

A Laser Scanning -based Approach to Automated Dimensional Compliance Control in Construction

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Abstract. The construction industry lacks solutions for accurately, comprehensively and efficiently tracking the 3D status of buildings under construction. Such information is however critical to the successful management of construction projects: it supports fundamental activities such as progress tracking and construction dimensional quality control. In this paper, a new approach for automated recognition of project 3D CAD model objects in laser scans is presented, with significant improvements compared to the approach previously proposed in (Bosché, et al., 2009). Then, for each recognized object, an algorithm is proposed to calculate its as-built pose. The estimated as-built dimensions are then used for automatically controlling its dimensional compliance. Experimental results demonstrate the performance, in real field conditions, of the object recognition algorithm, and show the potential of the proposed approach for as-built dimension estimation and control.

1 Introduction

1.1 Need: Effective and Efficient Site 3D Status Tracking

It has been repeatedly reported that construction performance is correlated to the availability and accuracy of information on site status, in particular 3D status (Akinci, et al., 2006; Navon, 2007). However, current techniques for site 3D status tracking are time and labor demanding, and therefore too expensive to be applied reliably and comprehensively on sites. Many research initiatives have already investigated the use of remote sensing technologies, in particular digital imaging and terrestrial laser scanning, to improve the efficiency and effectiveness of site data collection. These initiatives have focused on two main applications: (1) Progress tracking and (2) Dimensional compliance control.

Several vision-based systems have been proposed for tracking construction progress (Memon, et al., 2005; Song, 2007; Fard & Peña-Mora, 2007; Ibrahim, et al., 2009). Their general strategy is to compare site digital pictures and the project 3D CAD model registered in a common coordinate system using camera pose estimation techniques. The work of Ibrahim, et al. (2009) appears to be the most promising by its level of automation and its robustness with changing site and environment conditions. Nonetheless, many limitations remain such as the size and type of detectable changes, and the robustness to unexpected occlusions. Additionally, the detection results cannot be used for further analysis, such as as-built dimension compliance checking. In the case of dimensional compliance control, Ordóñez, et al. (2008), for instance, proposed an image-based approach for controlling dimensions of flat elements, but it requires significant human input. Shin and Dunston (2009) also recently presented results on the evaluation of Augmented Reality (AR) for steel column inspection (anchor bolt positions and plumb). These results demonstrate the feasibility of accurate AR-based steel column inspection. However, the system must be entirely manipulated by a skilled person and inspections can be fairly time-consuming. Overall, as already noted by Rabbani and van den Heuvel (2004), approaches based on the analysis of single images will always

present limitations due to the fact that they aim at extracting 3D information from 2D images. This is an ill-conditioned problem that is difficult to solve, particularly in the context of construction sites.

Contrary to digital imaging, laser scanning accurately senses 3D data. Thus, it has also been suggested for application in progress tracking and dimensional quality control (Cheok & Stone, 1999; Gordon, et al., 2003; Arayici, et al., 2007). Gordon, et al. (2003), for instance, present a system that uses 3D free-form shape recognition algorithms for automatically recognizing CAD objects in laser point clouds. The 3D free-form shape recognition approach that they chose, although very general, is limited in complex situations such as with construction site scans that present significant levels of occlusions and clutter, and for which the search objects don't necessarily have very distinctive features. Then, Shih and Wang (2004) reported a laser scanning -based system for controlling the dimensional compliance of finished walls, and Biddiscombe (2005) reported the use of laser scanning on an actual tunneling project for controlling as-built dimensions. Similarly, Gordon, et al. (2004) and Park, et al. (2007) reported results on the use of laser scanning for structural health monitoring. Despite these many works and the industry-wide acknowledgement of the accuracy and versatility of laser scanners (Jacobs, 2004), the use of laser scanning on construction sites remains very limited. The probable reason is that currently proposed systems (such as those above) present low levels of automation, limited robustness with varying site conditions, and/or poor efficiency (*e.g.* in terms of the number of elements that can be investigated in a day).

Bosché, et al. (2009) recently proposed a *quasi* fully-automated system for recognizing project 3D CAD model objects in site laser scans. The focus is on large site scans that aim at capturing data from many objects simultaneously. The investigated scan and the project 3D CAD model are first registered in the same coordinate system (the only manual step). Then, the point clouds corresponding to the CAD objects present in the scan are automatically recognized. The system is robust with occlusions (both external and self occlusions) and efficient. Its accuracy and robustness with respect to the error due to coarse registration are also good but could be improved as demonstrated in this paper. In (Bosché, et al., 2008), the authors further discuss the feasibility of using the point clouds of recognized objects for automatically estimating their as-built dimensions (*i.e.* pose and shape). However, no implementation was presented.

1.2 Contribution

The main contribution of this paper is a method for automatically estimating the as-built dimensions of building elements using object recognition results obtained using an improved version of the object recognition algorithm previously published in (Bosché, et al., 2009). It is shown through multiple experiments that, altogether, this project 3D status tracking system performs well with respect to: its level of automation, its accuracy, its robustness with occlusions, and its scalability. Its use for automated dimensional compliance control is very promising.

2 CAD-Scan Registration

In (Bosché, et al., 2009), a method was presented for the automated recognition of project 3D CAD model objects in construction site dense laser scans. More exactly, the system enables the extraction from a given scan of the point clouds corresponding to the objects constituting

the project 3D CAD model. This method relies on the registration of the investigated laser scan and the 3D CAD model in a common coordinate system (the spherical coordinate system of the laser scan is chosen). However, this registration is performed manually by picking at least three pairs of corresponding points in the scan and model. It is known that such a *coarse registration* is not reliable, because it relies on only a few pairs of matched points for which the correspondence is not even ensured. In fact, one of the purposes of the registration is to perform construction dimensional quality control which aims at verifying these correspondences. In order to ensure and potentially improve the registration, it is proposed to implement an *Iterative Closest Point (ICP)* -based fine registration algorithm.

The ICP algorithm was originally proposed by Besl and McKay (1992) and Chen and Medioni (1992). It aims at fine registering two 3D shapes, *data* and *model* shapes, for which no correspondences are known a priori, but that are already coarsely registered. Since these initial works, many variants of the ICP algorithm have been proposed. Variations have been proposed for: the selection of data points, the identification of matching model points, the error metric to be minimized, and the termination criterion. The calculation of the matching model points being undeniably the most computationally expensive part of ICP algorithms, several accelerations methods have also been proposed. A good review of many of these variants published until 2001 can be found in (Rusinkiewicz & Levoy, 2001). More recently, an interesting acceleration method was proposed by Park and Subbarao (2003) that combines the matching speed of *point-to-projection* matching algorithms to the accuracy and convergence speed of *point-to-plane* matching algorithms. The fine registration algorithm presented herein uses a similar idea to accelerate the calculation of a *point-to-point* matching algorithm.

In the specific case of the fine registration of dense point clouds with CAD models, several works have been published, mainly with application in dimensional compliance control in manufacturing (Moron, et al., 1995; Tarel & Boujemaa, 1999; Prieto, et al., 2002). However, the problem at hand has some characteristics that differ from those solved by these methods: (1) large site scans typically include many points acquired from objects that are not part of the project CAD model (*e.g.* equipment, tools, temporary structures, people), so that it cannot be assumed that scans can be manually cleaned from data that do not correspond to the objects of interest prior to perform the fine registration; and (2) Project 3D CAD models are not constituted of a single object but a set of objects, for which individual recognition results are sought.

As a result, the following ICP algorithm is proposed:

- *Selection of data points*: All data points are used (data sampling can be performed implemented, but this is not covered here).
- *Matching metric*: Similarly to Moron, et al. (1995), the model is considered to be in a format in which the surfaces of the objects are all triangulated. Then, a model point is matched to each scanned data point. It is calculated as the closest of the orthogonal projections of the data point on the objects' triangulated facets. This implies that, contrary to the metric used in (Moron, et al, 1995), points that have no orthogonal projection on any of the objects' facets are rejected (for the given iteration). This corresponds to rejecting “objects’ border points” from the registration process¹. The

¹ This rejection criterion is different but somewhat related to the rejection of “border points” suggested by Turk and Levoy (1994) in the case of the registration of two meshes.

interesting advantage of rejecting such points is that it enables, for point matching acceleration, the implementation of efficient facet culling techniques normally employed in image rendering. Due to space constraints, the implemented point matching algorithm cannot be detailed here.

- *Error metric*: The Mean Square Error (MSE) of the Euclidean distance between pairs of matched points is used as error metric. Additionally, points are rejected when:
 - *The Euclidean distance between two matched points is larger than a threshold, τ_D .* τ_D is automatically adjusted at each iteration, i , with the formula: $\tau_{Di} = \sqrt{MSE_{i-1}} + \varepsilon_{Const}$, where MSE_{i-1} is the MSE obtained at the $(i-1)^{th}$ iteration, and ε_{Const} is a fixed distance that can be interpreted as the maximum distance at which objects with dimensional deviation should be searched for. In the results presented later, $\varepsilon_{Const} = 50\text{mm}$.
 - *The angle between the normal vectors to two matched points is larger than a threshold τ_A .* In the results presented here, $\tau_A = 45^\circ$.
- *Termination criterion*: the iterative process is stopped when the MSE improvement between the current and previous iterations is larger than 2mm^2 .

3 Object Recognition

At the end of the registration process above, it is known from which CAD model object, if any, the model point matched to each scan point is obtained. Therefore, each CAD object can be assigned an as-designed point cloud and a corresponding as-built point cloud. The as-built point cloud can then be analyzed to infer the recognition of the object itself, using the recognition metric defined in (Bosché, et al., 2009), and, afterwards, to estimate its as-built dimensions (Section 4).

4 Dimensional Compliance Control

Let's consider a single object, that is recognized in one scan using the method above and the recognition criterion defined in (Bosché, et al., 2009), and thus for which an as-built point cloud has been extracted from that scan. The goal is now to extract the object's *as-built dimensions* from this point cloud. *As-built dimensions* refer to both the *pose* and the *shape* of the object.

In this paper, we assume that “*each object's as-built shape dimensions comply with the specified tolerances*”. This assumption, although not generally acceptable, can be considered genuine for prefabricated elements, such as steel or precast concrete elements, for which shape dimensions should comply with tolerances prior to erection (MNL, 2000; AISC, 2005). Future research will consider the more generalized case for which as-built shape dimensions cannot be assumed compliant with specifications (*e.g.* cast-in-place concrete).

After the registration process presented in Section 2, the CAD model of the object is “aligned” with its as-built point cloud. However, this alignment is performed globally, considering all CAD model objects. It is thus proposed to re-apply the ICP registration algorithm of Section 2 with, as input, the scan-registered object's CAD model and its corresponding as-built point cloud extracted from the scan. This second fine registration process results in a further refinement of the registration of each object model with its corresponding point cloud, independently from the other objects. It is referred to as *object fine*

registration by comparison to the *model fine registration* performed in Section 2. At the end of the object fine registration, the CAD model of the object is considered to be in its *as-built pose*. This pose can then be directly compared to the *as-designed pose*, *i.e.* the pose of the object's CAD model prior to the object fine registration. The difference between an object's as-built dimension and its corresponding as-designed one can be compared to the tolerance defined in the project specifications – these may be specific to the project or refer to industry standards such as AISC 303-05 (AISC, 2005) and MNL 135-00 (MNL, 2000). Similarly, dimensional compliance control can be performed with inter-object dimensions (*e.g.* distance between columns).

5 Experimental Results

Experiments have been conducted to compare the performances of: (1) the proposed registration approach (*Coarse + Fine*) to the one originally proposed in (Bosché, et al., 2009) (*Coarse*), and (2) the proposed approach for object dimensional (pose) compliance control. The experiments use the same data set as in (Bosché, et al., 2009):

- *Five laser scans* acquired at different stages of the construction of the steel structure of one of the buildings of the Portland Energy Center (PEC) power plant project in Toronto, Canada. Table 1 summarizes the main characteristics of the five scans. One of the scans, Scan 4, is displayed in Figure 1(a).
- The *3D CAD model* of the building's steel structure containing 612 objects with a total of 19,478 facets. The objects have various sizes, ranging from large beams to small tie bars. The CAD model of the building's structure is displayed in Figure 1(b).

Table 1: Characteristics of the five scans used in the experiments.

Scan ID	Number of points	Resolution (μrad)	
		Hor	Vert
1	691,906	582	582
2	723,523	582	582
3	810,399	582	582
4	650,941	582	582
5	134,263	300	300

5.1 Object Recognition

First of all, experiments are conducted to assess the object recognition performance achieved as a result of the proposed novel model registration algorithm. Results obtained with Scan 4 are displayed in Figure 1 and recognition statistics are presented for the five scans in Table 2. These results are good. The reported recall, specificity and precision rates are higher than those reported in (Bosché, et al., 2009), thus justifying the use of the additional fine registration step.

5.2 Dimensional Compliance Control

Then, we investigate the performance of the proposed approach for as-built dimension estimation. Figure 2(a) shows the 16 columns of the structure, and Figure 2(b) the location of the top and bottom center points of a given column. These points are used to calculate the deviations between the estimated as-built and as-designed object poses and other dimensions. Table 3 reports the estimated pose deviations for each of the 16 columns. Then, Table 4 reports the estimated deviations between *structurally connected* columns, *i.e.* columns that are directly connected by beams.

Unfortunately, for all the reported values (in particular the estimated as-built poses), the ground truth, or at least the values that would have been measured manually on site, are not available. As a result, the author cannot demonstrate here whether the reported deviations are true.

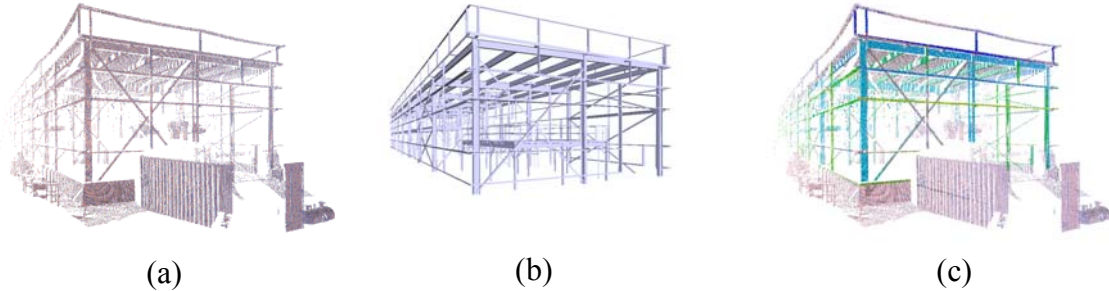


Figure 1: Performance of the proposed approach for 3D CAD model object: (a) Scan 4; (b) 3D CAD model after registration with the scan; (c) object recognition results where each point cloud corresponding to a CAD object is displayed with a unique color. Points in gray (same color as in (a)) are those that have not been matched to any CAD object. Note that some colors may appear identical but are in fact different.

Nonetheless, the reported results are very promising. All the values in Table 3 and Table 4 seem realistic in terms of order of magnitude. It can be noticed that the estimated deviations tend to increase with the distance from the scanner to the object (see location of scanner in Figure 2(a)). This increase is likely related to the typical decrease in accuracy of laser scanners with distance, and, from a certain distance, it seems too significant for reliable dimensional compliance control. Therefore, either a more accurate laser scanner should be used, or only objects at shorter distances to the scanner should be controlled. In that regard, it must be noted that, in Scan 4, the distances of the 16 columns to the scanner range from 20m to 80m, which is quite far. More accurate estimations could thus be obtained for all columns by simply positioning the same scanner at a more central location.

Table 2: Object recognition performance results (recall $R\%$, specificity $S\%$ and precision $P\%$) for the 5 scans.

Scan ID	$R\%$	$S\%$	$P\%$
1	83%	92%	92%
2	82%	94%	93%
3	85%	94%	93%
4	87%	94%	91%
5	87%	99%	83%

6 Conclusion

This paper presented an approach for the *fully automated* tracking of the as-built 3D status of construction sites using laser scanning and project 3D CAD models. The first contribution is the improvement of an initial approach for automated recognition of project 3D CAD model objects in large site laser scans. The second contribution is a method for estimating as-built dimensions, more exactly here as-built poses, of objects. This system, to the knowledge of the author, is the only reported remote sensing -based system that aims at both recognizing objects in laser scans and estimating their as-built dimensions. Experimental results are very promising. The system performs well, particularly when accuracy, robustness with respect to occlusions and level of automation are simultaneously considered. And, compared to what is argued in previous publications about laser-based systems, it is quite efficient. Indeed, the complete analysis of a scan, like Scan 4, takes less than 30 minutes, which is short compared to the amount of information extracted from the scan.

However, future work should compare the accuracy of the estimated as-built poses with ground truth (or at least with results obtained with traditional manual approaches). Further, a method for estimating the as-built shape of non-prefabricated objects must be developed so that the system enables more comprehensive dimensional quality control.

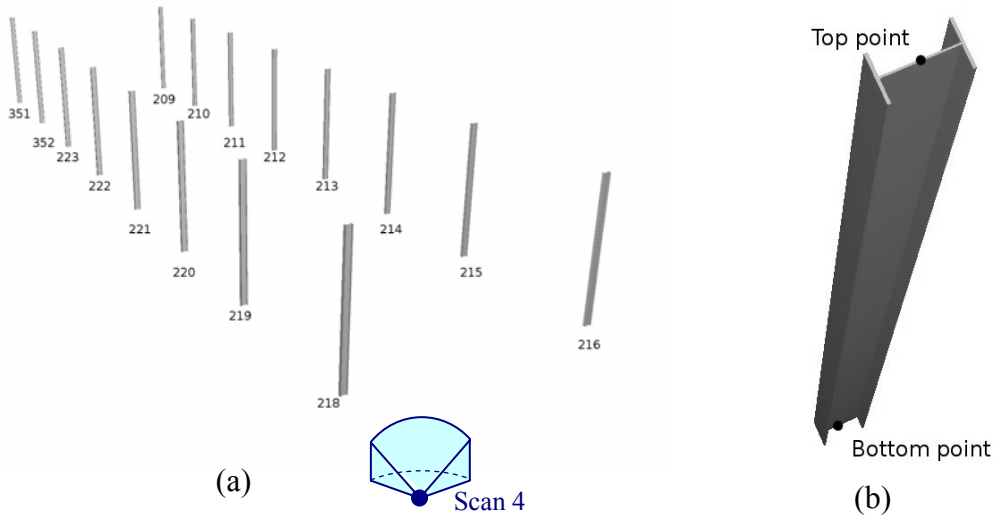


Figure 2: (a) The 16 exterior columns of the structure of the PEC building and the location of the scanner for Scan 4; (b) The *top center point* and *bottom center point* of a column.

Table 3: Dimensional quality control of the 16 exterior columns, from Scan 4. ΔXYZ is the difference between the as-built and as-designed location of a point (here bottom and top center points (Figure 2(b))); $\Delta plumb$ is the difference between the as-built and as-designed plumb.

Obj ID	ΔXYZ (mm)		$\Delta plumb$ (%)
	Bottom Point	Top Point	
209	10.2	19.0	0.33
210	12.7	17.8	0.38
211	11.3	16.9	0.34
212	8.2	12.0	0.26
213	23.3	5.2	0.23
214	16.7	16.0	0.11
215	16.6	11.3	0.32
216	7.7	2.2	0.10
218	1.8	1.0	0.0
219	4.9	7.0	0.11
220	4.2	16.5	0.21
221	11.1	6.0	0.22
222	6.0	4.8	0.09
223	11.3	13.4	0.31
352	6.8	16.4	0.30
351	5.4	19.8	0.31

Table 4: Dimensional quality control of the 16 exterior columns, from Scan 4. ΔXYZ is the difference between the as-built and as-designed distances between the bottom and top center points (Figure 2(b)) of the pair of *structurally connected* columns.

First Obj. ID	Second Obj. ID	ΔXYZ (mm)	
		Bottom Point	Top Point
210	209	-5.2	-1.3
211	210	1.2	-0.9
212	211	3.0	-4.9
213	212	30.9	-6.7
214	213	-25.2	2.6
215	214	-7.7	-8.4
216	215	3.6	1.5
219	218	3.3	-3.2
220	219	-0.8	-0.8
221	220	6.6	-2.2
222	221	-4.8	2.4
223	222	5.3	-9.8
352	223	-4.5	-3.0
351	352	-1.3	-3.4

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