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Citation for published version:
Turkan, Y, Bosche, FN, Haas, C & Haas, R 2010, Towards automated progress tracking of erection of concrete structures. in *6th International AEC Innovation Conference.* 6th International AEC Innovation Conference, Altoona, United States, 9/06/10.

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
6th International AEC Innovation Conference

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Download date: 30. Nov. 2021

TOWARDS AUTOMATED PROGRESS TRACKING OF ERECTION OF CONCRETE STRUCTURES

Yelda Turkan[1], Frederic Bosche[2], Carl T. Haas[3], Ralph Haas[4]
[1] PhD Candidate, Department of Civil Engineering, University of Waterloo, Ontario, N2L 3G1, Canada; phone 519-888-4567 x 33929; fax 519-888-4300, e-mail: yturkan@engmail.uwaterloo.ca
[2] Post Doctorate, Computer Vision Laboratory & DDM Competence Center, ETH Zurich, HIT H 11.1, Wolfgang-Pauli-strasse 27, 8093 Zurich, Switzerland; phone +41-44-633-7012; e-mail: bosche@vision.ee.ethz.ch
[3] Professor, Department of Civil Engineering, University of Waterloo, Ontario, N2L 3G1, Canada; phone 519-888-4567 x 35492; fax 519-888-4300, e-mail: chaas@civmail.uwaterloo.ca
[4] Professor, Department of Civil Engineering, University of Waterloo, Ontario, N2L 3G1, Canada; phone 519-888-4567 x 32176; fax 519-888-4300, e-mail: haas@engmail.uwaterloo.ca

Abstract
One of the main criticisms of the construction industry is that projects are too often completed behind schedule (and/or with cost overruns). Schedule delays may result from poor planning, but also from poor progress control, because, if progress deviation is identified too late, then actions can often not be taken to avoid the impact of these delays on the overall project schedule. Progress tracking of erection of concrete structures in particular is a very demanding task requiring intensive data collection. It is because erection of concrete structures involves many steps like erection of scaffolding, formwork and rebar assemblies, concrete placement, and removal of scaffolding and formwork. Current manual tracking methods, based on foremen daily reports, are typically time consuming and/or error prone. Three dimensional (3D) Laser Scanners (LADARs) are capable of capturing and recording the 3D status of construction sites with high accuracy in short periods of time and have thus the potential to effectively support progress tracking. An automated object recognition system has recently been developed to recognize project 3D CAD model objects from site laser scans. A novel system is proposed here which combines this 3D object recognition system with architect and engineer provided BIM and schedule information into a 4D object recognition system, with a focus on progress tracking. This new system improves the one originally proposed by Bosche et al. (2009). It is demonstrated with real life data acquired over the course of construction of the new Engineering V Building at the University of Waterloo.

Keywords: Construction Progress Tracking, Laser Scanning, 3D CAD models, 4D Object recognition system

1. BACKGROUND & MOTIVATION

As depicted in Figure 1, Construction project management activities include a forward flow of design intent and project planning information and a feedback flow of project or facility state information (Navon and Sacks, 2007, Haas, 2008). Project planning and design activities result in three-dimensional (3D) design files, project specifications, and schedules that may be combined into multidimensional CAD models or Building

Information Models (BIM). These constitute the primary information sources for forward flow of design intent (*as-designed/as-planned*). Feedback flow of information (*as-built*), on the other hand, is usually derived from monitoring activities. The comparison of the as-built and as-planned information enables an objective control of the performance.

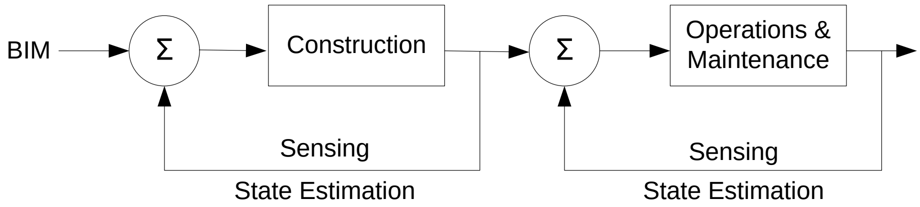

Figure 1 Information Flow in the Control Loop (Haas, 2008)

Numerous critical project performance control tasks, such as construction structural (or civil trades) progress and productivity tracking and construction quality assessment and quality control (QA/QC), require the comparison of *three-dimensional* as-designed and as-built. Additional, this information must be available at the *object* level (i.e. for each column, for each beam, etc.).

Multidimensional CAD models, or more generally now Building Information Models, are built upon projects' 3D models which can be seen as 3D representations of the *as-designed* project dimensional specifications, and which organize 3D as-designed information at the object level.

Three dimensional sensing technologies, on the other hand, such as total stations, Global Positioning Systems (GPS), Radio Frequency Identification (RFID), Ultra Wide Band (UWB) tags, 3D laser scanning technologies (also called LADAR or LIDAR), and modern photogrammetry are being investigated for providing 3D as-built information. Three dimensional laser scanning, in particular, enables fast, accurate and comprehensive acquisition of 3D as-built information. Three dimensional laser scanning has already been used in the construction industry for several applications such as: (1) as-built drawings of industrial plants, (2) structural layouts and measurement of infrastructure such as bridges, freeways, monuments, towers, (3) building redesign or expansion, (4) creating GIS map, and (5) documentation of any important landmarks or historical sites. However, there have been impediments to taking full advantage of this technology, since the currently available commercial software packages do not enable the automated organization of the data at object level – some manual and sometimes semi-automated approaches exist, but are very time consuming, must be used by experts, and are thus very expensive. However, in the case a project 3D+ model is available, then the method developed by Bosche (2009) can overcome this limitation. This method will be explained further in this section.

Three dimensional laser scanning technology

Three dimensional (3D) Laser scanning, also known as LADAR (Laser Detection and Ranging), is an imaging technology which has been used in industry since the late 1970s. However, its benefits were not recognized entirely until the 1990's because of the high cost and poor reliability of the early devices. Developments on computers, optics, and micro-chip lasers increased reliability of the laser scanners while decreasing their cost (Cheok, 2002). Accordingly, today's technology makes LADAR possible to capture very accurate and comprehensive 3D data for an entire construction scene (Stone and Cheok, 2001). The spatial information captured is stored as dense range point clouds or point clouds.

Laser scanning is probably the technology which is currently the best adapted for accurately and efficiently sensing the 3D status of projects (Cheok, 2000). In fact, the terrestrial laser scanning hardware, software and services market has experienced exponential growth in the last decade and the AEC-FM industry is one of its major customers (Greaves and Jenkins, 2007). This shows that owners and contractors are aware of the potential of using this technology for sensing the 3D as-built status of construction projects. However, laser scanners are currently used only to extract a few dimensions, or capture existing 3D conditions. Most of the data included in the laser scans are discarded, and hence laser scans are not being used at their full potential. As mentioned above, laser scanned point clouds need to be segmented at the object level to take advantage of their full potential, because information at the object level is necessary for progress tracking (and other control tasks). Currently proposed systems either only allow data visualization (Fard and Peña-Mora, 2007) or require time consuming manual data analysis to organize data at the object level. The method developed by Bosche (2009) overcomes this limitation when a 3D model of the construction is available.

An object recognition method that uses 3D a priori information

The approach of Bosche et al (2009) used here recognizes the 3D model objects in laser scans by robustly aligning them. The approach is robust with respect to occlusions due to 3D model objects and non-3D model object (e.g. temporary structures, equipment, people). However, with some modifications that will be explained later, its performance can be improved, in particular in the case it is applied for progress tracking. It consists of a series of four consecutive steps:

- Convert the 3D CAD model into a triangulated mesh (e.g. OBJ or STL formats);
- Manual Model coarse registration
- Model fine registration
- Object Recognition

This approach and its experimentally validated performance have been published in (Bosche et al., 2009) and (Bosche, 2009).

Construction progress tracking

Accurate and efficient construction progress tracking allows project managers to detect any schedule delays in advance, and gives the opportunity to take immediate actions to minimize their impacts. Current practice of progress tracking mostly depends on foremen daily reports which involve intensive manual data collection. These daily reports are then studied by field engineers and superintendents along with 2D as-planned drawings, project specifications and construction details to review the progress achieved by that date. After that, they study the construction schedule to identify the work needed to be done by that date. This requires a significant amount of manual work that may impact the quality of the progress estimations (Kiziltas and Akinci 2005). In conclusion, current manual methods for progress tracking may not be sufficient to study project progress precisely and quickly.

Most research in automated project progress tracking, in contrast to manually based quantity collection efforts, aims to automate the measurement of physical quantities in-place by using spatial sensing technologies. This is feasible because virtually the final product of every construction project is a tangible physical object. An intuitive way to assess the project progress would be to geometrically compare the as-built condition with the planned condition. This concept has been supported by a number of research studies. Cheok et al. (2000), for example, demonstrated real-time assessment and documentation of studied construction process on the basis of 3D as-built models by using a terrestrial laser scanner. Jaselskis et al. (2005) investigated the potential benefits of using laser scanning on transportation projects, concluding that laser scanning can be very effective for the purpose of safe and accurate construction measurement. Golparvar-Fard M. et al. (2009) proposed an automated method for progress monitoring using daily photographs taken from a construction site. In this research, they calibrate (internal and external calibrations) series of images of the site, and consequently reconstruct a sparse 3D as-built point cloud of that site. This allowed them to compare as-built data with 3D as-planned data, and monitor the progress. Bosche et al. (2008) introduced an automated approach for project progress tracking by fusing three dimensional (3D) Computer-Aided Design (CAD) modeling and time stamped 3D laser scanned data which underlies the research presented here.

The research presented here builds upon the approach by Bosche (2009) for 3D CAD object recognition in dense point clouds (Bosche, 2009), but improves it for progress tracking purposes. It is true that progress related to inspections, tests, calibrations, etc., are non-spatial, so there is much opportunity for future research efforts to automate progress tracking in these areas. Already, some progress has been made with rugged, hand held computers that can be used to automate the data entry process to some extent and to reduce transcriptions errors introduced by having to transcribe hand-written reports into project control computers.

2. NEW APPROACH

The approach presented in this paper combines 3D point clouds, project 3D CAD models and schedule information to track construction progress. The dense 3D point clouds used in this project are obtained using a 3D laser scanner. The laser scans provide information of current site conditions for automated progress tracking. Meanwhile, the 3D CAD model combined with schedule information (the 4D model) provides designed (as-planned) spatial characteristics of the facility under construction. This is done manually; i.e. the 3D CAD model is modified manually according to the construction schedule using commercial CAD software. To extract useful information for progress tracking, laser scans and the 4D model are co-registered (i.e. registered together within the same coordinate system). Once registered, as-built objects can be recognized using the object recognition system, and progress estimated. A conceptual view of the components of the proposed research is given in Figure 2. In the figure, the parallelogram boxes show input/output data, while the trapezoid and rectangular boxes showing manual operations, and automated processes respectively. The dashed arrows in the figure indicate updates to the project schedule.

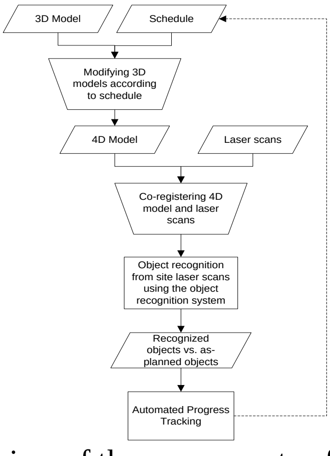

Figure 2 Conceptual view of the components of the proposed approach

Recognizing Project CAD Objects in a Site Laser Scan

As discussed above, as-built data needs to be accessible at the design object level, so that meaningful comparisons can be made with the project's CAD model. The approach by (Bosche, 2009) is used here to recognize 3D CAD model objects from site laser scans efficiently. The approach has shown very good recognition performance.

Calculating Expected Project CAD Objects in a Site Laser Scan

In addition to recognizing the objects that have been built, the approach by (Bosche, 2009) also enables the calculation of the objects that are expected to be found in a given scan. This is very important because, based on the location of the scanner when the given scan is acquired, many constructed objects are generally occluded. As a result, by first assessing which objects are expected to be recognized in a given scan, more robust conclusions on the progress can be made. In other words, expected progress is view-dependent, and Bosche's approach is able to take this into account.

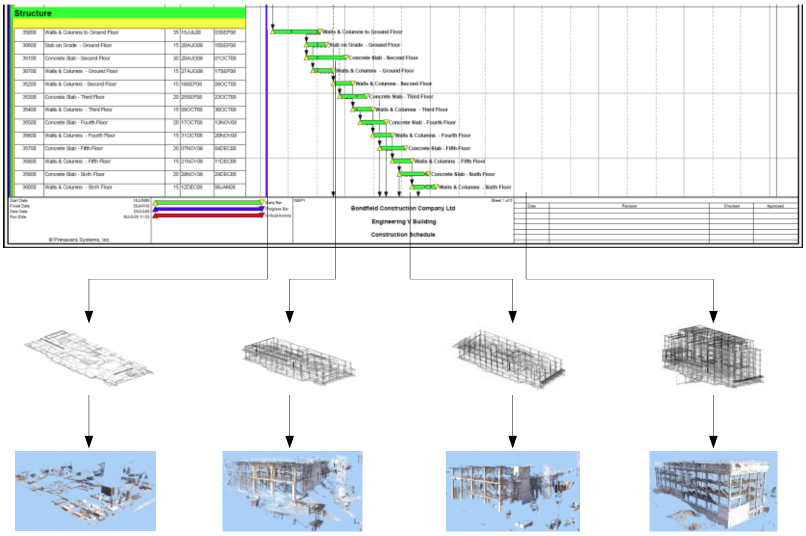

Figure 3 Four Dimensional (4D) Model for object recognition

Progress Tracking of Erection of Concrete Structures

An automated construction progress tracking method for tracking of concrete structures is presented here. To do this, the 3D CAD model, the construction schedule, and site laser scan data of the project are related via design object codes. Concrete structure objects are retrieved from their site laser scans automatically using the object recognition algorithm as explained above. The intent is to enhance this approach with schedule information to be able to track concrete structure objects over time and consequently track progress automatically.

The presented approach improves the one originally proposed by Bosche et al. (2009) that uses the project 3D model to generate as-expected point clouds. This could give misleading object recognition results because the 3D model is the representation of the complete structure. Instead, using a 4D model (3D CAD model + schedule) to produce as-expected point clouds and retrieve construction objects from them would give better results (Figure 3). It is so, because the completed final structure has occlusions, especially if it is a dense structure with opaque floors such as concrete slabs. For this reason, Bosche's approach is used here by modifying the 3D model to be matched with each scan for by using schedule information, i.e. the 4D model.

3. EXPERIMENTS

The Engineering V Building at the University of Waterloo is a six-storey concrete structure building. The Building is connected to the existing engineering complex by an enclosed pedestrian bridge.

The building 3D CAD model and the original construction schedule produced by the design company and the contractor respectively have been obtained for this research. Production of the 3D CAD model in Revit™ format (a BIM standard) was a substantial investment in professional time by the design company (RJC) and a significant contribution to this research effort for which they should be acknowledged. The original construction schedule of the Engineering V Building at the University of Waterloo main campus was provided by Bondfield Construction Company Limited, the general contractor.

Field Data Acquisition - Laser Scanning

The Engineering V Building was scanned while under construction using a Trimble™ GX 3D Laser Scanner starting in July 2008 until May 2009. Since it is recommended not to use this scanner with external temperatures under zero degrees Celsius, no scan has been performed between November 2008 and March 2009[1].

The Trimble™ GX 3D Scanner is an advanced surveying and spatial imaging sensor that uses time-of-flight technology which means that the scanner calculates distances by shooting a laser pulse and measuring the time taken for the pulse to return to the scanner after reflecting off an object. The Trimble™ GX 3D scanner allows collecting millions of points with very high spatial resolution. Its main technical properties are given in Table 1.

Table 1: Characteristics of the Trimble™ GX 3D scanner

Laser Type		Pulsed; 532nm; green
Distance	Range	2 m to 200m
	Accuracy	1.5 mm @ 50 m; 7 mm @ 100 m
Angle	Range	Hor: 360°; Vert: 60°
	Accuracy	Hor: 60 μrad; Vert: 70 μrad
Maximum Resolution		Hor: 31 μrad; Vert: 16 μrad
Acquisition Speed		up to 5000 pts/s

Object Recognition & Results

An example experiment is given in this section to demonstrate the performance of the object recognition software. It uses a scan acquired on October 30, 2008. The 3D CAD Model in STL format and the scan are used as input data. The 3D CAD model contains 1573 objects including columns, beams, walls and concrete slabs, and the time-stamped 3D model contains 240 objects. The scan contains 1,060,650 points and has an angular resolution of 582 μrad horizontally and vertically.

Object Recognition Process

Step 1 - Convert 3D Model: Converting the 3D CAD model into triangulated mesh format (currently the OBJ and STL format is supported) is the first step of the object recognition process. Figure 4 presents the triangulated mesh model which contains 44,234 facets - an average of about 28 facets per object.

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1 *Commercial scanning companies use warming huts to scan in the winter*

Step 2 – Coarse registration: The second step of the process is to co-register the STL-formatted 3D model and the laser scan. This is done using a manual approach consisting in selecting at least three pairs of corresponding 3D points in the scan and the model. This has been done using the Trimble® RealWorks® software package. Figure 5 shows the co-registered 3D model and Scan 1.
Step 3 – Fine registration: This additional step is performed automatically to optimize the alignment of the model and scan obtained from the coarse registration step. A robust approach is used here. More details can be found in (Bosche, 2009).
Step 4 – Point matching: At the end of Step 3, points in the scan have been optimally matched to points on the surfaces of the 3D CAD model objects. As a result, an as-built point cloud can be extracted from the scan for each model object, by matching the points to the objects' meshes. Figure 6 shows the matched points for Scan 1.
Step 5 – Object recognition: A robust metric is then used to infer the recognition of each model object. For each model object, the covered surface of its recognized as-built points is compared to an automatically calculated robust threshold $Surf_{min}$. In the case of Scan 1, $Surf_{min}$ equals 0.1 m^2. Figure 7 shows recognized CAD model objects in the scan. In this figure, each object is represented using a different color – some objects may appear with similar colors (e.g. columns in yellow) but these are actually different.

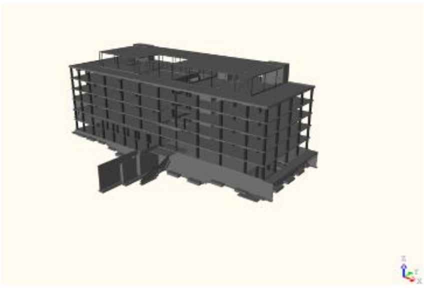

Figure 4 STL-formatted 3D CAD model.

Figure 5 3D model referenced in the scanner's spherical coordinate frame.

Figure 6 Points matched in Scan 1.

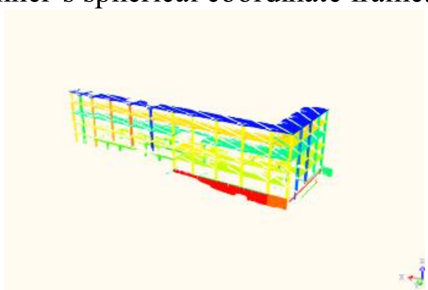

Figure 7 Object recognition results obtained with Scan 1.

Recognition Statistics

Recognition performance statistics are presented in Table 2. The columns present the values defined below:

Col. 1: Date of the scan.
Col. 2: Number of objects which are expected to be recognized in the scan when using the entire 3D CAD model (i.e. of the complete structure).
Col. 3: Number of objects which are actually recognized in the scan when using the entire 3D CAD model.
Col. 4: Number of objects which are expected to be recognized in the scan when using the time stamped 3D CAD model (i.e. 4D model).
Col. 5: Number of objects which are actually recognized in the scan when using the time stamped 3D CAD model (4D model).

Table 2 Object Recognition Statistics

Scan No.	Scan Date	Planned (3D)	Recognized (3D)	Planned (4D)	Recognized (4D)
1	2008-10-30	349	73	131	74
2	2009-04-17	439	203	383	203
3	2009-05-05	291	116	270	120

First of all, Table 2 shows that the use of the 4D model leads in two cases to a higher number of recognized objects. Although the difference appears very small here, a more detailed analysis of the results, for the first scan for example, shows that while almost all of the 74 objects recognized using the 4D model were indeed present in the scan[2], eight objects (10%) recognized using the 3D model were wrongly recognized. A typical example is the recognition of a column that is not yet constructed, but for which the connecting reinforcing steel from the column is present.

A second interesting result shown by Table 2 is that, although the 4D model obviously provides a better prediction of the number of objects expected to be recognized in the scan (Column 4 compared to Column 2), this number is still often twice larger than the number of actually recognized objects (Column 5). There are two reasons that explain this discrepancy:

- <u>Inadequate model</u>: The time-stamped 3D model that we were using for the recognition did not match the as-built status of the building at the time of the scan. For example, some elements are typically built in successive steps (e.g. an elevator shaft), while, in the 3D model, these are stored in a single object. As a result, some of these objects were sometimes expected to be seen although they were not in the scan. Also, some objects were left in the model (e.g. foundation elements) and thus were sometimes expected to be recognized although backfilling had already been completed. Finally, some discrepancies have been found between the 3D model of the building and the actual building (possibly resulting from some unreported change orders). This typically resulted in the system failing to recognize these objects.
- <u>Occlusions from non-CAD objects</u>: At the time of the scan, many temporary structures were present in front of and inside the building, resulting in significant occlusions and therefore resulting in the failure of the system to recognize many objects located far away from the scanner (17 columns and several more objects were for instance too occluded to be recognized).
- <u>Lack of scans from more than one perspective</u>

Overall, we note that, although some discrepancies did exist between the 3D model and the construction site status, the difference between Columns 4 and 5 mainly results from the occlusions due to temporary structures. For a better understanding of the situation, Figure 8 shows the colorized 3D model showing the recognition results as well as all the points that were not matched to any object. It shows that the temporary structures have a significant impact on the recognition of objects located far from the scanner (>50m), but not otherwise. As a result, we argue that by combining the recognition obtained with several scans from different perspectives and points in time, the progress of the construction could be tracked reliably.

[2] Only one element was wrongly recognized: a column for which only the formwork was in place. Note that this column was also wrongly recognized when using the complete 3D model.

Figure 8 Non matched cloud points and the 4D model colorized based on the recognition results (red: planned but not recognized; green: planned and recognized). Note that the elements colored in red at the bottom of the building are foundation elements that were already covered at the time of the scan.

4.CONCLUSIONS & FUTURE WORK

An automated concrete superstructure construction progress tracking method using LADAR technology is presented here. Progress tracking is a critical management task for construction projects, and the current manual tracking methods such as using foremen daily reports, are time consuming and/or error prone. The novel system proposed here automates and increases the accuracy of this time-consuming management task. The system aims at improving a recently developed automated object recognition system (Bosche et al., 2009) by combining it with schedule information. Preliminary experimental results show that performance is indeed improved. Further experiments are being conducted using a significant field database, acquired during the construction of the structure of the Engineering V Building at the University of Waterloo. In addition, we will investigate the automated update of the project schedule using the feedback information provided by the proposed system.
Although progress and productivity tracking is possible using 3D sensing technologies, some limitations remain. While structural elements such as columns, beams, and slabs can be tracked easily using these technologies, the current system cannot track finish trades such as painting, and tiling. More generally, it may not be well adapted for indoor progress tracking.

5.ACKNOWLEDGEMENT

The authors would like to thank Mike Moffat from Read Jones Christoffersen (RJC) for providing the 3D CAD model of Engineering V Building, and Ken Williamson from Bonfield Construction for allowing Yelda Turkan to take the scans of the construction. The authors would also like to thank to Sue Goodings and Arash Shahi from University of Waterloo for their help during this work.
This research is partially founded by CRD, NSERC, and Swiss National Science Foundation, grant number IZK0Z2-127892/1.

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