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Automated Progress Tracking Using 4D Schedule and 3D Sensing Technologies

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Abstract

Efficient and effective construction progress tracking is critical to construction management. Current manual methods, which are mainly based on foremen daily reports or quantity surveyor reports, are time consuming and/or error prone. Three dimensional (3D) sensing technologies, such as 3D laser scanners (LADARs) and photogrammetry are now being investigated and have shown potential for saving time and cost for recording project 3D status and thus to support some categories of progress tracking. Although laser scanners in particular and 3D imaging in general are being investigated and used in multiple applications in the construction industry, their full potential has not yet been achieved. The reason may be that commercial software packages are still too complicated and time consuming for processing scanned data. Methods have however been developed for the automated, efficient and effective recognition of project 3D CAD model objects in site laser scans. A novel system is thus described herein that combines 3D object recognition technology with schedule information into a combined 4D object recognition system with a focus on progress tracking. This system is tested on a comprehensive field database acquired during the construction of the structure of the Engineering V Building at the University of Waterloo. It demonstrates a degree of accuracy for automated structural progress tracking and schedule updating that meets or exceeds typical manual performance.

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

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1. Introduction

Construction project management activities necessitate forward flow of design intent and feedback flow of project or facility state information (Figure 1) [1]. Project planning and design activities that result in 3D design files, project specifications, and schedules (that can be combined in Building Information Models (BIMs)) constitute the primary information source 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. The comparison of the as-built (feedback) and as-planned (forward) information enables an objective measure of the progress and more generally project performance.

Project control tasks, such as construction structural (or civil trades) progress and productivity tracking and construction quality assessment and quality control (QA/QC) require 3D as-designed (as-planned) and as-built information segmented at the object level. Three dimensional (3D) Computer-Aided Design (CAD) Models and Building Information Models (BIMs) are being used more frequently for project and facility life cycle management. These tools have been key technologies for forward flow. Building Information Models are replacing CAD models as they provide more comprehensive information about the construction design. BIMs are still typically built on a project's 3D model which is a 3D representation of the as-designed project dimensional specifications, and organizes 3D as-designed information at the object level. However, sensing technologies do not naturally produce object oriented data.

Three dimensional sensing technologies, such as total stations, Global Positioning Systems (GPS), Ultra Wide Band (UWB) tags, 3D laser scanning (also called LADAR), and modern digital photogrammetry are being investigated for providing 3D as-built information for the feedback flow. They produce their data in various formats. Three dimensional laser scanning, a key technology for feedback information flow because it provides fast, accurate, comprehensive and detailed 3D as-built information about the scene being scanned, produces vast point clouds of data.

Three dimensional laser scanning technologies have already been used in the construction industry for several applications such as creating as-built drawings of industrial plants, and measuring deterioration of infrastructure such as bridges [2], freeways [3, 4, 5], monuments, and towers. However, their full potential hasn't been achieved yet, since the currently available commercial packages do not allow automated segmentation of the data at the object level – some manual and sometimes semi-automated approaches exist, but they are very time consuming, must be operated by experts, and are thus very expensive. However, a method developed by Bosche et al. [6, 7] can overcome these limitations, if a project's 3D model is available. This method will be explained in Section 2.

1.1. Three dimensional laser scanning technology

Three dimensional (3D) Laser scanning, also known as LADAR (Laser Detection and Ranging), is an advanced imaging technology which has been used in industry since the late 1970s. Because of the high cost and poor reliability of early devices, they were not widely utilized until the early 1990s. Technological developments related to computers, optics, and micro-chip lasers make it possible for today's LADAR technology to capture comprehensive and very accurate 3D data for an entire construction scene using only a few scans [8]. The 3D data is stored as dense point clouds. Each point in these point clouds is defined as a "x, y, z" coordinate triplet in the scanner's coordinate system.

Among other three dimensional (3D) sensing technologies, laser scanning is currently most likely the best adapted technology for sensing the 3D status of projects accurately and efficiently [9]. Shih et al. [10] investigated the use of 3D laser scanning data to monitor project progress. They concluded that schedule-based scanning facilitates a detailed definition for partially completed construction work, and also provides as-built proof for geometric measurement and visualization. A formal methodology was developed in [11] for active construction quality control using laser scanning, embedded sensors and integrated project models. The authors concluded that these reality capture technologies can be employed for accurate as-built data collection on construction sites, and they can be leveraged to improve quality control processes. Akinci et al. [12] proposed a simulation-based framework to model information flow processes from a job site to a field office to measure and highlight existing deficiencies, and to model and demonstrate the effect of using laser scanners and radio frequency identification in streamlining the data collection process for the same project. Their simulation results showed that the time spent on non value adding activities in the information flow can be reduced significantly by utilizing these automated reality capture technologies. Tang et al. [13] investigated techniques developed in civil engineering and computer science to automate the process of creating as-built BIMs. In a similar research effort, Brilakis et al. [14] emphasized that having access to an as-built model of an existing facility can enhance project planning, improve data management, support decision making, and increase the productivity, profitability and accuracy of a construction project. They stated that as-built data can be collected automatically using laser scanners, but interpretation and merging of point clouds, stitching and object fitting are all performed manually. Therefore, they proposed an approach to automate the generation of as-built BIMs of constructed facilities by using hybrid video and laser scan data as input.

In a study by Greaves and Jenkins [15], it is shown that the three dimensional laser scanning hardware, software, and services market has grown exponentially in the last decade, and the AEC-FM industry is one of its major customers. 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' current usage in the industry often does not go beyond capturing existing 3D conditions and extracting a few dimensions, tie-in points and cross sections from the three dimensional point clouds of the construction, because current software for point cloud analysis requires time consuming manual data analysis to segment data at the object level. Recently released commercial tools based on algorithms such as those described in early work by Kwon et al. [16], do allow manually guided, semi-automated fitting of pipe spools (assemblies) to selected volumes of point clouds, but there is still costly labor input required. Thus, most of the information contained in the laser scans is not extracted, so that laser scans are not being used to their full potential. As previously indicated, as-built information needs to be organized at the object level to be used to its full potential, and information at the object level is a must for progress tracking purposes and other control tasks.

1.2. Construction Progress Tracking

Typical practice for progress tracking mostly depends on foremen daily or weekly reports which involve intensive manual data collection and entail frequent transcription or data entry errors. These reports are then studied by field engineers and/or 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 planned to be done by that date. This requires a significant amount of manual work that may impact the quality of the progress estimations [17]. On building projects, progress numbers may even be simply the claims made by the subcontractors, negotiated with or summarily verified by the general contractor. In conclusion, current manual methods for progress tracking have limitations in studying project progress precisely, objectively, and quickly.

Most research on 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 for many categories of work such as earth moving, structural erection, and masonry, because products of these construction processes are tangible physical objects. For non-volumetric progress such as painting, tests, and surface treatments, other automated approaches to progress tracking are being investigated by many researchers including the authors of this paper. An intuitive way to assess the 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. [9], for example, demonstrated real-time assessment and documentation of construction processes such as site preparation on the basis of 3D as-built models by using a terrestrial laser scanner. Jaselskis et al. [5] 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. A scheduling and progress control system called Photo-net is introduced in [18, 19]. The system relates time-lapse digital images of construction activities with CPM for progress control. Golparvar-Fard et al. [20, 21, 22] proposed an alternative image-based method for progress monitoring using daily photographs taken from a construction site. In this research, they calibrate (using 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. Wu et al. [23] proposed another image-based approach to estimate project status information automatically from construction site digital images. They developed an object recognition system to recognize construction objects of interest successfully from their construction site digital images. The approach exploits advanced imaging algorithms and a three dimensional computer aided design perspective view to increase the accuracy of the object recognition, and thus enables acquisition of project status information automatically. El-Omari and Moselhi [24] proposed a system that integrates different technologies such as barcoding, RFID, 3D laser scanning, digital images, and tablet PCs to automate data acquisition from construction sites to support efficient progress tracking and control of construction projects. They merged 3D laser scan images with digital photo images to produce 3D images of the scanned objects [25] in order to estimate quantities of work performed and calculate percent of work completed for each activity. However, their method requires manually selecting common points between the scan and the photographs in order to calculate volume of investigated objects. Thus, calculating work progress for an entire construction project with this method would require a significant amount of manual data processing. Bosche et al. [26, 27, 28] introduced a quasi-automated approach for project progress tracking by fusing 3D CAD modeling and time stamped 3D laser scanned data. This work forms the basis for the further research developments presented herein.

1.3. Contribution

The contribution of the approach presented in this paper is an automated construction progress tracking and schedule updating system which fuses 3D object recognition algorithms with 4D schedule data (Section 2). It implements an automated progress feedback loop, and it uses new and unique logical inferencing algorithms. The only manual step required is to register laser scan data with the 3D CAD model in the same coordinate system by choosing at least three pairs of corresponding points both in the scan and the model. The object recognition system [7] used is very accurate and robust to occlusions sourced from both 3D model and temporary construction objects. Compared to the system originally proposed in [7], the progress tracking system presented herein uses a 4D model (combination of 3D model and schedule data) to improve recognition of CAD model objects from their laser scans. Once the object recognition step is completed, progress estimates are made for each activity, and the schedule is updated automatically based on the progress estimates. It is shown through multiple experiments that the progress tracking system achieves promising results (Section 3.2), especially when the full feedback loop is implemented.

2. New Approach

The approach presented in this paper combines three dimensional (3D) point clouds with project 3D CAD model and schedule information to track construction progress. On one hand, 3D laser scan data provides current site conditions. On the other, the 3D CAD model combined with schedule information (the project 4D model), provides designed (as-planned) spatial characteristics of the facility under construction over time (Figure 2). Using such a 4D model, a time-stamped 3D CAD model can thus be formed automatically for a given date.

The proposed system for automated progress tracking and schedule updating requires the 3D point clouds and the 4D model to be registered in the same coordinate system to be able to extract useful data for progress tracking. Once registered, as-built objects can be recognized, progress estimated, and the schedule updated all automatically (Figure 3).

2.1. Three dimensional (3D) Object Recognition

The recognition system is built upon the algorithm proposed by Bosche et al. [7] to recognize designed 3D model objects in laser scanned point clouds. The approach is robust with respect to occlusions sourced from either 3D model objects or non 3D model objects (e.g. temporary structures, equipment, people). The approach requires converting the input 3D model into triangulated mesh format (OBJ and STL are currently supported) as a pre-step, and 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.

The coarse registration step (step 1) is currently performed manually, while the model fine registration and object recognition steps (steps 2 and 3) require that the user define only a few input parameters (though default parameter values generally achieve satisfactory results).

Turkan et al. [29] empirically demonstrated 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. [29] were manually defined from the complete model, the original system of Bosche [7] has been improved in [30] to enable the user to import true project 4D models (Figure 2). Therefore, the system automatically constructs the right time-adjusted 3D model – which is to be compared to the laser scan – based on the laser scan's acquisition date.

2.2. Three Dimensional Progress Calculation

Construction progress at date *ScanDate* is calculated by the system based on the object recognition results from the analysis of scans acquired on that date. 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 dates earlier than *ScanDate* are considered already built, and similarly the objects built during activities with start dates later than *ScanDate* are considered not built. This is done by the algorithm assigning 100% recognized progress to the activities with the end dates earlier than *ScanDate*, and 0% recognized progress to the activities with start dates later than *ScanDate*. This assumption is made under the premise that, if the system is used frequently enough, then only on-going activities need to be assessed.

For each on-going activity, the system compares the number of recognized objects with the number of expected objects, i.e. scheduled and visible from scanner's location(s). If the number of expected objects for the activity is equal to zero, then the recognized progress is assigned as 0%. Otherwise, the recognized progress for the on-going activity *i* at date *ScanDate* is calculated as:

$$Prog_{recognized,i} = \frac{\left|\{Obj_{recognized}\} \cap \{Obj_{expected}\}_i\right|}{\left|\{Obj_{expected}\}_i\right|} \times 100 \qquad [1]$$

where $\{\mathrm{Obj}_{\mathrm{Expected}}\}_{\mathrm{i}}$ is the set of expected objects for activity i, $\{\mathrm{Obj}_{\mathrm{Recognized}}\}$ is the set of recognized objects and $|\bullet|$ is the cardinality operator.

It is possible that the objects recognized on *Scan day 1* may not be recognized on *Scan day 2* due to temporary occlusions, scanning from a different location, etc. This would lead to lower recognized progress estimation for *Scan day 2* than *Scan day 1*. To prevent such situations; when calculating recognized progress for *Scan day 2*, its recognized progress estimation value is compared with the one of *Scan day 1*, and the higher value is assigned as recognized progress of *Scan day 2*. This is agreeably not optimal and keeping track of the recognition of each individual object would be much more appropriate. Nonetheless, the chosen heuristic currently leads to sufficiently good results demonstrating the potential impact of the proposed system.

Scheduled progress for each activity is calculated using the following formula:

$$Prog_{scheduled,i} = \frac{|Scan\ date - Start\ date_i|_s}{|End\ date_i - Start\ date_i|_s} \times 100 \qquad [2]$$

where $\mathrm{StartDate_i}$ and $\mathrm{EndDate_i}$ are the start and end dates of the activity i, and $|\mathrm{Date_B} - \mathrm{Date_A}|_\mathrm{s}$ is the duration (e.g. number of seconds) between $\mathrm{Date_A}$ and $\mathrm{Date_B}$.

It is important to emphasize here that the system calculates the recognized visible progress by considering only the objects visible from the scanner's location(s).

2.3. Schedule Update

The schedule is updated based on the estimated progress. First, scheduled progress is calculated for all *on-going* activities using Equation 2. Then, for an on-going activity *i*: If $Prog_{Recognized,i} \neq Prog_{Scheduled,i}$, $EndDate_i$ is delayed (or brought earlier) according to, $Prog_{Recognized,i} - Prog_{Scheduled,i}$. Finally, the non-started activities are updated based on the predecessor-successor relationships.

The resulting updated schedule can then be used: (1) by management to identify deviations and then implement corrective actions, but also (2) for the analysis of scans acquired at future dates.

3. Experiments

A set of experiments has been conducted using real life data to evaluate the performance of the proposed approach. The data collected includes a 3D BIM, construction schedule, and frequent laser scans of the corresponding site. Obtaining this data was the result of a significant and cooperative 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. If implemented as regular practice, this effort would be substantially reduced.

3.1. Data

The data is composed 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 main campus (a six-story building with cast-in-place concrete structure). The design company produced the 3D CAD model with two levels of detail (i.e. Level 1: Building structure 3D model, Level 2: All 3D column elements in the model, all 3D beams in the model etc. defined as single layers) in *Autodesk Revit*^{TM}, with 1,573 3D elements including columns, beams, walls and concrete slabs (Figure (2a)). The original construction schedule, including 20 activities, was produced by the general contractor with three levels of detail (i.e. Level 1: Building Project, Level 2: Floor 1, Floor 2, etc. Level 3: Walls & Columns-Floor 1, Concrete Slab – Floor 1, etc.) in *Microsoft Project* (Figure 4).

The construction site was scanned using a *Trimble*^{TM} *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. For regular project use, a warming hut could be used. The *Trimble*^{TM} *GX 3D* scanner uses time-of-flight. Its main technical properties [31] are given in Table 1.

The experimental results presented in the following section were obtained using seven different scans conducted on five different dates (Table 2). The scans contain between 250,000 and 1,200,000 points each, with horizontal and vertical resolutions of 582 μrad x 582 μrad. Figure 5 shows one of the scans conducted on September 8, 2008.

As mentioned in Section 2.1, the approach used here requires converting the 3D CAD model into triangulated meshes, with a distinct mesh for each model element. The system currently supports the ASCII STL and OBJ formats which are widely available in common CAD and BIM software. Then, the schedule provided in Microsoft Project format, is augmented with an additional field for each activity that states the IDs of the corresponding 3D model objects.

3.2. Results

The proposed approaches for 3D object recognition and 3D progress tracking were used to process the data. The following results were obtained:

3D Object Recognition: Table 2 shows the object recognition performance of the approach by using recall and precision rates. 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. High recall rate indicates that most building 3D elements present in scans are recognized, and high precision rate shows how well the recognition is done without recognizing elements that are not present in the scans. Therefore, it can be said that the proposed object recognition approach achieves very good performance (98% recall and 96% precision on average). A more detailed analysis of these results shows that, for both recall and precision, the small errors (i.e. false negative rate and false positive rate respectively) generally result from 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. It is possible to further decrease these two errors by increasing the object recognition threshold that is expressed as a minimum recognized surface, $Surf_{min}$ (m^2). For each object, its recognized surface, $Surf_R$, is calculated based on the number of recognized points, their distances to the scanner and the scan's angular resolution. If $Surf_R$ is larger than or equal to $Surf_{min}$, then the object is considered recognized; it is not otherwise. Both $Surf_R$ and $Surf_{min}$ are calculated as a function of the scan's angular resolution. Thus the object recognition metric used here is invariant with the scan angular resolution and the distance between the scanner and the object. The reader is referred to [7, 28] for more detail.

As described in Section 2, the approach requires having a 4D model of the structure to automatically recognize its objects from their laser scans, and calculate its progress. In this project, the 4D model didn't include information about rebar or formworks. Thus, object recognition and progress estimation couldn't be performed to that level of detail.

3D Progress Tracking: Table 3 and 4 present the progress tracking results for the scan data acquired between August 12, 2008 and August 29, 2008 using the original project schedule and the constantly automatically updated project schedule respectively. Three different types of progress are given in Table 3 and 4: The Recognized Visible Progress, The Scheduled Progress, and The Actual Visible Progress as defined in Equations [1] and [2], and [3] respectively.

$$Prog_{Actual,i} = \frac{\left|\{Obj_{Actual}\} \cap \{Obj_{Expected}\}_i\right|}{\left|\{Obj_{Expected}\}_i\right|} x100 \qquad [3]$$

where $\{\mathrm{Obj}_{\mathrm{Expected}}\}_{\mathrm{i}}$ and $\{\mathrm{Obj}_{\mathrm{Actual}}\}$ are the sets of respectively expected and actual visible objects for activity *i,* and $|A|$ is the cardinality of A. This progress is estimated manually by visually observing object recognition results together with the scan data.

Table 3 shows the progress tracking results (on-going activities only) for the scans acquired between August 12th, 2008 and August 29th, 2008 using the original schedule of the construction project without updating, and Table 4 shows the progress tracking results for the same scan data set using the constantly updated schedule. In Table 4, the original schedule is used to obtain the progress tracking results for the first scan (acquired on August 12th, 2008), while all the other results are obtained using the updated schedules, i.e. schedules output from the analysis of the previous scans.

In Table 3, it can clearly be seen 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. Some of the results presented in Table 4 tend to show that these differences were in fact mainly due to the use of a non-updated schedule. For instance, the difference was decreased from 9% (57% - 48%) to 0% (48% - 48%) for Activity 8 and from 3% (3% - 0%) to 0% (0% - 0%) for Activity 9 on August 19, 2008. This shows that using updated schedules, which are generated automatically by the system, improves the system's performance in the case that a project is behind schedule. However, there is still 8% difference between the scheduled and recognized progress values for Activity 8 on August 21, 2008, 14% difference for Activity 9 on August 26, 2008, and 10% and 17% differences for Activities 8 & 9 on August 29, 2008 respectively (Table 4). Multiple reasons may explain these values. First, the project was observed to be indeed a bit behind schedule. Then, the scans did not provide data on all objects related to the on-going activities (visibility issue). Therefore, the complete tracking of their progress could not be achieved. 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*. Another reason may be found in the progress estimation formulas. In any case, this shows the importance of having all objects present in the scans, i.e. good planning for scanning is essential prior to the project start to ensure having all the objects to be tracked in the scans so that more precise progress estimates can be made by the system. Thus, any difference between recognized and scheduled progress could then lead to the only conclusion that the project is either behind or ahead of schedule.

Despite these issues, the recognized visible progress appears similar to the actual visible progress (this relates to 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 on-going activities, then the recognized visible progress would have been similar to the expected progress (when using the constantly updated schedule with the current system).

4. Conclusions

An automated construction progress tracking system 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 and updating project schedule automatically. Experimental results show that the system's performance 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. Another reason may be found in the progress estimation formulas. The current approach takes occlusions into account when calculating the recognized progress, but this does not necessarily lead to appropriate results. For instance, the system will recognize 100% progress in the case 4 out 10 objects of an activity are built and visible in the scan(s), and the 6 others are not built yet and are invisible in the scan. However, there are also cases when taking occlusions into account gives more appropriate results. In any case, this shows the importance of having all objects present in the scans, i.e. *planning for scanning*. The system already enables calculating updated schedules, and the experimental results presented in this paper show that using updated schedules instead of the original project schedule gives better progress estimation results. It is expected to have better results, i.e. recognized progress corresponds to expected progress, in the case of having a comprehensive field data. Thus, as future work, the system will be tested using a significant field database, acquired during the construction of the structure of the Engineering VI Building at the University of Waterloo. 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 weight in the calculation of the recognized progress, regardless of the earned value associated with them or the complexity to build them). Although these are sufficient to prove the feasibility of using the approach of Bosche [7] to monitor progress, this limitation will be addressed by combining the system with Earned Value Theory.

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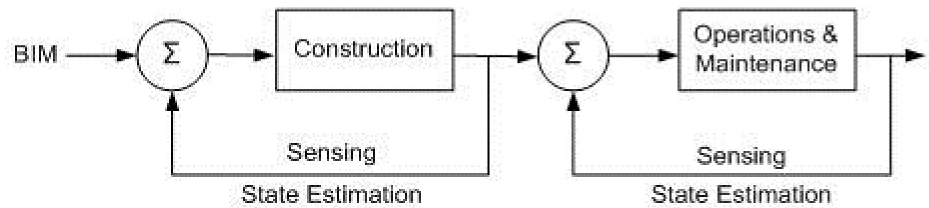
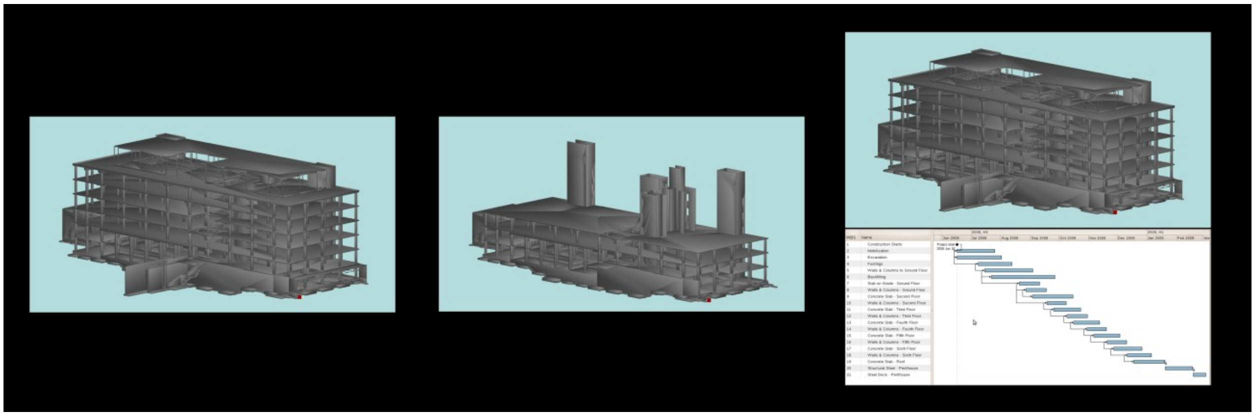
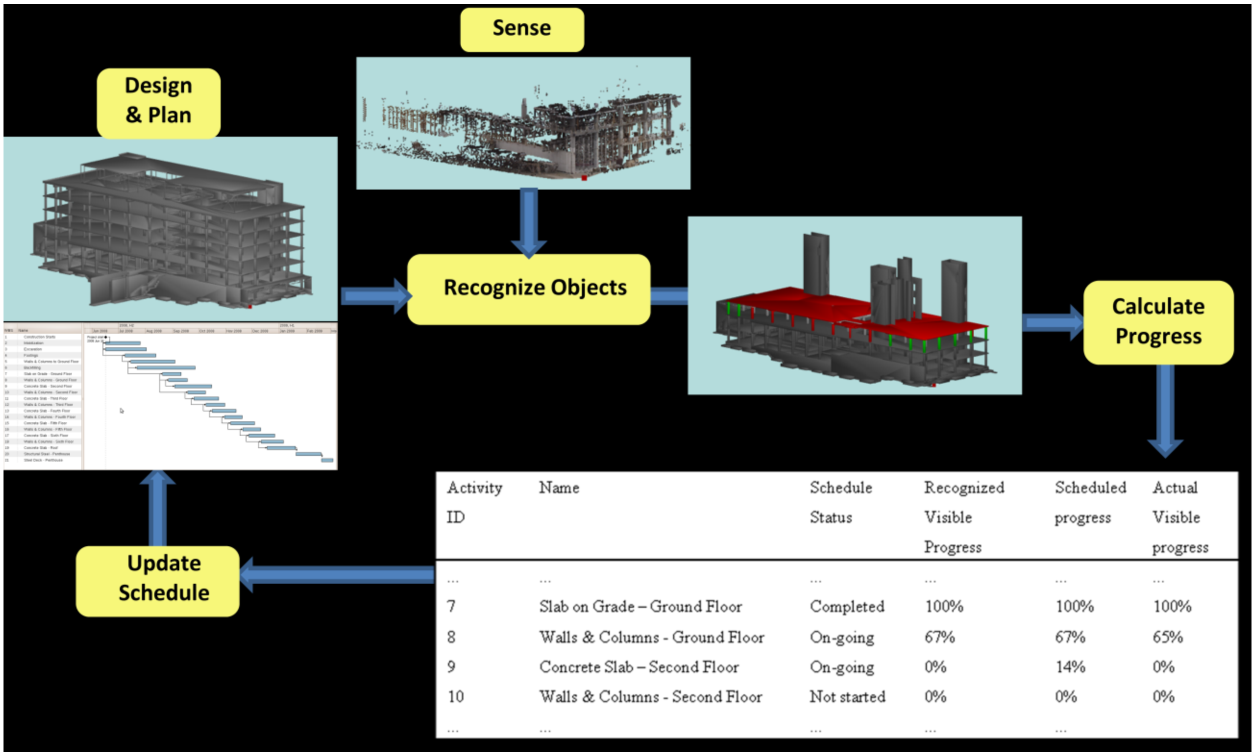


Figure 1: Information Flow in the Control Loop



(a) (b) (c)

Figure 2: (a) 3D model, (b) time-stamped 3D model and (c) 4D model.



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	On-going	67%	67%	65%
9	Concrete Slab – Second Floor	On-going	0%	14%	0%
10	Walls & Columns - Second Floor	Not started	0%	0%	0%
…	…	…	…	…	

Figure 3: Procedure for automated progress calculation and schedule update

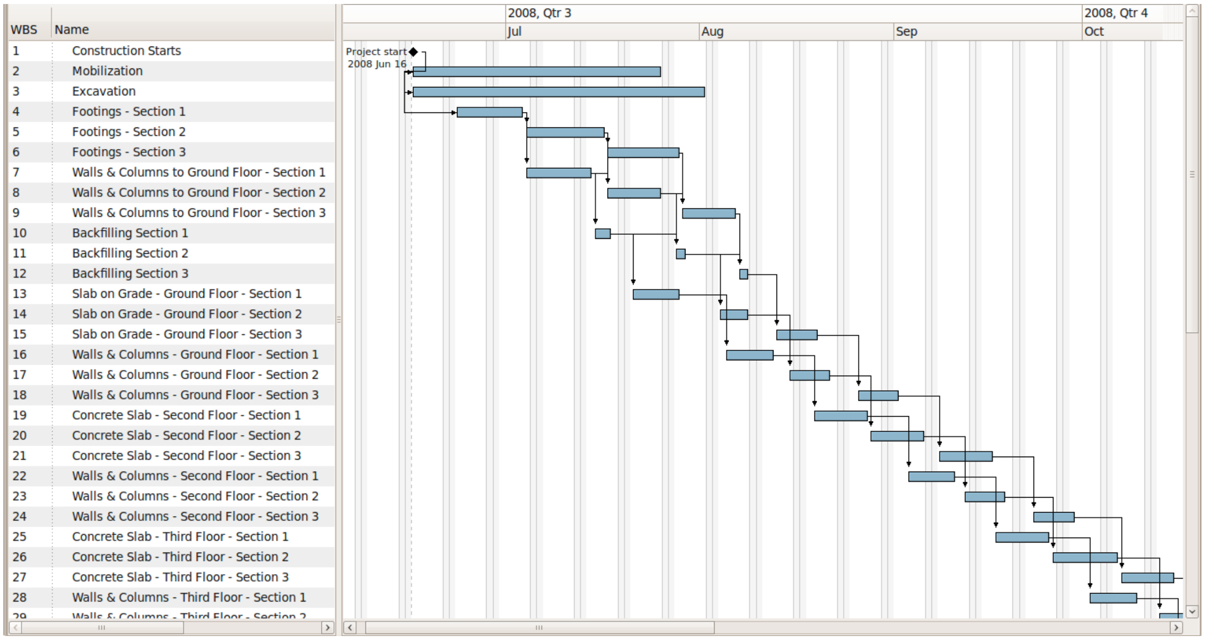


Figure 4: Construction schedule of the Engineering V building

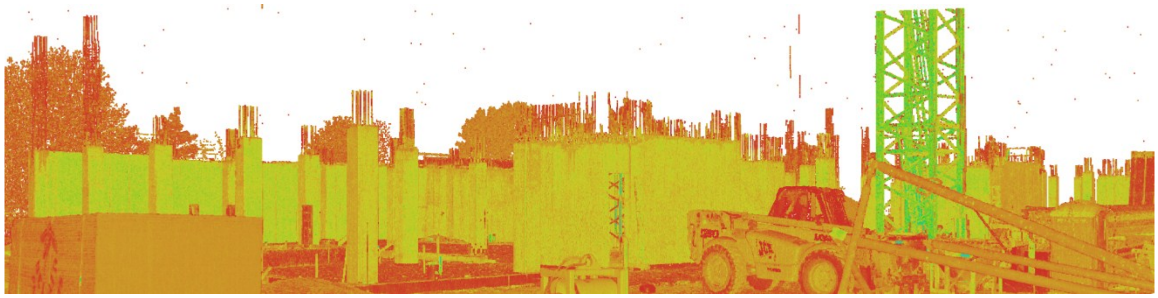


Figure 5: Scan acquired on August 29, 2008

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

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	Scan Date	Recall rate	Precision rate
1	August 12, 2008	100%	96%
2	August 19, 2008	98%	96%
3	August 21, 2008	98%	95%
4	August 26, 2008_ST1	100%	98%
5	August 26, 2008_ST2	98%	95%
6	August 29, 2008_ST1	97%	96%
7	August 29, 2008_ST2	97%	94%
Overall		98%	96%

Table 3: Progress tracking using the original construction schedule for the scans acquired between August 12th 2008 and August 29th 2008 (On-going activities only) : Recognized Progress, Scheduled Progress and Actual Progress are calculated using Equations [1], [2] and [3] respectively.

Scan Day	ID	Activity Name	Start Date	End Date	Recognized Visible Progress	Scheduled progress	Actual Visible Progress
2008-08-12	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	67%	67%	65%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	21%	32%	20%
	9	Concrete Slab – 2nd Floor	2008-08-18	2008-09-16	0%	0%	0%
2008-08-19	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	67%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	48%	57%	48%
	9	Concrete Slab – 2nd Floor	2008-08-18	2008-09-16	0%	3%	0%
2008-08-21	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	49%	67%	50%
	9	Concrete Slab – 2nd Floor	2008-08-18	2008-09-16	0%	10%	0%
2008-08-26	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	60%	71%	65%
	9	Concrete Slab – 2nd Floor	2008-08-18	2008-09-16	0%	27%	0%
2008-08-29	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	71%	86%	72%
	9	Concrete Slab – 2nd Floor	2008-08-18	2008-09-16	0%	40%	0%

Table 4: Progress tracking using the constantly updated construction schedules for the scans acquired between August 12th 2008 and August 29th 2008: Recognized Progress, Scheduled Progress and Actual Progress are calculated using Equations [1], [2] and [3] respectively.

Scan Day	ID	Activity Name	Start Date	End Date	Recognized Visible Progress	Scheduled progress	Actual Visible Progress
2008-08-12	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	67%	67%	65%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	21%	32%	20%
	9	Concrete Slab – 2nd Floor	2008-08-18	2008-09-16	0%	0%	0%
2008-08-19	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	48%	48%	48%
	9	Concrete Slab – 2nd Floor	2008-08-22	2008-09-22	0%	0%	0%
2008-08-21	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-01	50%	58%	50%
	9	Concrete Slab – 2nd Floor	2008-08-22	2008-09-22	0%	0%	0%
2008-08-26	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-02	67%	67%	65%
	9	Concrete Slab – 2nd Floor	2008-08-22	2008-09-22	0%	14%	0%
2008-08-29	7	Slab on Grade - Ground Floor	2008-07-20	2008-08-19	100%	100%	100%
	8	Walls & Columns - Ground Floor	2008-08-04	2008-09-03	71%	81%	72%
	9	Concrete Slab – 2nd Floor	2008-08-22	2008-09-26	0%	17%	0%