of the scanner are presented in Table 1. It must be noted that, in this experiment, geo-referencing technologies are not used and referencing is performed manually. The developed algorithm is then run with the goal of retrieving all 3D CAD objects in the scanned data and subsequently deducing the construction advancement. The following input parameters are used:

- <u>Time Uncertainty</u>: A one day uncertainty is used so that work completed earlier or later by one day can be identified. This implies that the scanned data is compared with three consecutive 3D CAD models extracted from the project 4D CAD model and centered on the day when the scan is conducted.
- <u>Range Threshold</u>: An as-planned cloud point is considered retrieved if the difference between its range and the range of the corresponding as-built point is less than 30 mm.
- <u>Retrieval rate Threshold</u>: A CAD element is considered retrieved if at least 50% of its as-planned cloud points are retrieved.

Table 1: Specifications of the Trimble GX3D Scanner

Model		GX3D
Laser Type		Pulsed ; 532nm ; green
Distance	**Range**	2m to 200m
	Accuracy	1.5mm @ 50m ; 7mm @ 100m
Angle	**Range**	H: 360º ; V: 60º
	Accuracy	H: 60µrad ; V: 70µrad

In this particular experiment, the scan is conducted with the entirely built structure (Figure 3 and Figure 4) and is assumed to have occurred on day 4, so that the as-built data is compared to the 3D CAD models for days 3, 4 and 5. This scan contains 206,360 points.

Table 2 summarizes the retrieval results. It shows that all CAD objects from the 3D CAD model of day 5 are retrieved. The retrieval rates of all CAD objects are high, including *column 1* and *column 2* despite the fact that 75% of their normally visible surfaces are occluded by *column 4* and *column 3* respectively. This demonstrates the robustness of this method with respect to occlusions due to other CAD objects. Overall, since this scan is assumed to have taken place on day 4 and all the objects of the 3D CAD model of day 5 are retrieved, it can be concluded that the construction is one day ahead of schedule.

Two additional results presented in this table can be further discussed. First, it is interesting to note that only 74% of the slab as-planned point cloud is retrieved. A reason for this low rate can be found in Figure 4. In this figure, the size of each point is proportional to the reflectivity of the signal received to estimate the range. Low reflectivity can be seen as an estimation of the range acquisition uncertainty and, as can be seen, most points obtained from the slab, especially from the top surface of the slab, have a low reflectivity. They may thus not have been detected because the *Range Threshold* (30mm) was too high with respect to the range acquisition inaccuracy. Another reason could be errors in the referencing. Indeed, in this case, even a little error in the referencing altitude would shift the slab as-planned point cloud vertically and thus considerably alter its retrieval, especially points from its top surface.

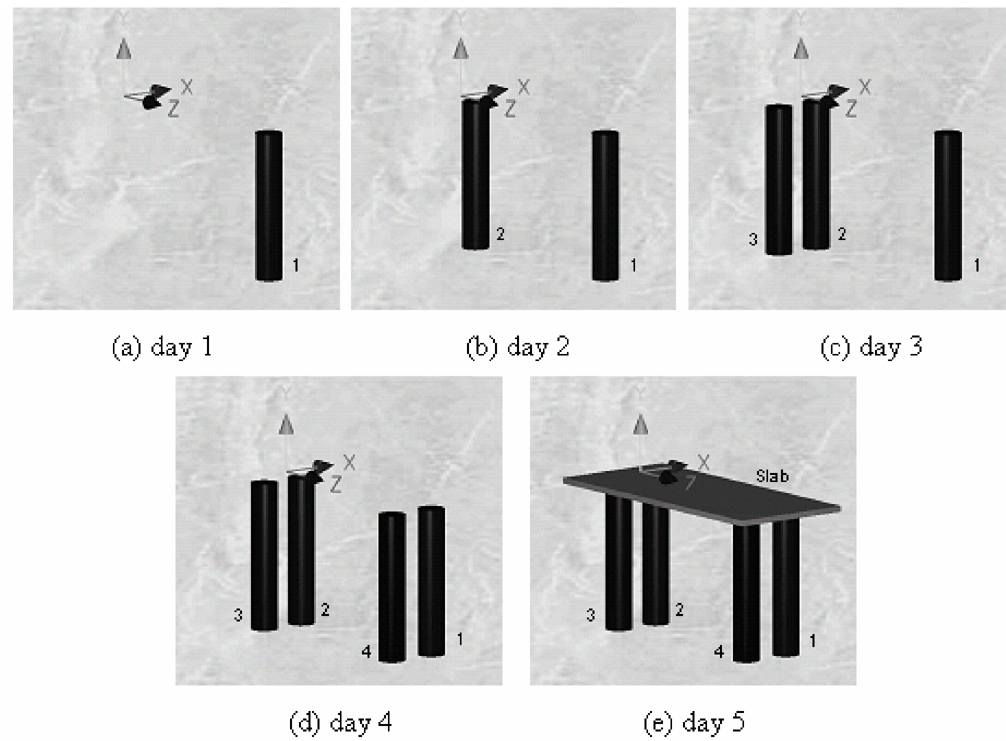

Figure 2: Simulated 4D CAD model of the project at each day of the five day construction project

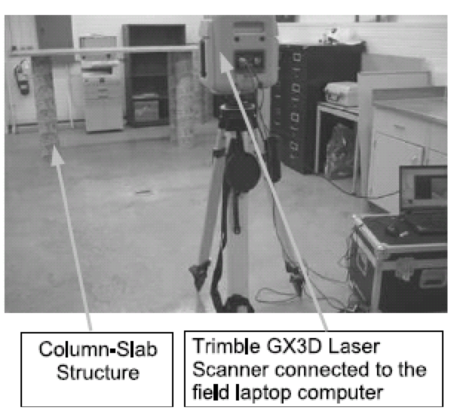

Figure 3: Experimental setup

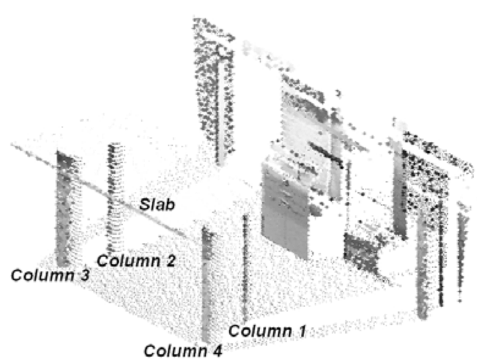

Figure 4: Scanned Point Cloud

The second interesting result is that the retrieval rate of *column 1* is different when comparing the as-built data with the different CAD models. The reason is that *column 1* is not occluded by *column 4* in the CAD model of day 3 but is in the CAD models of days 4 and 5 as well as in reality.

Overall, the retrieval results are very promising and demonstrate that this approach has great potential for being used to robustly, efficiently and automatically assess work progress.

Table 2: Experimental Retrieval Results

Day	Calculated Values	CAD Element				
		Column 1	*Column 2*	*Column 3*	*Column 4*	*Slab*
3	Number of as-planned points	15,042	4,678	17,490	0	0
	Number of retrieved points	4,684	4,411	16,403	16,120	3,479
	Retrieval rate	31%	94%	94%	N/A	N/A
	Retrieved?	NO	YES	YES	NO	NO
4	Number of as-planned points	5,079	4,678	17,490	17,880	0
	Number of retrieved points	4,423	4,411	16,403	16,120	3,479
	Retrieval rate	87%	94%	94%	90%	N/A
	Retrieved?	YES	YES	YES	YES	NO
5	Number of as-planned points	5,079	4,678	17,490	17,880	4,712
	Number of retrieved points	4,423	4,411	16,403	16,120	3,479
	Retrieval rate	87%	94%	94%	90%	74%
	Retrieved?	YES	YES	YES	YES	YES

Conclusion and Future Work

In the paper, a new approach for automatically retrieving 3D CAD elements (as-planned) within 3D scanned point clouds (as-built) is described. Experimental results demonstrate that this approach could be used to automatically assess construction progress. Future work will focus on confirming these results with real-life structures. Additionally, considerations for uncertainty in referencing as well as in measured values (pan, tilt and range) will be added to the current algorithm.

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