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FUSING 4D MODELLING AND LASER SCANNING FOR CONSTRUCTION SCHEDULE CONTROL

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The construction industry remains one of the riskiest of all. This risk is mainly the result of a poorly controlled, and thus uncertain, environment. For instance, construction progress is often improperly controlled, resulting in some unnoticed errors with considerable impact on later project activities, and ultimately project success. Better progress control requires, among other things, better project three-dimensional (3D) as-built status control. Until recently, comprehensive and accurate 3D as-built status control remained almost impossible because the lack of adequate technology made it too time- and labour-intensive. However, the progress made in the last two decades in 3D (even 4D) modelling, and more recently in laser scanner (and also photogrammetry), is such that fast and accurate 3D as-built status control is now conceivable. In this paper, a system for automated construction progress control using laser scanning and 4D modelling is presented. Given a laser scan of a construction site and its acquisition date, the system quasi-automatically recognizes the building elements that (1) are expected to be built at that date and (2) visible in this 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. Experimental results demonstrate these features and the significant potential of this approach.

Keywords: automation, project management, quantity surveying.

INTRODUCTION

The construction industry remains one of the riskiest of all, not only with respect to workers' safety, but also from the point of view of the probability and extent of failure with respect to budget and schedule. For instance, the UK National Audit Office (NAO) reported in the *"PFI: Construction Performance"* (NAO 2003) that 22% of the surveyed 37 Private Finance Initiative (PFI) projects completed before Sumner 2001 showed actual costs exceeding the contracted ones, and 24% were delivered late. While three times lower than the values reported in the earlier NAO report *"Modernising Construction"* (NAO 2001), they remain quite high considering the fact that they were under the Private Finance Initiative, a procurement scheme aimed at better transferring risk from the government (the client) to the contractors and thus aiming at significantly improving such performance criteria. Another study commissioned by HM Treasury in 2002 (Mott MacDonald 2002) looked at both PFI and non-PFI projects, and showed that while PFI projects generally do well, non-PFI projects consistently under-estimate project delivery cost and schedule.

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Progress measurement is for schedule control one of the most important tasks of project management (Memon 2005, Kiziltas and Akinci 2005). It is however generally carried out inaccurately and untimely. The reason is that, current approaches for acquiring as-built information are too labour-intensive and inaccurate (Rebolj 2008, Navon 2007, Davidson 1995). As-built information collection is thus conducted very infrequently, resulting in late corrective actions and consequently schedule delays (Ibrahim 2009, Navon 2007, Tsai 2007). Progress measurement thus remains one of the most challenging problems faced by construction project management (Saidi 2003).

New field technologies have the potential to support efficient and effective progress control (CIB 2009, Song 2007). These currently include global navigation satellite systems (GNSS) (e.g. GPS), Radio Frequency Identification (RFID), tablet PCs, Ultra-Wide Band (UWB), laser scanning and photogrammetry (Teizer 2010), with the former three in the most advanced stage of industry acceptance and use.

It must be noted that these technologies are not competing with one another, as they do not aim at controlling the same aspects of progress. First of all, tablet PCs simply enable manually acquired field data to be entered into the construction information management systems directly from the field. Then, RFID and UWB enable wireless identification of objects and consequently some coarse estimation of their locations (through triangulation). GNSS enables a more accurate but active acquisition of object locations outdoors (10cm-1m). Laser scanning and photogrammetry are used for much more accurate acquisition of object poses (< 10cm). It should also be added that while GNSS, RFID and UWB are used for estimating progress by tracking assets all over the supply chain, laser scanning and photogrammetry are being developed for estimating progress by recognizing objects at their final installed/built location. As a result, GNSS, RFID and UWB appear a priori more interesting for engineered items. Laser scanning and photogrammetry present the potential of detecting not only the presence of objects but also their pose in accurate terms, as well as the final assembly or placement of bulk materials (e.g. concrete). Contrary to GNSS, RFID and UWB, they thus support the creation of *as-built* information models.

The paper presents the most recent results of research aimed at developing a laser-scanning based system enabling: (1) project progress/schedule control, and (2) dimensional quality control and consequently as-built 3D model creation. While preliminary results on dimensional quality control have been provided in (Bosché 2009), the focus here is only on construction progress control. In the next section, the two main technologies used in the system, namely 4D modelling and 3D laser scanning, are presented. It is followed by the presentation of the integrated schedule control system. The section "Experiments" then presents experiment results demonstrating the performance of the system with real field data.

ENABLING TECHNOLOGIES

The system presented here is built upon two important technologies, 4D modelling and 3D laser scanning, which are briefly reviewed here.

4D Modelling

In construction, a 4D model is the result of the integration of a 3D model with a corresponding construction schedule -- possibly including the resources and their 3D representations (Koo and Fischer, 2000) (see Figure 2c). A 4D model thus represents the *as-planned* construction process. Hartmann et al. (2008) show that construction professionals believe that 4D modelling can provide great benefits in construction operations analysis during planning. The work presented here shows that 4D modelling can also benefit project control during construction operations.

3D Laser Scanning

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 realized 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 the reliability of the laser scanners while decreasing their cost. Accordingly, today's technology makes it possible for LADAR to capture very accurate and comprehensive 3D data for an entire construction scene (Cheok et al., 2002). The spatial information captured is stored as dense 3D 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 et al., 2000). In fact, the terrestrial laser scanning hardware, software and service 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.

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 maps, and (5) documentation of important landmarks or historical sites. However, a key impediment to taking full advantage of this technology is that currently available commercial software packages do not enable fully automated segmentation of the data at the object level (Bosché 2009).

Integration of 4D Modelling and Laser Scanning

4D modelling and 3D laser scanning together enable construction 3D control. Indeed, a project 4D model provides *as-planned 3D status over time*; laser scanning, when conducted over time, enables to gather comprehensive and accurate data on *as-built 3D status over time*. Comparing, at any time *t*, whether the as-built 3D status corresponds to the as-planned one, allows any observed deviation to trigger corrective actions (e.g. schedule review, review of construction method, re-construction, re-design, etc.). This is leveraged in the system presented herein that demonstrates very good performance for *automated progress control* and thus potential for *automated schedule updating*. But, as shown in (Bosché, 2009), the system also enables *dimensional quality control* and *as-built 3D model generation*.

AUTOMATED PROGRESS CONTROL

Overview

As summarized in Figure 1, the proposed system uses the project 4D model ("Design and Plan") and field laser scanned data ("Sense") to recognize the model objects ("Recognize Objects") in the scanned data. The recognition results thus enable the system to automatically infer and estimate progress ("Calculate Progress") and consequently update the construction schedule ("Update Schedule"). The progress and updated schedule can be analyzed by management to identify required corrective actions, but the updated schedule is also important to enable proper analysis of future scans. The three steps above, namely "Recognize Objects", "Calculate Progress" and "Update Schedule", are detailed below.

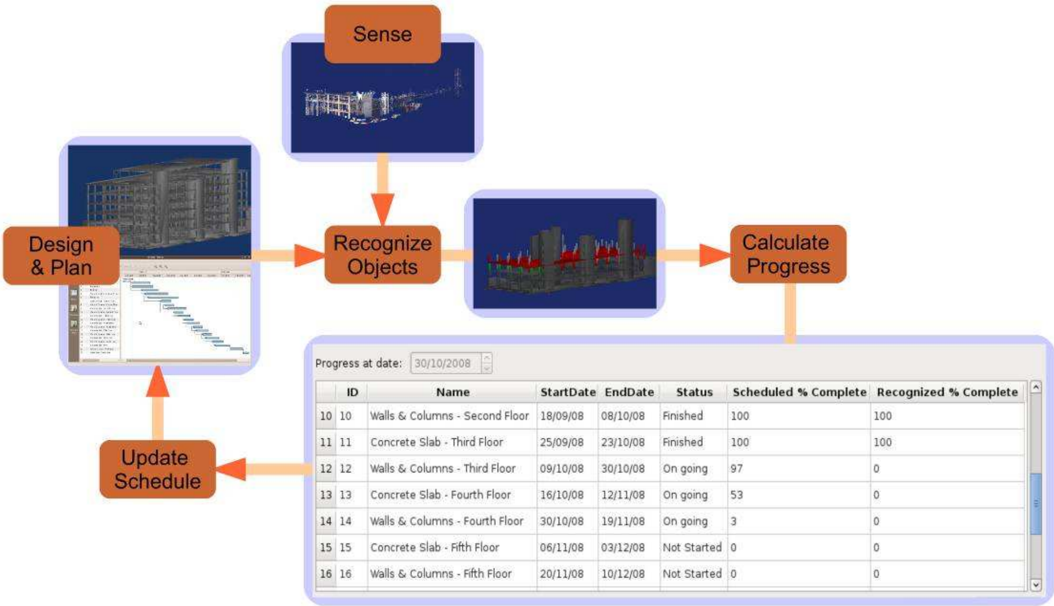


Figure 1: Procedure for automated progress calculation and schedule update.

3D Object Recognition

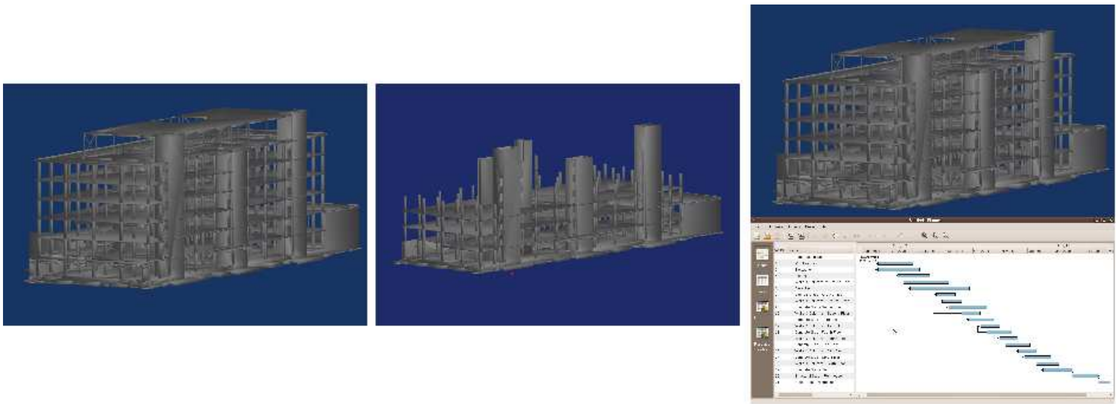
The scan recognition system is built upon the algorithm proposed by Bosché (2009) to recognize designed 3D model objects in laser scanned point clouds. In summary, this approach, which requires converting the input 3D model into a triangulated mesh format (OBJ and STL are currently supported), follows a three-step process:

1. *Manual Coarse Registration* performed by manually matching *n* pairs of points selected in the 3D model and in the scan;
2. *Model fine registration* implementing a robust Iterative Closest Point (ICP) algorithm;
3. *Object Recognition* using a robust surface-based recognition metric.

Out of these three steps, the coarse registration (step 1) is currently carried out manually, while steps 2 and 3 just require the user to define a few input parameters (but default values generally lead to good results).

The approach published in (Bosché 2009) uses the entire project 3D model to recognize objects in scans conducted at different moments in time during its construction. This has implications on its theoretical and practical performance as demonstrated by Turkan et al. (2010). In addition, Turkan et al. (2010) empirically demonstrate how the use of a time-adjusted 3D model improves the system's performance.

While the time-adjusted 3D models used by Turkan et al. (2010) were manually selected from the complete model, the system presented here enables the user to import true project 4D models (see Figure 2), so that the system automatically constructs the right time-adjusted 3D model based on the date of acquisition of the laser scans being processed.



(a) (b) (c)

Figure 2: (a) 3D model, (b) time-stamped 3D model and (c) 4D model (the schedule can be visualized in Figure 3).

3D Progress Calculation

The system currently calculates progress based on the analysis of scans acquired at date *ScanDate* as follows. First, the system only estimates progress for the activities that are *on-going*, i.e. with scheduled start date earlier than *ScanDate* and scheduled end date later than *ScanDate*. 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. These assumptions are justified by the fact that, if the system is used frequently, then only on-going activities need to be assessed. Then, given the input scans, the system compares the number of objects from all *on-going* activities that have been *recognized* to those that are *expected*, i.e. that are part of any on-going activity (i.e. *scheduled*) and are *visible* from the scanner's location. The recognized progress for activity *i* is thus calculated as:

$$\mathrm{Pr}\,og_{\mathrm{Recognized},i} = \frac{\left|\{Obj_{\mathrm{Recognized}}\} \cap \{Obj_{Expected}\}_i\right|}{\left|\{Obj_{Expected}\}_i\right|} \times 100 \qquad [1]$$

where $\{Obj_{Expected}\}_i$ is the set of expected objects for activity *i*, $\{Obj_{\mathrm{Recognized}}\}$ is the set of recognized objects, and $|A|$ is the cardinality of A.

It is important to note that the system effectively calculates the *recognized visible progress* by considering only the objects visible from the scanner's location(s). This approach could be challenged by arguing that it should always consider all objects, included ones. However, the intention here is to isolate the performance of the progress estimation algorithm from the issue of whether or not the set of analyzed scans contains sufficient data for all objects part of the investigated schedule activities. This issue, that is certainly critical, is discussed further later in this paper.

A limitation of the current approach is that it does not enable recognition of work conducted ahead of schedule. Nonetheless, this could be done by running the system a second time with also objects selected from coming activities so that their early construction can be detected.

Schedule Update

Based on the estimated progress, the schedule is updated as follows. First of all, the scheduled progress at the date *ScanDate* for all *on-going* activities is calculated as:

$$\Pr og_{Scheduled,i} = \frac{\left|ScanDate - StartDate_i\right|_s}{\left|EndDate_i - StartDate_i\right|_s} \times 100 \qquad [2]$$

where $StartDate_i$ and $EndDate_i$ are the start and end dates of the activity *i*, and $\left|Date_B - Date_A\right|_s$ is the number of seconds between $Date_A$ and $Date_B$.

Then, if $\Pr og_{\mathrm{Re}cognized,i} \neq \Pr og_{Scheduled,i}$ then $EndDate_i$ is delayed (or brought earlier) according to $\Pr og_{Scheduled,i} - \Pr og_{\mathrm{Re}cognized,i}$. All the non-started activities succeeding activity *i* (based on the precedence links) are then also sequentially delayed (or brought earlier).

The resulting updated schedule can then be used: (1) by management to identify deviations and then implement corrective actions, (2) by management to estimate project completion date, and (3) for the analysis of scans acquired at future dates. The current system thus performs a *complete schedule control loop*, although it currently only considers built 3D objects.

EXPERIMENTS

In order to estimate the performance of the proposed approach, a set of experiments has been conducted using real life data. It is acknowledged that this data, i.e. a 4D model of a project and frequent laser scans of the corresponding site, is incomplete. However, it is really unique and its acquisition was the result of a tremendous effort from the different partners of the project, i.e. the owner (the University of Waterloo), the general contractor (Bondfield Construction Company Limited), the design company (RJC) and our research team.

Data

The data consists of a 3D model, a schedule and a set of field laser scans obtained for the construction of the Engineering V building on the University of Waterloo campus (a six-storey concrete structure building). The building 3D CAD model, with 1,573 3D elements including columns, beams, walls and concrete slabs (see Figure 2(a)), was produced by the design company in *Autodesk RevitTM*. The original construction schedule, containing 20 activities (see Figure 3), was produced by the general contractor on *Microsoft Project*.

The construction site was scanned using a *TrimbleTM GX 3D* laser scanner from July 2008 until May 2009. Since it is recommended not to use this scanner with external temperatures under zero degrees Celsius, no scan was performed between November 2008 and March 2009. The *TrimbleTM GX 3D* scanner is an advanced surveying and spatial imaging sensor that uses time-of-flight technology and allows collecting millions of points with high spatial resolution. Its main technical properties are given in Table 1. The experimental results presented below were obtained using 6 different scans conducted on four different dates. Two scans were conducted on September 9th 2008 (Scans 1 and 2), two scans on October 24th 2008 (Scans 3 and 4), one scan on October 30th 2008 (Scan 5) and one scan on November 6th 2008 (Scan 6). The scans contain between 250,000 and 900,000 points each, with horizontal and vertical resolutions of 582 µrad x 582 µrad. Figure 4 shows one of the scans conducted on October 24th 2008.

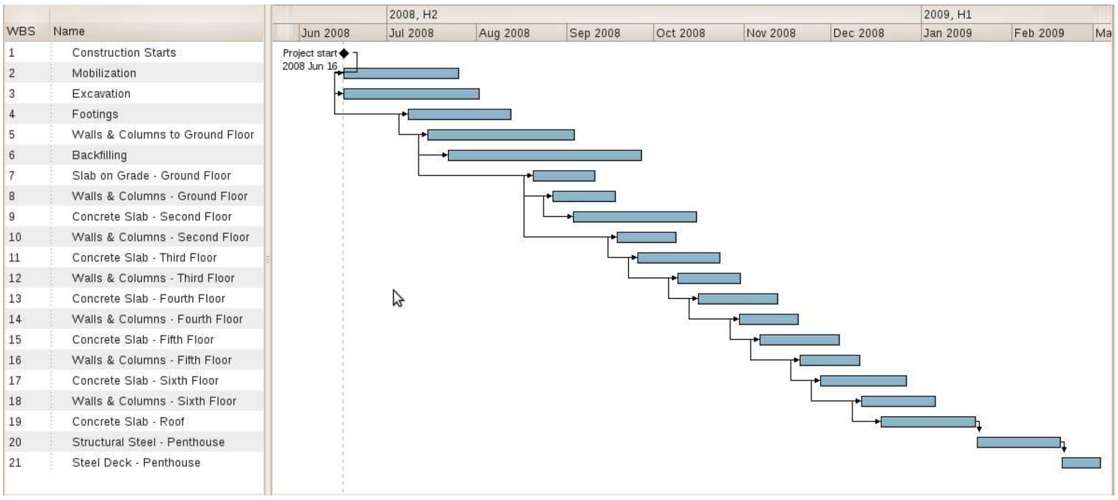


Figure 3: Construction schedule of the Engineering V building.

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

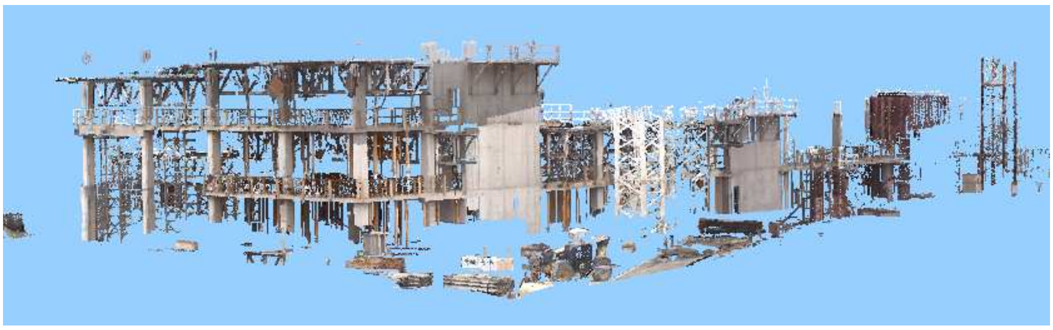


Figure 4: Scan 3.

Results

The experimental data was processed using the proposed approaches for 3D object recognition and 3D progress tracking. The following results were obtained:

3D Object Recognition: As can be seen in Table 2, that summarizes the object recognition performance, the proposed approach achieves very good performance. It enables the recognition of most building 3D elements present in scans without recognizing elements that are not in them.

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 (here a value of 5 was used) - see (Bosché 2009) for more detail.

Another source of error that has been noticed is the confusion between actual cast-in-place objects and the formworks used for their construction. This error has several origins that include, but not only, the point recognition threshold (automatically estimated, but generally around 10mm) and the scanner's accuracy (see Table 1). An approach for overcoming this limitation would be to combine 3D and colour information, possibly by fusing laser scanning and vision data.

Table 2: Object recognition performance: The recall is the percentage of 3D elements present in the scan(s) that are actually recognized. The precision is the percentage of recognized 3D elements that are actually in the scan(s).

Scan ID	Recall	Precision
1	100 %	93 %
2	96%	94%
3	97%	94%
4	94%	88%
5	93%	90%
6	93%	98%
Overall	95%	92%

3D Progress Tracking and Schedule Control: Table 3 presents the schedule control results obtained on October 24th 2008 using the original project schedule and automatically combining the object recognition results from the two scans acquired on that day (Scan 3 and Scan 4 in Table 2). This table reports the Recognized Visible Progress and the Scheduled Progress as defined in Equations [1] and [2], as well as the *Actual Visible Progress* which is calculated as:

$$\Pr og_{Actual,i} = \frac{\left|\{Obj_{Actual}\} \cap \{Obj_{Expected}\}_i\right|}{\left|\{Obj_{Expected}\}_i\right|} \times 100$$

[3]

where $\{Obj_{Expected}\}_i$ is the set of expected objects for activity i, $\{Obj_{Actual}\}$ is the set of objects actually in the scan(s), and $|A|$ is the cardinality of A.

The activities of interest here, i.e. on-going, are activities 12 and 13 (see Table 3). For both, the results show that the recognized visible progress is similar to the actual visible one. This simply results from the performance of the object recognition step. In the case of activity 12, the difference is due to a few elements to which a few points (between 5 and 15) are wrongly associated by the system. These situations could be avoided by using a high object recognition threshold, as suggested earlier. Note that at 50m, with the resolution of these two scans, 15 points represent a surface of 1.2 dm2 which is very small. As a result, a higher threshold would still be acceptable.

Table 3 also shows that the recognized visible progress values are quite different from the scheduled one. This could lead to the conclusion that the project is behind schedule. However, although the project was indeed behind schedule (based on the original schedule that we were provided), it must be noted that the two positions from which the two scans were acquired (on the ground nearby the building) could not actually enable the complete tracking of the progress of the construction of all elements of activities 12 and 13. For instance, many 3rd floor columns were invisible from both locations. This indicates that, however good the proposed system is, there is a serious issue with respect to ensuring that a set of scans will enable capturing all necessary data. In other words, this suggests the need for *planning for scanning*.

Although the progress estimation results are not perfect here, we note that the system is already able to calculate an updated schedule using the method described earlier, which would then be used to perform a more reliable analysis of the scans conducted in following days, for instance with Scan 4 conducted on October 30th 2008.

Table 3: Progress control on October 24th 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
...	...	...	...	...	...
10	Walls & Columns - 2nd Floor	Completed	100%	100%	100%
11	Concrete Slab - 3rd Floor	Completed	100%	100%	100%
12	Walls & Columns - 3rd Floor	On-going	38%	70%	44%
13	Concrete Slab - 4th Floor	On-going	4%	31%	0%
14	Walls & Columns - 4th Floor	Not started	0%	0%	0%
15	Concrete Slab - 5th Floor	Not started	0%	0%	0%
...	...	...	...	...	

CONCLUSIONS

This paper presented an automated system for progress and schedule control using laser-scanned data as input. The system is demonstrated using real-life complex data. The experimental results demonstrate good overall performance of the object recognition approach. Nonetheless, some limitations have been observed where the system often confuses a cast-in-place element with its form. This issue could be resolved by combining 3D and colour information, possibly by fusing laser scanning and vision data. The experiments presented here provide some insight on the potential of using the object recognition output for progress control. While the incompleteness of the input data for a proper performance assessment mostly explains less than perfect results, it also raises the issue of ensuring that a set of scans captures all necessary data. Therefore, *planning for scanning* needs to be addressed.

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