METRIC FOR AUTOMATED DETECTION AND IDENTIFICATION OF 3D CAD ELEMENTS IN 3D SCANNED DATA

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ABSTRACT

Being able to efficiently compare as-built against as-planned 3D states is critical for performing efficient building and infrastructure construction, maintenance, and management. Three-dimensional (3D) laser scanners have the potential to be successfully applied to these tasks. Recent commercial products allow the comparison of 3D scanned and 3D CAD data based on CAD forms. Their current use is however limited due to the large amounts of manual data processing required for extracting useful information. By using 3D Computer Aided Design (CAD) models as representations of 3D specifications and Global Positioning System (GPS) technologies, the authors present an approach for automating the comparison of 3D sensed data and 3D CAD data. This new approach does not perform this data comparison based on CAD forms but on point-clouds.

This paper discusses the fundamental differences between the two approaches, describes the theoretical implementation of the proposed approach, and presents laboratory experimental results confirming the potential impact of the proposed method on industry's practices.

KEYWORDS: Three-dimensional data, LADAR, Computer aided design, Global positioning technologies, Automated Information Retrieval.

INTRODUCTION

The asset construction and management industry constantly requires comparing planned conditions and different historical as-built conditions with the aim of estimating such things as quality, work progress, deterioration, etc. This comparison may involve different types of information. For instance, work progress can be estimated by comparing planned and achieved three-dimensional (3D) work outputs, the quality of concrete maturity can be estimated by comparing planned and achieved concrete maturity temperatures. 3D information is of major importance for the industry and comparing 3D as-built to 3D as-planned data is therefore critical during the entire asset life cycle (Akinci 2004). However, while planning asset construction with 3D models is getting more common, traditional 3D as-built information acquisition methods are very time and labour demanding. As a result, comparing 3D as-built states with 3D models is still very tedious (Navon 2007).

The fast development and use of 3D Computer-Aided Design (CAD) engines and more generally of Building Information Models on one side, and 3D laser and 3D Global Positioning

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System (GPS) technologies scanners on the other side provide an opportunity to improve industry practices. Currently, state-of-the-art software allows semi-automatically fitting 3D primitives to manually segmented 3D scanned point clouds, and these can then be compared to primitives used to build the planned 3D CAD model of the scanned asset (Akinci et al. 2006).

While this approach demonstrates the potential impact of the combined use of these new technologies, it presents several limitations. In this paper, the authors review these limitations and present a new approach. The fundamental differences between the two are discussed and a description of the theoretical implementation of the proposed approach follows. Then, experimental results obtained with this new approach are presented. The authors conclude with a discussion on the current achievements and identify directions for their future research.

3D SCANNED AND CAD DATA COMPARISON STRATEGY

Currently Available Approach

The comparison of as-built and as-planned conditions requires that the two data be represented in comparable formats (Gordon et al. 2003). Typical available 3D laser scanner software includes tools for comparing 3D scanned and 3D CAD data. The approach used by this software, as well as in other research work, consists in fitting 3D primitive forms (parallelepipeds, spheres, cylinders, etc.) to manually segmented point clouds from the 3D scan. The fitted primitives can then be compared to the primitives used in the 3D CAD models by matching them and analyzing matching errors (Akinci et al. 2006; Kwon et al. 2002). This approach is now on referred to as the "CAD-to-CAD comparison approach" and is schematized on the left diagram of *Figure 1*.

This CAD-to-CAD comparison approach, presents major limitations. First, it requires the segmentation of the scanned data prior to fitting CAD primitives. 3D scanned point-clouds constitute complex unstructured sets of data. Without a priori knowledge, automated unsupervised segmentation of complex unstructured data sets generally provides not sufficiently good results (Johnson and Hebert 1999). As the quality of object (primitive) fitting algorithms is dependant on the quality of the segmentation of the raw data, current 3D point-cloud management software requires manual segmentations of point-clouds. Even then, the complexity of 3D scanned point-clouds, containing both data of interest (generally elements of the built asset) and data of no interest (workers, equipment, temporary structures, etc.), generally leads to tedious manual segmentation. This ultimately reduces the benefit attractiveness of using such methods, to the point that industry professionals don't systematically agree with its potential benefit, when compared to traditional manual surveying methods.

Additionally, this CAD-to-CAD comparison method requires fitting 3D primitives to scanned point-clouds that are sometimes referred to as 2½D data – since information can often not be obtained from the back of scanned objects. This requires the "guess" of the remaining ½D that is an additional source of error (Bosche and Haas 2006) in the fitting process.

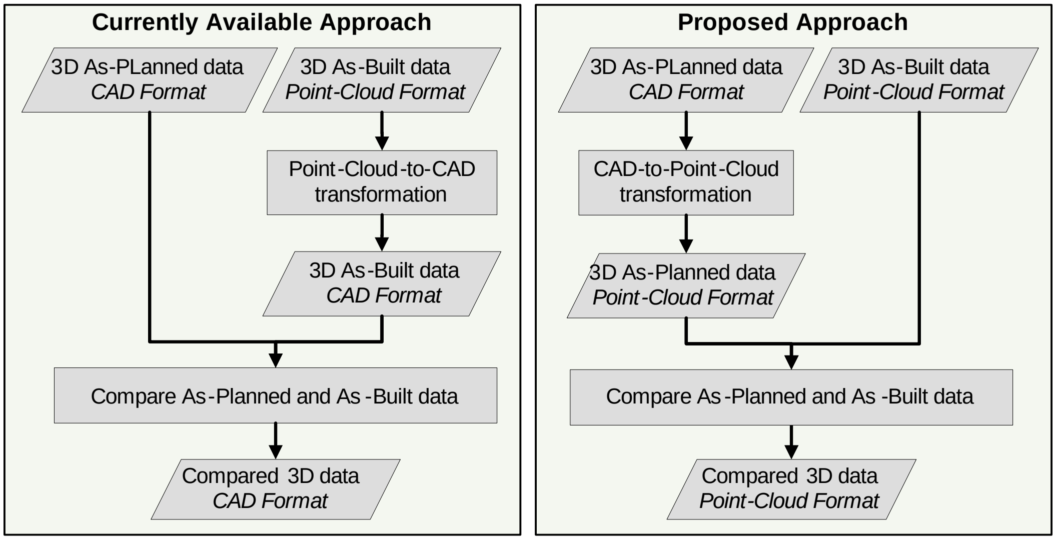

Figure 1: Currently available and proposed approaches for retrieving 3D CAD elements within 3D sensed data.

Proposed Approach

Because of the different limitations of the previous method, a new approach is proposed. Instead of aiming at processing the 3D scanned data to extract 3D CAD primitives that can be compared to primitives used to create the 3D CAD model, it is suggested, as schematized on the right diagram of *Figure 1*, to process the 3D CAD data to extract a point cloud that could be compared to the 3D scanned point cloud. In other words, if the 3D scanned point cloud is referred to as the "as-built point cloud", it is suggested to extract from the 3D CAD model, the corresponding "as-planned point cloud" and then compare the two. This approach is now on referred to as the "Point-Cloud-to-Point-Cloud comparison approach".

Contrary to the CAD-to-CAD comparison approach, the Point-Cloud-to-Point-Cloud comparison approach does not require to transform the 3D scanned point cloud, but to transform the 3D CAD data into a 3D point cloud, the "as-planned point cloud". The calculation of the as-planned point cloud can be performed by using the global location and orientation of the laser scanner to position it in the 3D CAD model and then deduce the point cloud corresponding to the as-built point cloud. Each as-planned cloud point thus directly refers to an as-built cloud point and the two can easily be compared.

This new approach does not require segmenting the unstructured scanned point cloud prior to perform the comparison. Additionally, deducing the as-planned point cloud from the 3D CAD model is the calculation of 2½D data from 3D data, which does not require any "guess" and thus does not result in any related error.

THEORETICAL IMPLEMENTATION OF THE PROPOSED APPROACH

The theoretical implementation of the proposed approach goes as follows:

1. The 3D CAD model is converted from its native format to the STL format (this is justified later in this section).
2. The as-planned point cloud is calculated using the 3D CAD model in STL format and the global positioning information – location and orientation – of the 3D laser scanner. The calculation of the as-planned point cloud works as follows. The

calculation of the i^{th} as-planned point, $\left(\overline{P_i};\overline{T_i};\overline{R_i}\right)$[3], requires locating and orienting the laser scanner within the 3D CAD model using its global position: location $(X_0;Y_0;Z_0)$ and orientation $(P_0;T_0)$. Then a ray is traced from the laser scanner with the same pan and tilt angles as those of the i^{th} as-built point, $(P_i;T_i;R_i)$. The first CAD element surface point intersected by the ray is thus the i^{th} as-planned cloud point. The corresponding range ($\overline{R_i}$) can be calculated and the CAD element from which this range was obtained can also be recorded $\left(\overline{C_i}\right)$ as an additional attribute of the as-planned point.

3. Sort all as-planned points by CAD attribute. Thus, an as-planned point cloud is deduced for each CAD element present in the as-planned cloud. The as-planned and as-built data have now the same format and can be directly compared to retrieve CAD elements within the 3D scanned data.
4. For each CAD Element, compare as-planned cloud points to their corresponding as-built points as follows.
    a. First, each as-planned cloud point is individually compared to its corresponding as-built point. Since both points have the same pan and tilt values, only their ranges are compared. For two corresponding points for which the difference in ranges is lower than a predefined "*Retrieved Point Distance Threshold*" parameter, it is considered that the as-planned point has been retrieved in the as-built data.
    b. For each CAD Element, deduce the retrieval rate of each CAD element as-planned point cloud, and consequently statistically infer its identification (using a predefined "*Retrieval Rate Threshold*" parameter).

This "ray tracing" calculation requires having full access to the 3D CAD model format. The use of the STL format is thus justified by the facts that: (1) it is open source while most common 3D CAD engine native formats are proprietary, and that (2) the model in this format remains similar to the original model in three-dimensional terms (Bosche and Haas 2006).

EXPERIMENTAL RESULTS

Experiment Description

In order to test the proposed Point-Cloud-to-Point-Cloud comparison approach, an indoor experiment has been conducted. A simple structure made of four columns and one board, simulating a column-floor structure, has been manually built in the laboratory with as much precision as possible with respect to its 3D CAD model that was previously developed using Bentley® Microstation®. Then, a laser scanner was positioned at a known location and orientation with respect to the built structure – in order to simulate known global locations and orientations of the scanner and the structure. The laser scanner used in this research is a Trimble® GX3D with characteristics presented in *Table 1*. *Figure 2* displays (1) the scanned scene with the located laser scanner and (2) a rendering of the 3D CAD model of the structure. The goal of the experiment is to scan the indoor scene with the laser scanner and automatically retrieve using the developed algorithm all CAD elements from the 3D CAD model (the four

[3] Where *P* is the pan angle from the global pan position of the laser scanner, *T* is the tilt angle from the global tilt position of the laser scanner, and *R* is the range from the laser scanner.

columns are referred to as *column_1*, *column_2*, *column_3*, *column_4* - and the floor is referred to as *slab*).

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

Table 1: Specifications of the Trimble GX3D Scanner

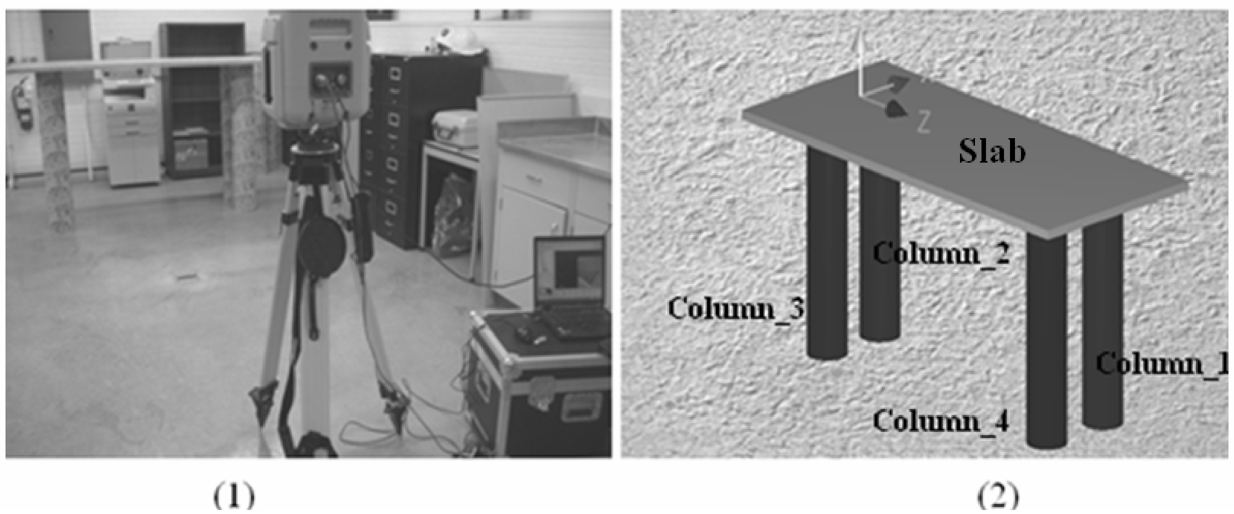

Figure 2: (1) The scanned scene with the structure and the laser scanner, and (2) a rendering of the 3D CAD model of the structure

Experimental Results and Analysis

This experiment was conducted with the following processing parameters:

- Uncertainty: In this experiment, no uncertainty (laser position and laser measurements) were considered for this experiment
- "*Retrieved Point Distance Threshold*" parameter: In this experiment, one as-built and its corresponding as-planned point are positively matched if the difference in their respective ranges is lower or equal to 15 mm.
- "*Retrieval Rate Threshold*" parameter: In this experiment, a CAD element is considered detected if at least 50% of the as-planned points that were obtained from that CAD element are retrieved in the as-built point cloud.

The scanned point cloud contains 206,360 points. The results obtained after running the developed algorithm are displayed on *Figure 3* and *Table 2*.**Error! Reference source not found.***Figure 3* displays the as-built, as-planned, and retrieved as-planned data – only 1% of the total number of cloud points is actually displayed to increase the clarity of the figures. In the particular figure displaying the retrieved as-planned data, the retrieved points are shown with circles and the not-retrieved ones are shown with asterisks.

Table 2 presents the output of the automated retrieval process. It shows that the four columns are detected with fairly high retrieval rates (between 0.85 and 0.96) with varying number of as-planned points per CAD element (from 3,330 to 15,500 points per CAD element). It shows that this approach is robust for the detection of CAD elements that are partially occluded by other CAD elements. Indeed, here about 75% of the surfaces of *column_1* and *column_2* are occluded by *column_3* and *column_4* but are still well identified. The floor *slab* was not detected although 44% of the as-planned points were retrieved in the as-built point cloud. This shows the impact of the value of the "Retrieval Rate Threshold" parameter. If a retrieval rate threshold of 40% had been considered acceptable – and it could definitely be argued to be – the floor would have been detected.

It must be noted that for lack of access to the original CAD format, the comparison is performed after converting the 3D CAD model to the STL format. This triangular approximation of surfaces introduces some error that certainly impacts the overall retrieval results. Additionally, the use of a pre-defined "Retrieval Rate Threshold" parameter does not consider differences in reflectivity of scanned points. Since reflectivity values partially capture uncertainties in range measurements, normalizing the "Retrieval Rate Threshold" parameter for each point with the reflectivity value could potentially improve individual point retrieval results. This will be added in future versions of the algorithm.

CAD Element	Number of As-Planned points	Number of Retrieved As-Planned points	% of As-Planned points retrieved	Detected
column_1	3,800	3,223	0.85	YES
column_2	4,032	3,556	0.88	YES
column_3	15,294	14,632	0.96	YES
column_4	15,468	13,516	0.87	YES
slab	3,332	1,459	0.44	NO

Table 2: Comparison/Retrieval results of the experiment

CONCLUSION AND FUTURE WORK

In conclusion, it can be seen that in this experiment the CAD model was fairly well retrieved in the scanned data although this included a lot more information (see all scanned points obtained from the back wall and the ground floor in *Figure 3*) and the surfaces of two CAD elements (*column_1 and column_2*) were about 75% occluded. These results are very promising especially when considering that this was obtained without using any segmentation algorithm.

No uncertainty in laser position and laser measurements were considered in this experiment, but these are currently investigated and new results will be presented in future publication. Additionally, future experiments will be conducted with real built structures in order to provide results in more realistic situations.

Overall, this new approach shows potential for use in the Architectural/Engineering/Construction and Project Management (AEC-FM) industry with applications in project performance assessment (productivity, quality), 3D scans database information retrieval, structural integrity assessment, etc.

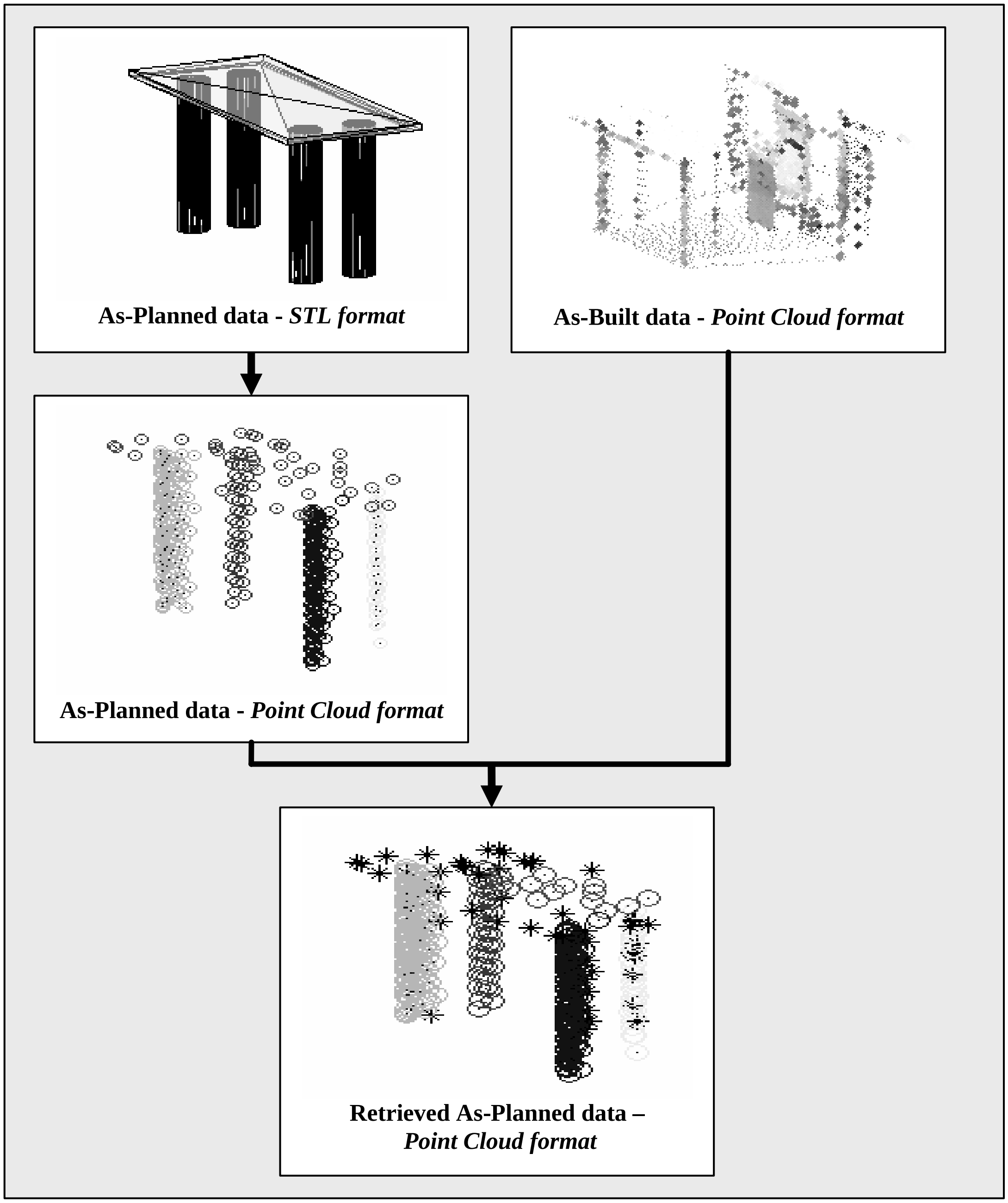

Figure 3: As-built and As-planned data at different stages of the comparison process for the experiment

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