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Automated progress control using laser scanning technology

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ABSTRACT

Assessing progress in construction activities is time consuming and requires the use of specialized personnel. Automated progress control could reduce the workforce, the cost, and the time used, reduce disagreements, and add to the overall efficiency of project management. Attempts have been made in the past to resolve this issue using image processing and other techniques but the results have not been satisfactory. A new attempt is now made to set up a system that can assess progress control with minimum human input. An experiment makes use of laser scanning technology. The initial results appear to be promising but there are still obstacles to surmount. The system is robust and accurate in laboratory conditions and constitutes proof of concept. Improvements are necessary to accelerate the registration process of multiple scans, to recognize objects of irregular shape, and to assess the practicality and economic feasibility of such a system.

1. Introduction

Construction progress control is a critical task in project management. Traditionally, construction managers walk around in the construction site to verify progress in different activities and understand the current status of the project. Current progress control is time consuming, requiring data collection and extraction from construction drawings, schedules, and budget information [35]. The quality of progress control depends on the quality of the inspector's field reports, which may sometimes contain entry mistakes. The quality of manually collected and extracted progress data is typically low [18]. Over the years, attempts have been made to streamline this process by using advanced computer technologies. For example, Abeid and Arditi [4] developed an automated real-time monitoring system that links time-lapse digital movies of construction activities, the critical path method (CPM), and visual progress control techniques. It enables managers at the contractor's and the owner's headquarters to follow developments at the construction site in real time. Zhang et al. [34] explored the potential of using computer vision technology in assisting project managers with determining the progress of construction from digital images captured on the site. The study focused on the quantity rather than the quality of the work and was limited to the superstructure of buildings. Gordon et al. [21] presented the details of an automated planning approach to support on-site construction inspections and thereby allow inspectors to both generate complete, detailed inspection plans and to consider numerous possible alternatives in detail.

Several researchers experimented with different imaging techniques to produce essential construction management information in an effective manner. For example, Abeid et al. [7] developed a method for recognizing the presence of a structural component in a digital picture taken at a construction site through the component's color and position. Abdel-Qader et al. [2] compared diverse image processing techniques and chose a series of techniques that work best for the identification of cracks in a bridge component. By combining image processing techniques and a database of construction materials, Brilakis and Soibelman [13] used a shape retrieval mechanism to recognize a range of construction material resources. They also used 3D imaging techniques to analyze construction project processes. Quinones-Rozo et al. [25] applied image processing techniques to quantify excavation progress. Golparvar-Fard et al. [18,19] proposed automated methods for progress monitoring using photographs taken from a construction site. Tang et al. [29], surveyed techniques developed in civil engineering and computer science that can be utilized to automate the process of creating as-built BIMs. Gong and Caldas [20] developed and evaluated several vision-based construction object recognition and tracking methods for construction video analysis. Walia and Teizer [32] simulated the processing of location data for collision detection and proximity analysis and demonstrated that real-time proximity detection of resources is feasible.

Most research on automated project progress control aims to measure the physical quantities in-place by using spatial sensing technologies [30]. However, these methods are mostly based on immature technologies, are cumbersome to use, and require frequent and constant manual intervention. Methods need to be developed that are not only easy to use, but are also based on mature technologies that have proved to be of value in day-to-day construction operations, such as laser scanning.

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Laser scanning is gaining increased recognition in civil engineering applications. 3D laser scanning is a relatively new surveying technology that captures the real scenery and translates it into a 3D virtual world. It utilizes light detection and ranging to produce accurate 3D representations of objects. A laser scanner consists of an emitting diode that produces a light source at a specific frequency. A mirror directs the laser beam horizontally and vertically towards the object. The surface of the object then reflects the laser beam. Using the principles of pulse time of flight, the distance to the object can be determined by the transit time. The result of a scan produces a collection of points in space, commonly known as "point clouds," which can be processed and combined into accurate 3D models [28]. The density of the points depends on the speed at which the laser travels the surface. A laser scanner can provide a fast, good quality and precise analysis and feature detection of any object.

Recently, more and more scholars picked on the laser scanning technique to monitor their construction project. For example, Hashash et al. [22] used laser scanning for predicting, monitoring, and controlling ground movements associated with excavations in urban areas. Walters et al. [33] developed a system that determines the thickness of a pavement in real time by laser scanning the surface of the subgrade prior to paving, and then scanning the surface after paving. Shih et al. [27] made a point-cloud-based comparison between as-planned and as-built progress schedules. Arayici [8] used a scanner to digitize all the 3D information related to real world objects such as buildings, trees, and terrain down to a millimeter of detail to facilitate the refurbishment process in the built environment. Walters et al. [33] used laser scanning to define the thickness of a concrete pavement. Bosche and Haas [10], Bosche et al. [11,12], and Turkan et al. [30] obtained promising results of progress monitoring using a 3D laser scanner and a simple 3D model. Cheok et al. [14,15] assessed and documented the construction process in real-time on the basis of 3D as-built models by using laser scanning technology. Randall [26] analyzed the construction engineering requirements of laser scanning technology for applications across all phases of the project life cycle and proposed a multidisciplinary framework to integrate applications of laser scanning technology with the fundamentals of three-dimensional model-based design.

The objective of this study was to develop an automated progress recording system that does not require any periodic human input measured by a professional either at the construction site or from photographs. In this research, data was obtained by using a laser scanner. A registration process was performed to combine different scans and obtain point clouds. A 3D model of the project that was developed earlier was superimposed on the point clouds. The volume of work completed was compared with the volume of work expected, and a percentage of progress was obtained. This new progress measurement method automatically calculates the percentage of completion of a construction activity.

2. Methodology of the study

This section describes the steps adopted in this study to capture, process, model, and integrate 3D laser scanner data about a construction process. The flowchart of the steps is presented in Fig. 1.

2.1. Design of a 3D/4D model

First, a 3D model of the structure is developed and the activities of the project are defined, using a 3D modeling software, such as MicroStation, Revit, or ArchiCad. For example, as was done in this study, the volume/surface area of the objects involved in each activity can be calculated by MicroStation V8i using the object's 3D coordinates. The same approach may be used if other software programs are used in developing the 3D model. Finally, using the facilities provided by Navisworks, a work schedule is linked with the 3D model making it a 4D model.

2.2. Capture of point cloud data

3D point cloud data is captured using a laser scanner that comes typically with its own software. There are two different types of scanners that are commonly used in 3D laser scanning. *Phase-based scanners* utilize a constant beam of laser energy that is emitted from the scanner. The change of phase of the laser light is measured to allow the scanner to calculate distances. Phase-based scanners are typically used in industrial applications or interior architectural spaces to populate detailed building information models of existing facilities. The advantage of this technology is the significant speed of data capture. It can capture hundreds of thousands to millions of 3D points per second, which is approximately ten times faster than most time-of-flight scanning systems. Thus, the Leica HDS 6000 laser scanner that was used in the laboratory experiment represents an appropriate selection. The major limitation of phase-based-scanners is a short range, but this limitation does not preclude its use in progress monitoring applications like the system proposed here. *Time-of-flight scanners* emit a pulse of light which measures the amount of time it takes to travel from the scanner to the object and back allowing the scanner to calculate the distance. The key benefit of this type of laser scanning technology is its long range. But these scanners can collect fewer points per second compared to phase-based scanners. Time-of-flight technology is typically used for topographic surveys of roadways and as-built structures.

First, the positions of the scanner in the construction site are decided. For a realistic representation of the object, a scanner is positioned in several locations and the object is scanned from different lines of sight. The scans are merged using the registration process and all the points on the object (not only those facing the scanner) are captured.

2.3. Registration and integration of the 3D model with point cloud data

Registration is the process of integrating several scans into a single coordinate system. This process involves using a system of constraints, which are objects that are placed at the same location every time a scan is performed. The registration process performs optimal alignment transformations to make sure that the targets used as constraints are aligned as closely as possible. Registration can be performed by commercially available independent software or by software provided by the manufacturer of the laser scanner, such as a program called Cyclone provided alongside the Leica HDS 6000 laser scanner that was used in this study.

After registration, the coordinates of all points are stored in a file that includes four columns of information that involve a point's ID number and its x, y, z coordinates.

In order to integrate the 3D model with point clouds, the 3D model is converted into a format that is compatible with the requirement of the software that handles point clouds. The coordinate system of the 3D model is set to correspond exactly to the coordinate system of the point clouds, and then the 3D model is superimposed on the point clouds.

2.4. Object definition and progress measurement

In the scan data, there are numerous points, including many points that are not related to the object under consideration. So, if the objective is to monitor the percentage of completion of an object, the points associated with the object need to be extracted from the original data. A java script was developed to count the number of points in the related portions of the point clouds. To account for construction and laser scanner tolerances, the true coordinates of the object in the 3D model are augmented by 0.7% increasing the volume of the object by 2% following [36] observation

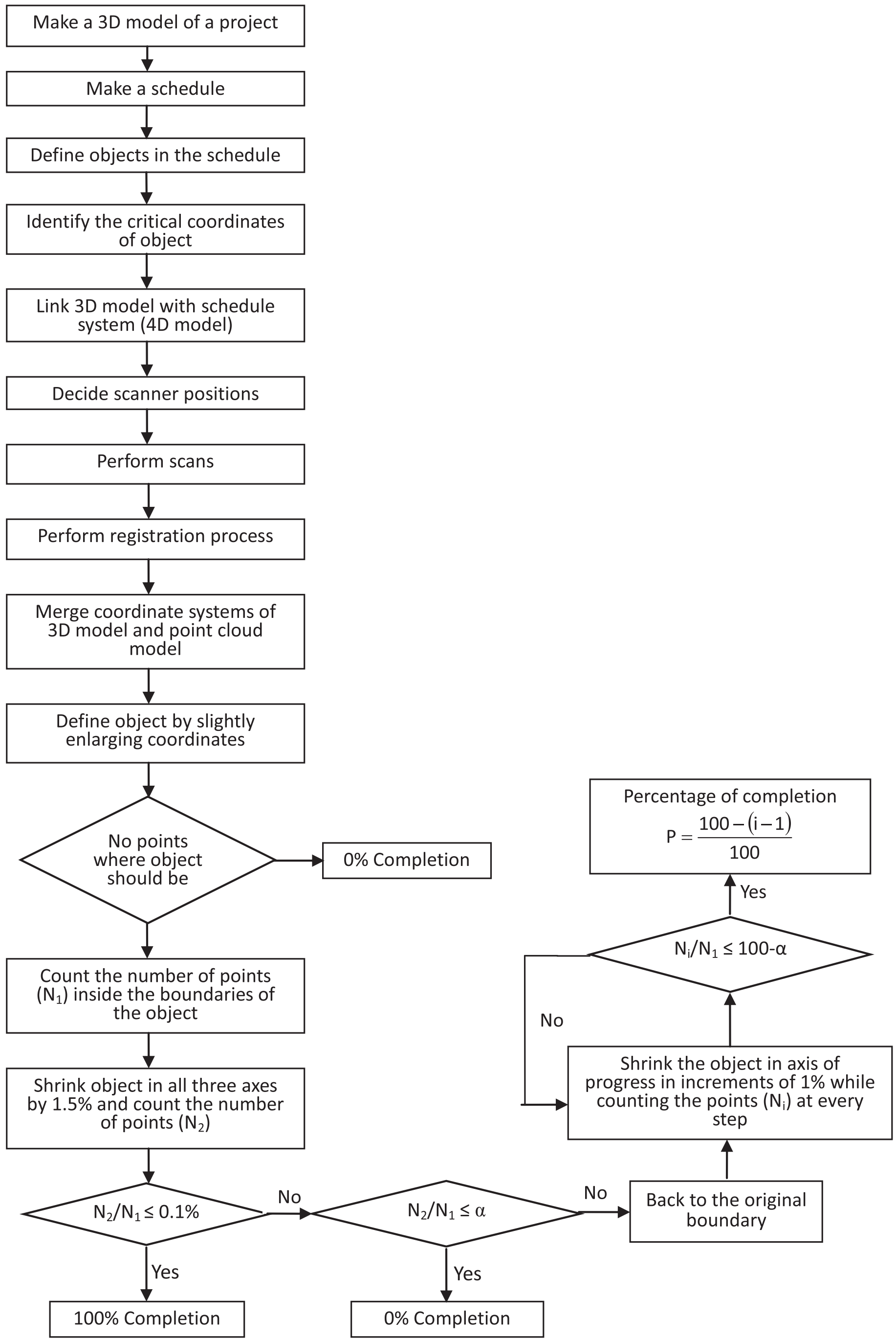


Fig. 1. Flow chart of the system.

in their laser scanner experiments. The points (N_1) in the point cloud that fall within the augmented object are counted. If no points are detected on any of the faces of the object, it is concluded that the percentage of completion is 0% (Fig. 2a). If points are detected within the boundaries of the object, a decision needs to be made about whether these points belong to the object being considered or to other objects or trash that are situated in the location where the 3D model indicates the object being considered should be. If the points represent the object considered, the points should appear on all the faces of the object. If the points represent trash or another object, whose shape is not the exact same shape as the object considered, the points do not appear on all faces of the object considered.

The method to judge if the points actually belong to a particular object involves first, shrinking the 3D model in all three directions by 1.5% along the normal of the surfaces, and then counting the number of points (N_2) inside the boundaries of all the faces of the object. The choice of shrinking the object by 1.5% in all directions is based on [36] work where they found that with a 0.015° resolution angle, the volume of the object they measured by using point clouds was larger by 2% than the actual volume. In this research, the setting of the scanner is "Super High" and the point spacing is 3.1 mm at 10 m. So the resolution angle is equal to: $\tan^{-1} =$ 3.1 mm/10,000 mm = 0.017° which is very close to 0.015°. It is assumed that the volume could have been 2% smaller too. So the object, if it exists, can be within 0.7% of the original boundaries

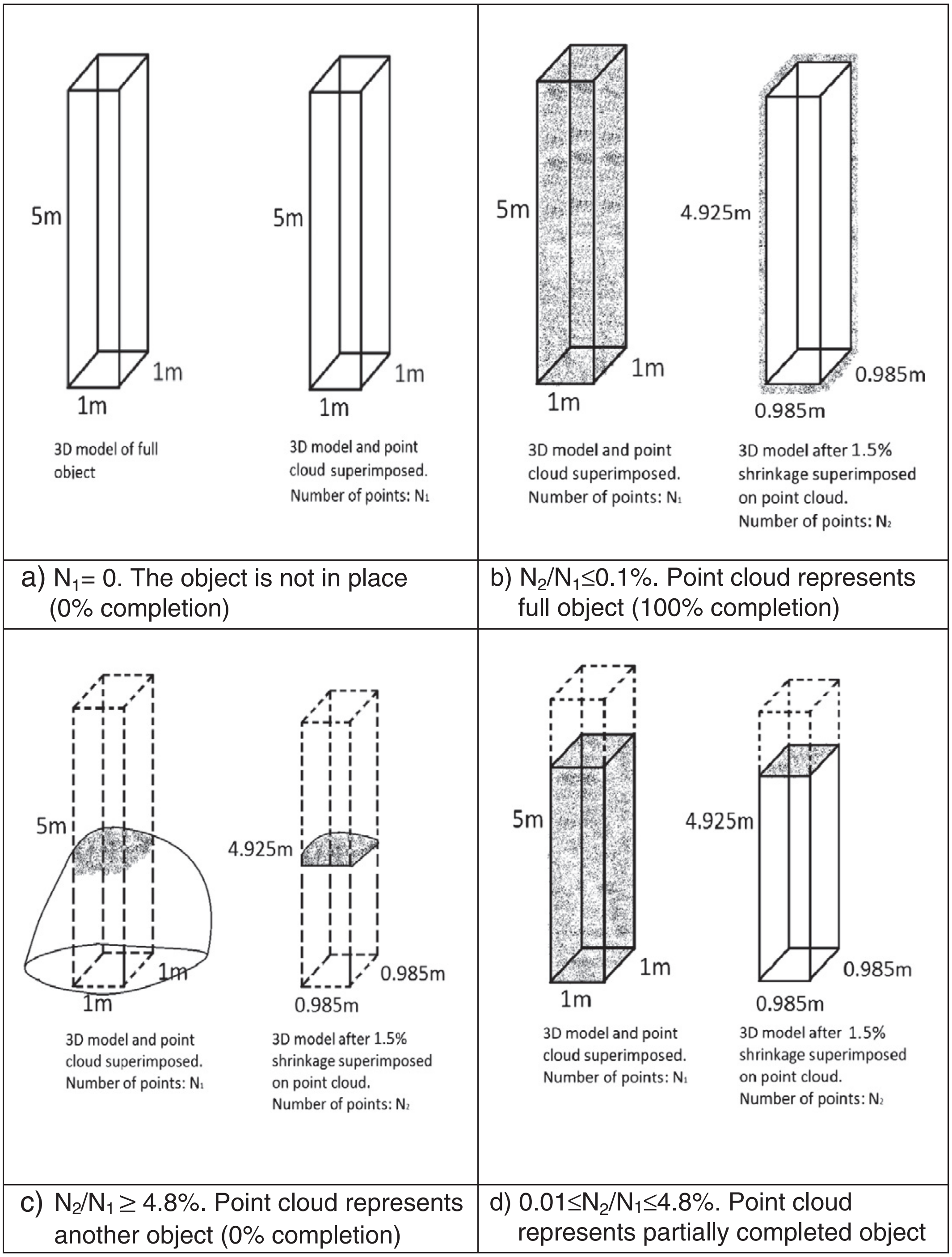


Fig. 2. Interpretation of point clouds.

making the volume of the object within ±2%. In the proposed method, the object is shrunk by 1.5% in all directions to account for a 0.7% tolerance on either side of the surface plus an additional 0.1% to compensate for the small difference between the resolution angles (0.7% + 0.7% + 0.1% = 1.5%).

After shrinking the 3D model of an object by 1.5%, if no points can be counted on any face of the object, this signifies that some parts of the object are in place since the scanner does not record points inside the object. Therefore, one can use the N_2/N_1 ratio to measure progress. If the ratio $N_2/N_1 \leq 0.1\%$, the object is considered to be completed 100% (see Fig. 2b). The N_2/N_1 ratio is set as 0.1% rather than a flat 0% in order to account for the few points that may appear on any face of the object as a result of noisy data.

If $N_2/N_1 \geq \alpha$, a threshold value, it is concluded that the points have nothing to do with the object considered, i.e., a percentage of completion of 0% (Fig. 2c). Again, the principle is based on the fact that all the points are located on the surface of an object. The threshold value is based on the shape of the object. The algorithm calculates different threshold values for different geometries. For example, as seen in Eq. 1, a 1 m × 1 m × 5 m rectangular column's footprint consists of

4.8% of its visible surface area (i.e., the four sides and the top, excluding the base).

$$\begin{aligned}\text{Percent Footprint Area} &= \frac{\text{Footprint area}}{\text{Visible area}} \\ &= \frac{\text{Footprint area}}{(\text{Visible area at the top}) + (\text{Visible area on four sides})} \\ &= \frac{(1\ \text{m} \times 1\ \text{m})}{(1\ \text{m} \times 1\ \text{m}) + [4 \times (1\ \text{m} \times 5\ \text{m})]} \\ &= 4.8\%.\end{aligned} \quad (1)$$

After shrinking the object in the direction of all three coordinates, if 4.8% or more than 4.8% of the points remain, it means that the point cloud does not represent the object in question and that only a foreign object is visible, which, by implication signifies that the rectangular column is not in place. On the other hand, if the ratio $N_2/N_1 < 4.8\%$, the object needs to be analyzed further to determine the percentage of completion (see Fig. 2d).

If $0.1\% < N_2/N_1 < 4.8\%$, the percentage of completion is determined by going back to the original boundary and shrinking the object in increments of 1% at a time while counting the points (N_i) at every step. The shrinking is done in the direction opposite to the direction of construction, either along the x-axis, the y-axis, z-axis, or along a curve. In this example, since the construction of the column proceeds upwards, the shrinking is done from top to bottom in the direction of the z-axis. At the same time, N_i/N_1 is also calculated. Shrinking iteration stops when $N_i/N_1 = 100 - \alpha$, i.e., $100 - 4.8\% = 95.2\%$ for the 1 m × 1 m × 5 m rectangular column in this example that has a footprint of 4.8% of its visible surface area. The percentage of completion is calculated by means of Eq. 2.

$$P = \frac{100-(i-1)}{100}. \quad (2)$$

3. Case study

A simple structure was designed and tested to illustrate the proposed method. Twenty 8.5″ × 11″ × 2″ (21.59 cm × 27.94 cm × 5.08 cm) reams of paper were used to build the four columns of a structure in order to monitor the construction process. Upon completion, the columns were topped by a timber slab. This simple structure was built on a conference table. The dimensions of the completed structure are shown in Fig. 3.

3.1. 3D model and work schedule

The project consisted of five activities, namely Column A, Column B, Column C, Column D, and Slab. A 3D model of this simple structure was produced by MicroStation V8i using the State plane coordinate system. The information was stored in a .dgn file. The as-planned work schedule is presented in Fig. 4, according to which, the structure was expected to be completed in a period of five days.

3.2. Capture of point cloud data

The test was conducted by using a Leica HDS 6000 laser scanner, black and white targets, two tripods, 20 reams of paper, and a wood board (see Fig. 5). The Leica HDS 6000 laser scanner is an ultra-high-speed phase-based scanner that has survey grade accuracy and full field of view. It has an integrated hard drive for data storage, and comes with its own software called Cyclone. Cyclone supports the use of targets to geo-reference scan data, as well as the ability to align overlapping areas of point clouds. It enables full visualization on a desktop, and allows users to import/export point clouds and 3D models.

As mentioned earlier, before scanning, the positions of the scanner need to be decided. In this test, two scans were performed. The scanner was positioned in the front and the back of the conference table. Daily scans were performed using exactly these two positions. Each scan was performed in high resolution (0.22 mrad divergence, and 3 mm spot size at exit, based on Gaussian definition) and lasted 3–5 min, collecting 2,593,869 points of data. The point clouds obtained every

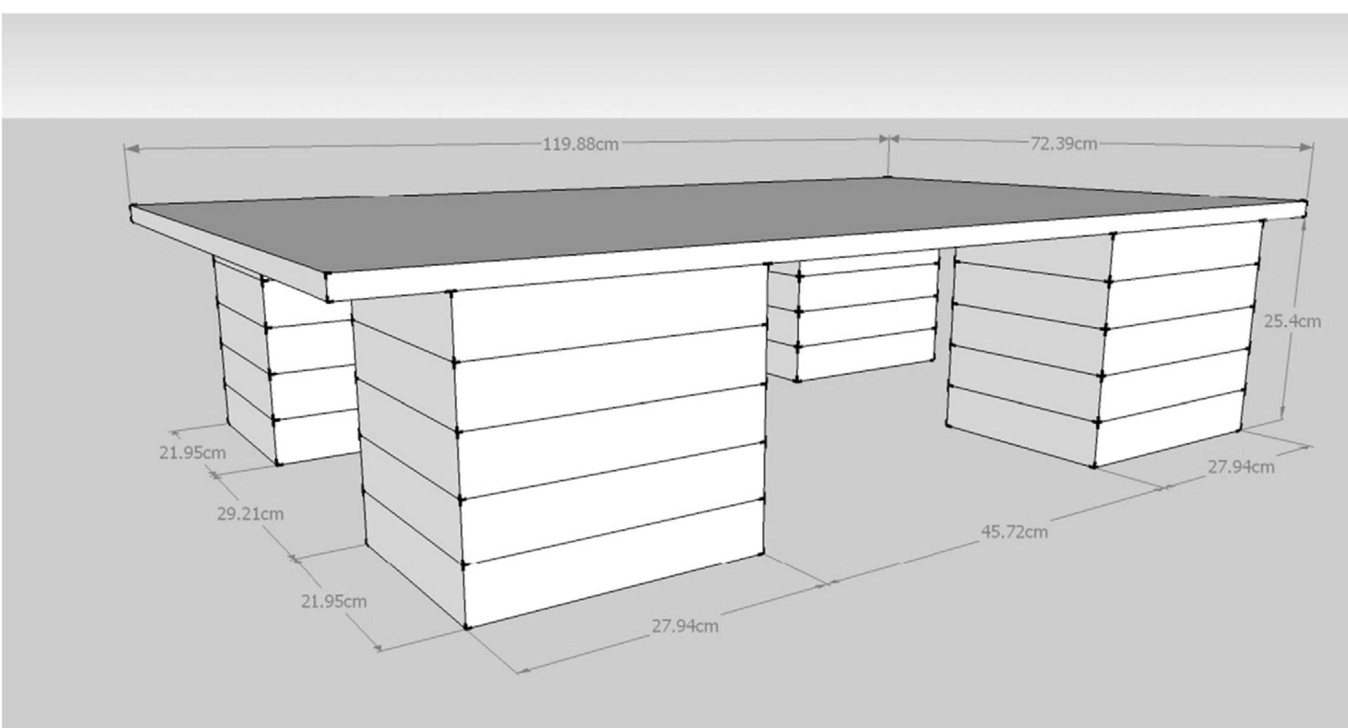


Fig. 3. Dimensions of the structure.

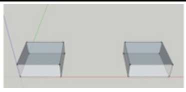
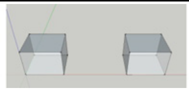
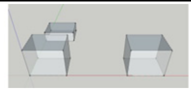
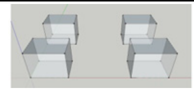
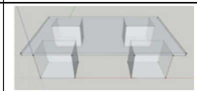
DAY 0	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
					
P_A=0% P_B=0% P_C=0% P_D=0% PSlab=0% Overall=0%	P_A=40% P_B=0% P_C=0% P_D=40% PSlab=0% Overall=16%	P_A=80% P_B=0% P_C=0% P_D=80% PSlab=0% Overall=40%	P_A=100% P_B=40% P_C=0% P_D=100% PSlab=0% Overall=60%	P_A=100% P_B=100% P_C=100% P_D=100% PSlab=0% overall=80%	P_A=100% P_B=100% P_C=100% P_D=100% PSlab=100% Overall=100%

Fig. 4. Construction schedule.

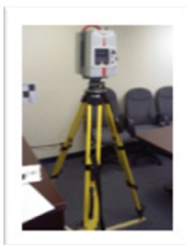
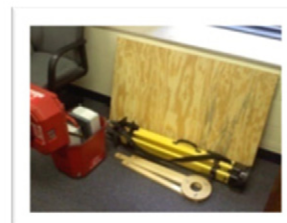
		
Leica HDS6000 Laser scanner	Black white targets and 20 reams of paper	Two tripods and a board

Fig. 5. Test equipment.

day are shown in Fig. 6, along with camera shots. The point clouds used the State plane coordinate system and were stored in a .pts file.

3.3. Registration and integration of the 3D model with the point cloud data

The position of the scanner in the first scan was set as the origin of the space coordinate system. Because the data are analyzed in the same way every day, only Day 3 is selected as an example to describe the process. The registration process of the two scans on Day 3 was performed by using Cyclone 5.8, the software program that accompanies the Leica scanner. The two scans were integrated into a single coordinate system by using the registration process described in Section 2.3. In this test, five black and white targets were used as constraints in each scan. After registration, the point cloud data were stored in a .pts file that lists the x, y, and z coordinates of each and every point. The coordinates of the critical corners of the object were acquired from the 3D model which had also been set using the State plane coordinate system, and which had been stored in a MicroStation .dgn file. Exchange of data between Cyclone and the .dgn file was performed by using the Cyclone™ Object Exchange (COE) data transfer utility that accepts not only Cyclone .pts files but also AutoCAD .dwg and .dxf files as well as MicroStation .dgn and .dxf files. When the 3D model (.dgn in this example) was integrated with point clouds (.pts in this example) by COE, the 3D

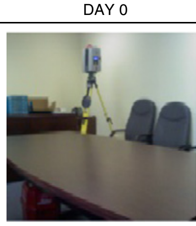
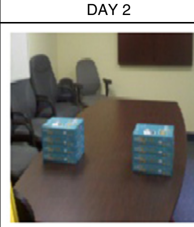
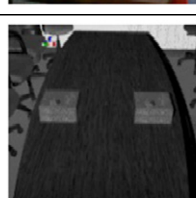
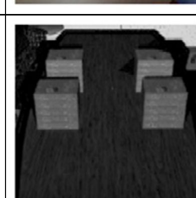
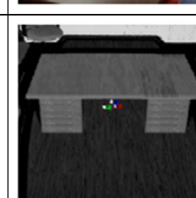
Schedule	DAY 0	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
Camera shot						
Point cloud						

Fig. 6. Scan data on one day intervals.

model and the point clouds fit each other very well since they both used the same system of coordinates. The resulting data were input into a java script which was developed to count the number of points inside the fence defined by these coordinates presented in Table 1.

3.4. Object definition and progress measurement

Four objects, Column A (Point count: N_{A1}), Column B (Point count: N_{B1}), Column C (Point count: N_{C1}) and Column D (Point count: N_{D1}) are used in Table 1 to explain this process. After shrinking the dimensions of Column A by 1.5%, very few visible points were observed ($N_{A2} = 10$), which indicates that column A is 100% complete since the ratio $N_{A2}/N_{A1} = 0.000086$ is less than 0.1%. The camera shot in Fig. 6 confirms that this result is correct.

When the dimensions of Column B were shrunk by 1.5%, a large number of points were counted inside the perimeter of all visible faces of the object ($N_{B2} = 15{,}826$) with a N_{B2}/N_{B1} ratio of 0.34. A threshold value of $\alpha = 37.5\%$ was calculated (Eq. 3), because the footprint area of Column B consisted of 37.5% of its total surface area.

$$\alpha = \frac{21.59 \times 27.94}{(21.59 \times 27.94) + (2 \times 21.59 \times 5.08) + (2 \times 27.94 \times 5.08)} = 37.5\%. \quad (3)$$

Since the N_{B2}/N_{B1} ratio is less than the threshold value of α (37.5%), Column B is only partially complete. Column B's percentage of completion is determined by shrinking column B in the Z axis, which is the natural direction of construction progress. The number of points after shrinking (N_{Bi}) is counted each time the Z dimension of the object is reduced by 1% starting from the original full length of Column B. As the iteration counter (i) is recorded, the N_{Bi}/N_{B1} ratio is also calculated. Shrinking stops when $N_{Bi}/N_{B1} = 100 - \alpha = 100 - 37.50 = 62.50\%$. Object definition and the shrinking iterations are automatically performed by a computer program that was developed by using a java script. The java program stopped after 61 iterations. The completion of Column B was calculated by using the relationship in Eq. 4. Indeed, the camera shot in Fig. 6 shows that only two of the five reams of paper are in place, indicating a rate of completion of 40%.

$$P = \frac{100-(i-1)}{100} = \frac{100-(61-1)}{100} = 40\%. \quad (4)$$

When the dimensions of Column C were reduced by 1.5%, a large number of points were counted inside the perimeter of all visible faces of Column C that has been shrunk ($N_{C2} = 20{,}263$). The N_{C2}/N_{C1} ratio of 0.64 is larger than the 37.5% threshold, which indicates that construction of Column C has not started yet (percentage of completion: 0%). Indeed, a visual inspection of the camera shots in Fig. 6 indicates that a hard hat is sitting where Column C should have been.

After shrinking the dimensions of column D by 1.5%, very few visible points were observed ($N_{D2} = 22$), which indicates that column D was 100% complete since the ratio $N_{D2}/N_{D1} = 0.000175$ is less than 0.1%. The camera shot in Fig. 6 confirms that this result is correct.

4. Implications of the study

Several research efforts have been conducted that involve linking activity-based construction schedules and 3D CAD models to describe discretely evolving construction [24]. Some of these 4D CAD prototypes culminated in commercial applications such as Innovaya that can be used alongside Revit and Tekla, and the Control Module of Vico Software. The utilization of 4D visualization allows a more intuitive understanding of the construction process than traditional 2D drawings and schedule information [9], a more efficient allocation of resources [16], avoidance of scheduling conflicts, and a better understanding of constraints and alternative construction methods [31].

Despite their obvious advantages, 4D CAD models have their limitations [23], the most important of which is that updating these systems with actual progress information is quite cumbersome (4D [1]). The only tool that shows a CPM generated bar-chart in synchrony with actual progress involves a system generated by Abeid and Arditi [4–6] and Abeid et al. [3] which displays a time-lapse movie of the construction site alongside a CPM-generated bar-chart. When chronological pictures or video are not available, progress is measured visually by inspectors and is subsequently entered into the system manually to update the work schedule. A system that automatically captures progress in different activities and forwards this information to a 4D BIM tool is expected to facilitate the site management's work, reduce the time spent on inspection, and eliminate highly subjective assessments that depend on individual inspectors. The principles described and the experimentation reported in this paper constitute an attempt in this direction and represent a proof of concept.

The system proposed in this paper is based on the use of laser scanning technology. Even though traditional progress reporting methods are popular, they have their shortcomings. Indeed the use of a construction professional to physically measure progress periodically on the construction site relative to each and every activity is time consuming, impractical, and costly; determining progress through the use of photographs taken at regular intervals is approximate and inaccurate. Goedert et al. [17] attempted to see if laser scanning is more appropriate than traditional surveying methods used for progress reporting, and

Table 1
Object definition.

Components	Coordinates of critical points	Number of points before shrinking (N_1)	Number of points after shrinking (N_2)	N_2/N_1	Interpretation
Column A	x = (−1.390,−1.161) y = (0.597,0.891) z = (−0.958,−0.681)	115767	10	0.000086	100% completed
Column B	x = (−1.888,−1.656) y = (0.565,0.865) z = (−0.958,−0.681)	46547	15826	0.34	Partially completed
Column C	x = (−1.438,−1.207) y = (1.316,1.617) z = (−0.958,−0.681)	31793	20263	0.64	0% completed
Column D	x = (−1.932,−1.698) y = (1.280,1.579) z = (−0.958,−0.681)	125884	22	0.000175	100% completed

concluded that laser scanning is cost-effective and that it saves time compared to traditional surveying methods. They also claimed that it can improve planning, design, analysis, and conceptualization of the building process. [36] observed that photogrammetric methods had serious limitations when collecting progress data on construction sites. They concluded that these limitations could be surmounted by the integrated use of laser scanning and photogrammetry, hence enhancing the speed and the accuracy of data collection from construction sites to support progress measurement and project control. It must however be stated that despite all its advantages, laser scanning does require personnel familiar with the equipment and the accompanying software; but this kind of personnel that can operate laser scanners is fairly commonly employed by surveying firms. A laser scanner-based system that measures progress automatically and with precision is expected to be easier, faster, less costly, and more practical than existing methods, but only field tests can confirm this expectation.

Even though the results presented in the preceding sections confirm that it is possible to achieve automated progress control by using laser scanning technology, a number of limitations need to be acknowledged regarding the present research. The first limitation concerns the construction environment. The test was conducted in the lab where conditions were convenient. In real construction conditions, many factors such as people, vehicles, and weather may interfere with the scans, and special care must be taken to make sure that the point cloud data are not distorted. The second limitation is that the shapes of the objects considered in the study are rectangular prisms. However, in a construction site, the shape of objects may not always be so simple (e.g., pipe, curved wall). In such situations, it is not easy to define each object's equation. The third limitation is the registration process which cannot be done automatically. The surveyor needs to work on the point cloud data manually to complete the registration process. In a real construction site, several scans (not only two scans as was the case in the study) need to be performed depending on the construction environment and this makes the registration process more involved. Finally, the cost of purchasing and deploying one or several laser scanners is not trivial. An economic analysis that compares the likely cost of such an operation compared to the traditional human inspection has not been conducted because the experimentation was performed in laboratory conditions.

5. Conclusion

A system is presented that demonstrates the feasibility of an automated process that measures construction progress by using 3D laser scanning. Three steps were taken to do this. First, a 4D model was developed by linking a 3D model with a work schedule. Second, point cloud data were captured by using 3D laser scanning technology on each day of the project. Third, the point clouds were superimposed on the 3D model and a Java program was developed to calculate progress in terms of the percentage of completion.

This system is able to calculate the percentage of completion of a simple structure composed of simple objects. The system can differentiate between the object whose progress is being measured and any and all other objects that can be on the way by shrinking the 3D model in different directions. Compared with image processing, this system effectively eliminates the negative impacts of color and lighting; also it is more accurate than image processing because point clouds establish a 3D environment to represent the construction site rather than fragmentary pictures. The most important contribution of the system is that once the point cloud data are imported to the computer, the system can proceed automatically without human interference. The results of the simple test presented here indicate that the basic principles behind the system are solid since all results are confirmed by camera shots.

In future work, the system should be tested in a real construction site. The system's performance in different weather conditions and with actual construction components that have irregular shapes needs to be tested. The economics of the operation as well as the practicality of the setup in actual site conditions need to be assessed.

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