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AUTOMATED PROGRESS TRACKING OF ERECTION OF CONCRETE STRUCTURES

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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, mainly based on foremen daily reports, are typically time consuming and/or error prone. Improved progress tracking requires better project three dimensional (3D) as-built status tracking. Until recently, accurate and comprehensive 3D as-built status tracking remained impractical since the available technology made it too time and labour intensive. However, developments made in 3D imaging technologies, specifically laser scanning and photogrammetry, and 3D (even 4D) modeling in the last two decades make fast and accurate 3D as-built status tracking possible. 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. A system for automated progress tracking recently developed (Bosche, 2009) combines 4D modelling and laser scanning. Given a laser scan of a construction site and its acquisition date, the system quasi-automatically recognizes the building elements that are expected to be built at that date and visible in the scan. Results from multiple scans obtained on the same date but from different locations can be aggregated, and the combined recognition results are used to automatically infer site progress status, and consequently update the schedule. In this paper, this system is tested with real life data acquired over the course of construction of the new Engineering V Building at the University of Waterloo. Experimental results demonstrate the significant potential of this system.

Keywords: Construction Progress Tracking, Laser Scanning, 4D modeling

1. Introduction

One of the main criticisms of the construction industry is that projects are too often completed behind schedule which affects construction productivity in terms of time and cost. 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. That is why project performance in the Architectural / Engineering / Construction and Facility Management (AEC & FM) industry needs to be assessed as thoroughly and as fast as possible in terms of quantities and elements put in place, tests conducted etc. 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. Traditional practice for construction progress assessment involves intensive manual data collection and processing which is labour intensive, expensive and generally results in partial and sometimes erroneous information.

Using new technologies in construction has been shown in several research efforts to improve productivity in construction projects and as a result, save time and cost. Razavi et al. (Razavi 2008) deployed a unique combination of GPS, RFID and hand held computing technologies to track key construction materials. The impact on project control and productivity has already been proven to be substantial, and the impact on the Canadian construction industry could be considerable if this technology becomes standard on large industrial projects. Some other similar achievements have occurred in the construction industry during the last decade. Earth moving activities have been changed fundamentally using GPS on earth moving equipment blades as feedback 3D cut-and-fill models as a control signal, and isometric graphical interfaces for the operators (Cho 2004, Kim 2002, Seo 2000).

Improved progress tracking, among other things, requires better three dimensional (3D) as-built status tracking. Until recently, accurate and comprehensive 3D as-built status tracking remained impractical since the adequate technology made it too time and labour intensive. However, developments made in 3D imaging technologies, specifically laser scanning and photogrammetry, and 3D (even 4D) modeling in the last two decades make fast and accurate 3D as-built status tracking possible. Three dimensional (3D) Laser Scanners, also known as 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. 3D laser scanning technology has already been used for maintenance and construction projects on existing industrial plants to develop as-built models, but there are limitations with current commercial software in terms of automated 3D image interpretation.

A system for automated progress tracking was recently proposed by Bosche (2009) that combines 4D modelling and laser scanning. Given a laser scan of a construction site and its acquisition date, the system quasi-automatically recognizes the building elements that are expected to be built at that date and visible in the scan. Results from multiple scans obtained on the same date but from different locations can be aggregated, and the combined recognition results are used to automatically infer site progress status, and subsequently update the schedule. In this paper, this system is tested with real life data acquired over the course of construction of the new Engineering V Building at the University of Waterloo. Experimental results demonstrate the significant potential of this system for automated 3D progress tracking, and this should result in improved construction productivity, as well as improved schedule and cost performance for the Canadian construction industry.

2. Background

Construction project management activities require forward flow of design intent and project planning information and a feedback flow of project or facility state information (Figure 1) (Navon and Sacks, 2007, Haas, 2008). Project planning and design activities that result in 3D design files, project specifications, and schedules may be combined in Building Information Models (BIM). These constitute the primary information sources for forward flow of design intent. Feedback flow of information, on the other hand, is usually derived from progress monitoring activities which are recently becoming more automated and integrated.

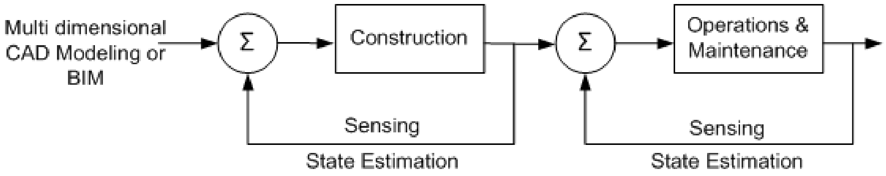

Figure 1 Information Flow in the Control Loop (Haas, 2008)

Multidimensional CAD modeling is one key technology for forward flow in current practice. Building Information Models will take the place of CAD modeling in the near future as they provide more comprehensive information about the construction design. Three dimensional sensing technologies, on the other hand, such as total stations, Global Positioning Systems (GPS), Radio Frequency Identification Devices (RFID), Ultra Wide Band (UWB) tags, 3D laser scanning technologies and modern photogrammetry are being investigated for providing information for the feedback flow. Three dimensional laser scanning is a key technology for 3D sensing as it provides fast, accurate and comprehensive information about the scene being scanned.

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: as-built drawings of industrial plants, structural layouts and measurement of infrastructure such as bridges, freeways, monuments, towers, building redesign or expansion, creating GIS map, and 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, if a project 4D model is available; the method developed by Bosche (2009) can overcome this limitation. This method will be explained further in this section.

2.1. 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.

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 earlier, 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 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.

2.2. Four dimensional (4D) modeling

In construction, a 4D model is a composition of project’s 3D CAD model with a corresponding construction schedule. In 4D models, components in 3D models are linked with the corresponding activities in construction schedules. A 4D model thus represents the as-planned construction process, and allows project managers to view the planned construction of a facility over time on the screen and to review a 3D CAD model for any time of the project. Hartmann et al. (2008) show that construction professionals believe 4D modelling can provide great benefits in construction operations analysis during planning. In this paper, it has been shown that 4D modeling can also benefit project control during the construction operations.

2.3. Integrating 4D modeling with Laser Scanning

Construction progress tracking in 3D is possible by using 4D modelling and 3D laser scanning together (Figure 2). This is feasible because a project 4D model shows as-planned 3D status over time; while laser scanning, when conducted over time, provides accurate and comprehensive data on as-built 3D status over time. Comparing these two at any time t would allow the observations of any deviations between the as-built and the as-planned data, so that corrective actions such as schedule review, review of construction method, re-construction, re-design etc. can be taken on time. This is leveraged in the system proposed by Bosche (2009). Its analysis presented herein demonstrates very good performance for automated progress tracking.

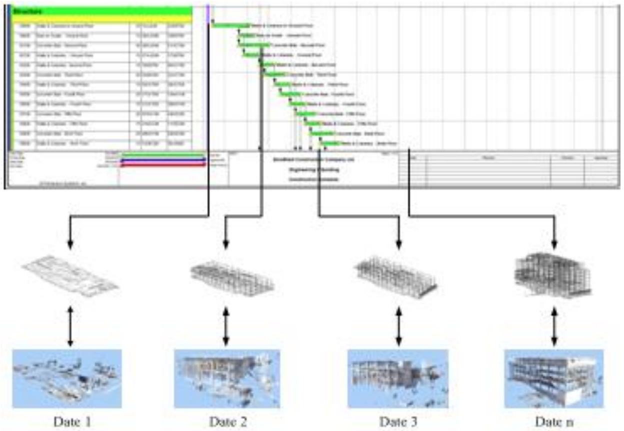

Figure 2 Four Dimensional (4D) Model for progress tracking

2.4. 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 essence, current manual methods for progress tracking may have limitations in tracking 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 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 visually 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 described here presents the experimental results based on the approach by Bosche (2009) for automated progress tracking by fusing 4D modeling with laser scanning. 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.

3. A system for Automated Progress Tracking

3.1. The Approach

The system used here 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. 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 then progress estimated based on the object recognition results. A conceptual view of the components of the approach used by the system is given in Figure 3. In the figure, the parallelogram boxes show input/output data, while the trapezoid and rectangular boxes showing semi-automated operations, and automated processes respectively. The dashed arrows in the figure indicate updates to the project schedule.

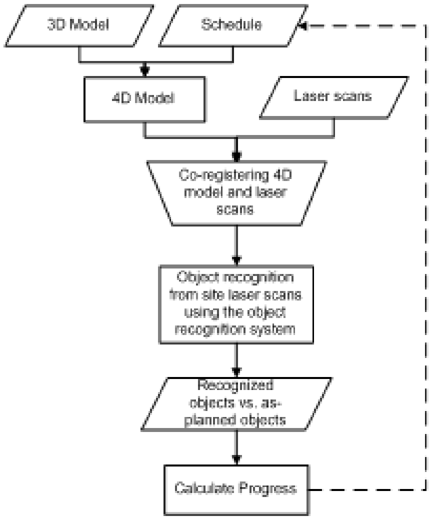

Figure 3 Conceptual view of the components of the system

3.2. Three dimensional (3D) Object Recognition

The system used here (Bosche, 2009) 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), and consists of the following:

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

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

3.3. Progress Calculation

Construction progress is calculated by the system based on the object recognition results from the analysis of scans acquired at date ScanDate. The system only estimates progress for the activities that are on-going, i.e. with scheduled start dates earlier than ScanDate and scheduled end dates later than ScanDate, as a first step. This means that all objects that are built during activities with end data earlier than ScanDate are considered already built, and similarly, the objects built during activities with start date later than ScanDate are considered not built. This assumption was made based on the premise that if the system is used frequently enough, then only on-going activities need to be assessed (Bosche et al. 2010).

The system compares the number of recognized objects with the number of expected objects, i.e. scheduled and visible from the scanner's location, for each on-going activity. Finally, the recognized and scheduled progress for the on-going activity i at date ScanDate are calculated as:

[1]

where is the set of expected objects for activity i, is the set of recognized objects. and are the cardinalities, i.e. number of elements of the sets, of and respectively.

[2]

where and are the start and end dates of the activity i, and is the number of seconds between and .

It is important to emphasize here that the system calculated the recognized visible progress by considering only the objects visible from the scanner's location(s). Furthermore, the authors acknowledge that the current estimations of the scheduled and recognized progresses have some limitations (i.e. all objects are given the same wait in the calculation of the recognized progress, regardless of the complexity to build them), Nonetheless, these are sufficient to prove the feasibility of using the approach of Bosche (2009) to control progress.

4. Experiments

Bosche's approach (2009) is tested using real life data in order to assess its performance. The data used here is very particular, and its collection was the result of a tremendous effort from different partners of the project, i.e. the owner (the University of Waterloo), the general contractor (Bondfield Construction Company Limited), the design company (Read Jones Christoffersen) and the research team.

4.1 Data

The data includes a 3D model, a schedule, and set of field laser scans obtained from the construction of the Engineering V Building located at the University of Waterloo's main campus, a six-storey concrete structure building.

The building 3D CAD model, with 1,573 3D elements including columns, beams, walls and concrete slabs was produced by the design company in Autodesk Revit^{TM} format. This model was converted into STL format by the university research team. The original construction schedule, including 20 activities, was produced by the general contractor on Microsoft Project. The Engineering V Building construction site was scanned using a Trimble^{TM} 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.

The Trimble^{TM} 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^{TM} GX 3D scanner allows collecting millions of points with very high spatial resolution. Its main technical properties are given in Table 1. The experimental results presented in this paper were obtained using eight different scans conducted at five different dates. One scan was conducted on August 19th 2008 (Scan 1), one scan conducted on August 21st 2008 (Scan 2), two scans on August 26th 8th 2008 (Scans 3 and 4), two scans on August 29th 2008 (Scan 5 and 6) and two scans on September 8th 2008 (Scans 7 and 8). The scans contain between 250,000 and 1,200,000 points each, with horizontal and vertical resolutions of 582 µrad x 582 µrad. Figure 4 shows one of the scans conducted on September 8th 2008.

Table 1: Characteristics of the Trimble^{TM} 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

Figure 4: Scan 8

4.2. Results

The experimental data were processed using the automated system for 3D object recognition and 3D progress tracking.

3D Object recognition: Table 2 presents the system's object recognition performance obtained with each scan. The system achieves very high performances with 98% recall, and 95% precision in average. (The precision is the percentage of recognized 3D elements that are actually in the scan(s), and the recall is the percentage of 3D elements present in the scan(s) that are actually recognized.)

In fact, a more detailed analysis of these results indicates that, for both recall and precision, the small errors (i.e. false negative rate and false positive rate respectively) generally result from objects for which only a few points were recognized, i.e. objects with only a few points acquired in the scan, or temporary objects with a few points wrongly recognized as coming from one building 3D element. These two errors can be removed by increasing the object recognition threshold that is related to the scan resolution and a minimum number of points to be recognized (5 points were used here) - see (Bosche 2009) for more detail.

Table 2: Object recognition performance

Scan ID	Scan Date	Recall	Precision
1	2008-08-19	98%	96%
2	2008-08-21	98%	95%
3	2008-08-26	100%	98%
4	2008-08-26	98%	95%
5	2008-08-29	97%	96%
6	2008-08-29	97%	94%
7	2008-09-08	100%	93%
8	2008-09-08	96%	94%
Overall		98%	95%

3D Progress Tracking: Table 3 presents the progress tracking results obtained for September 8, 2008 using the original project schedule and automatically combining the object recognition results from the two scans acquired on that day (Scan 7 and Scan 8 in Table 2). This table reports t~~T~~he Scheduled Progress, t~~T~~he Recognized Visible Progress, and t~~T~~he Actual Visible Progress as defined in Equations [1], [2], and [3] respectively.

[3]

where is the set of expected objects for activity i, is the set of objects actually in the scans. and are the cardinalities, i.e. number of elements of the sets, of and respectively. This Progress is estimated manually.

The progress of on-going activities (activities 9 and 10 in Table 3) needs to be assessed here in order to evaluate the automated progress tracking system's performance. Table 3 shows that the recognized visible progress values are quite different from the scheduled ones. This could lead to the conclusion that the project is behind schedule. Although the project was indeed behind schedule (based on the original schedule provided), it is noted that the two positions from which the two scans were acquired did not provide data on all objects related to the two on-going~~ose~~ activities. Therefore, they didn't enable the complete tracking of their progress. This signifies the importance of capturing a set of scans which covers all the necessary information for progress tracking. In other words, this suggests the need for planning for scanning. However, the recognized visible progress appears similar to the visible progress (this relates to~~result from~~ the very high recall and precision rates of the object recognition algorithm). Therefore, it can be concluded that, if the scans did contain data about all the objects related to activities 9 and 10, then the Recognized Visible Progress would have been similar to the Scheduled Progress. Table 4 shows progress tracking results for the other scan days. The results presented in Table 4 are only for on-going activities, and it can be seen that similar results as for September 8 are obtained~~ for the other scan days~~.

It must also be noted that~~Finally~~, using updated schedules for the progress estimation is expected to improve these results (only the initial schedule is used here, but this one differs significantly from the current state of the site). The current system is already able to calculate an updated schedule. This feature of the system will be improved in the future, and tested with a comprehensive data set.

Table 3: Progress tracking on September 8, 2008: Recognized Progress, Scheduled Progress, and Actual Progress are calculated using Equations [1], [2] and [3] respectively.

Activity ID	Name	Schedule Status	Recognized Visible Progress	Scheduled progress	Actual Visible Progress
~~7~~...	...~~Slab on Grade - Ground Floor~~	...~~Completed~~	...~~100%~~	...~~100%~~	...~~100%~~
8	Walls & Columns - Ground Floor	Completed	100%	100%	100%
9	Concrete Slab – 2nd Floor	On-going	52%	70%	54%
10	Walls & Columns – 2nd Floor	On-going	0%	24%	0%
11	Concrete Slab – 3rd Floor	Not started	0%	0%	0%
...~~12~~	...~~Walls & Columns – 3rd Floor~~	...~~Not started~~	...~~0%~~	...~~0%~~	...~~0%~~

Table 4: Progress tracking results for the Scans 1-6 (On-going activities only)

Scan Day	Activity ID	Activity Name	Recognized Visible Progress	Scheduled progress	Actual Visible Progress
2009-08-19	7	Slab on Grade - Ground Floor	67%	100%	65%
	8	Walls & Columns - Ground Floor	48%	57%	44%
2008-08-21	8	Walls & Columns - Ground Floor	49%	67%	46%
	9	Concrete Slab – 2nd Floor	0%	10%	0%
2008-08-26	8	Walls & Columns - Ground Floor	60%	71%	62%
	9	Concrete Slab – 2nd Floor	0%	27%	0%
2008-08-29	8	Walls & Columns - Ground Floor	71%	86%	72%
	9	Concrete Slab – 2nd Floor	33%	40%	31%

5. Conclusions & Future Work

An automated construction progress tracking method which fuses 4D modeling and laser scanning is tested with the data collected from a concrete superstructure construction site in this paper. 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 system used here automates and increases the accuracy of this time-consuming management task by calculating construction progress automatically. Preliminary experimental results show that performance of the method is promising. Incomplete input scan data explains less than perfect results here, and indicates the importance of ensuring that a set of scans captures all necessary data for progress tracking, i.e. planning for scanning needs to be addressed.

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, it is planned to investigate the automated update of the project schedule using the feedback information provided by the current 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.

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