A 3D Point-cloud-based Verification of As-built Construction Progress

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Abstract: Point clouds were overlapped to reveal differences between two working days. The same type of comparison was made between 2003.2.11 and 2003.12.11. Comparisons between the original schedule and real schedule (the catch-up schedule) were also made. The overlapping test provides one of the most comprehensive checking methods of the as-built progress in a digital format. Examples show that the overlapping comparisons help identify the addition and removal of objects scanned from 50 meters away. The geometric information is feasible for construction inspection and records. Limitations and benefits of overlapping are discussed.

1 INTRODUCTION

A thorough computer representation of an as-built 3D construction site was difficult to create. Defining the as-built description of the construction progress involved three challenges: retrieve geometric data, represent data in 3D computer format, and define the progress by newly made differences.

1.1 Representation of As-built Data in 3D Computer Format

Photogrammetry technologies use pictures taken from different angles to retrieve as-built geometries and represent the results in 3D computer formats (for example, VRML format) for Internet browsing. Compared with manual measurement and input, photogrammetry is faster. Although photogrammetry was used in the preservation of archaeological as well as architectural objects (Hanke and Ebrahim 1999; Debevec et al. 1998), the number of objects and the level of details made the modeling process inefficient.
1.2 Progress Defined by the Comparison of As-built Data

Construction site monitoring is an on-going process that records and monitors data for immediate and post-construction analysis (Al and Salman 1985; Atkin 1986; Shih 2002). 4D technologies have applied databases and 3D modeling tools to create time-based construction descriptions as a means for facilitating inspection (McKinney and Fischer 1998; Dzeng and Wang 2003; Dawood et al. 2003). Links have been established between databases and corresponding 3D objects at specific time periods. The 3D models can be reviewed visually in different orientations to reveal construction conflicts early enough to make changes to work schedule.

The monitoring of a site and its schedule-related activities require object identification and a thorough record of site occurrences. To achieve this goal, time-based 3D (4D) monitoring focuses on a pre-construction study that allows for better management of a site (Haymaker and Fischer 2001). However, pre-construction simulations cannot necessarily take into account every incident that might occur to the different parts of a building under construction.

1.3 A Range Finder’s Approach

A 3D laser range finder with commercial software can model existing facilities four times faster than photogrammetry (Besuner and Springfield 1998). The range finder, which uses laser beams to locate the position of a point on a surface, has been used in construction for a long time. Recent developments have enabled the tool to cover a large area for the continuous recording of a surface configuration. For example, rapid local area scans and 3D modeling were used for the improved planning and control of construction equipment operation (Cho et al. 2002). Project efficiency has also increased. If each point takes a theodolite about five seconds to aim, a laser scanner that projects 999*999 points in 999 seconds is 4995 times faster for the same amount of laser points. The resolution of a view can be increased by tiling scans with the highest resolution of each from left to right and from top to bottom. Once a scan is done, its corresponding computer format is stored as a point cloud model. The cloud format can then be transferred into a polygonal model.

2 RESEARCH PURPOSE

This study tries to define a method to verify as-built construction progress between two days. The method should be able to provide geometric property for dimension-related checks as well as an integrated, macro view of the as-built construction site in a 3D computer format.
3 COMPARISON OF AS-BUILT DATA

The point clouds recorded by the 3D scanner include almost all of the visible objects, such as the columns, beams, machinery, facilities, materials, and even waste products, from the location of scanner. The records are very comprehensive and useful for following proofs and construction progress studies. The method for comparison is made in three major steps:

- Retrieve and register as-built geometries;
- Define as-built construction progress by applying a Boolean operation to intersect cloud pairs;
- Represent as-built progress in 3D computer format using point clouds with the intersected regions to represent as-built data.

The comparison of as-built data was made by two methods: an analogical comparison and an overlapping comparison. Although all the data retrieved by a 3D scanner are represented in computer format, the formal comparison was made by identifying objects from the clouds before identifying its corresponding item in the schedule. This basic type of comparison was extended to an overlapping comparison of two scans made from almost the same orientation to directly reveal the differences between the two sets of as-built data.

The process did not intend to interpret 3D objects automatically from the point clouds. Instead, the process revealed overlapped parts automatically as a way to contrast the new additions with existing objects. Since the construction may only be half-way through a region or a component, it would be much more efficient if human judgement is used to identify a partially constructed subject.

The applied method revealed the difference between two subjects by overlaying their configurations. The criteria of the investigation focused on how much detail could be found from the data collected at a place about 50 meters away, with only three scans made from two different orientations. Although the scope did not cover 100 percent of the whole site, the capability of the as-built scans was shown through the presence of the differences.

The presentation of the data was made by a particular browsing format (.oct) in a web environment to enable the observation and quality control of construction schedule. Because the computations involved in retrieving and processing a large amount of scan data is enormous, the execution of this system does not allow for effective problem management unless a fast PC and a large amount of RAM are used. The characteristics of data enable non-intrusion collection and the representation of real time construction progress, which were rarely done in the past.

The exemplification of the two types of comparisons is shown by exterior works. The working flow of a building structure started with the installation of vertical columns and followed by horizontal columns, steel floors, and concrete floor. The vertical steel columns were one of the most obvious categories for recording and identification from point clouds.
3.1 Analogical Comparison

The comparison format was made between 2003.2.11 and 2003.12.11 over approximately 11 months. The installation period between the second segment and the roof was made between 2003.1.18 and 2003.4.23 when the vertical columns and small beams consisted of the main part of the structures. Scans were made each week. The underlined text in Table 1 states the original schedule, and the text in normal type states the actual progress. This table was designed to compare the differences between the catch-up schedule and the original working schedule by referring to the scan data of that day.

Table 1 Comparison between catch-up schedule and original schedule

<table>
<thead>
<tr>
<th>Photos</th>
<th>3D point clouds and catch-up schedule</th>
<th>Original schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="2003.3.17" /></td>
<td>Installation of the 3rd segment steel structure 2003.2.6~2003.6.23 Zone B completed, zone A 1/2 completed</td>
<td></td>
</tr>
<tr>
<td><img src="image2.jpg" alt="2003.3.24" /></td>
<td>Installation of the 3rd segment steel structure 2003.2.6~2003.6.23 Zone A &amp; B completed</td>
<td></td>
</tr>
<tr>
<td><img src="image4.jpg" alt="2003.4.15" /></td>
<td>Installation of the 4th segment steel structure in zone A 2003.4.25~2003.5.1; Zone B completed, zone A started 2F structure RC 2003.4.19 – 2003.5.9; 2F steel decks</td>
<td></td>
</tr>
</tbody>
</table>

196
The catch-up schedule and the original schedule are listed to the right of the table. The information between the two columns includes photos, scan dates, and the 3D point clouds of the actual progress. As shown in Table 1, the third segment of the steel columns and beams was installed on 2003.3.24, as opposed to the original working schedule of between 2003.2.6 and 2003.2.23. The actual schedule was about one month behind. The decks on 2F, which was scheduled between 2003.2.12 and 2003.2.17, was about two months behind the original schedule. Compared to the catch-up schedule of Tab. 1, the actual working progress was, in fact, completed earlier than the scheduled dates of 2003.4.19 and 2003.5.9. Since the overlapped part is retrieved by the program automatically in a different color, the only thing an inspector has to do is to separate the point clouds by regions with specific colors. Foreground scan, background scan, and overlapping parts can be assigned to different layers (on/off as needed) and colors for easier identification. The small figures listed in Table 1 and 2 are screen captures which unfortunately provide less information than the interactive views in the original 3D browsing environment.

3.2 Overlapping Comparison

A comparison of the as-built point clouds with the original design models was made to show the progress of the steel structure (Shih and Wang 2004). However, a comparison of the construction progress in as-built computer form between two schedule days was not previously made. For a more specified indication of changes and locations, point clouds were overlapped to reveal the difference between the two dates, like the intersection function from a Boolean operation (Figure 1). The two scans made on each day were overlapped beforehand in order to simplify reading and to reduce scene complexity. An analysis was conducted to the data scanned between 2003.6.30 and 2003.12.11, as is illustrated in Table 2. The steel structure assembly was followed by the installation of scaffolds, dust curtains, curtain walls, handrails, and other miscellaneous items. The amount of items added to the point clouds has complicated the overlapping result, as compared to the one made of steel columns and beams only. A comparison case is made between 2003.6.30 and 2003.7.7. The top image in Table 2 shows the overlapped result and the point cloud of 2003.7.7, with the point cloud from 2003.6.30 hidden. The light-colored cloud represents construction already done. The dark-colored cloud represents the part of the cloud that did not exist before, i.e., the part of construction that has been recently added to or demolished.

![Figure 1 The intersection between regions A and B](image-url)
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## Table 2: Comparison between catch-up schedule and original schedule

<table>
<thead>
<tr>
<th>030630 vs 030707_T4</th>
<th>dark color (black) - new</th>
<th>light color (yellow) - old</th>
</tr>
</thead>
</table>

### Remarks

- **2003.6.30**
  - New dust curtain between 7-9F
  - Overlapping illusion of beam on 8F, zone A
  - Concrete forms removed on 2F, work on 2F
  - Forms were removed on 3F

- **2003.7.7**
  - [Image of construction progress on 2003.6.30]
  - [Image of construction progress on 2003.7.7]

198
Changes in construction can be identified from the photo records as follows:

- New scaffold and dust curtains: New dust curtains had been added between 7-9F in zone B. Old dust curtains, which had been added between 4-6F before 2003.6.30, are overlapped and presented in light color;
- Concrete form removal: Concrete forms were removed from the parapet on 2003.7.7. The difference in thickness (in dark color) was shown as a way to verify the change;
- Change from rebar to form installation: Part of the forms on 3F was removed and was shown as new change.

4 PROBLEMS ENCOUNTERED

The scan technology is currently available, but the construction industry has to accept the idea of inspections with the cloud format as legitimate. The limitation also comes from the initial cost of the equipment and the computing power required along with data manipulation, such as registration or reviewing by rotation. This paper only illustrated its usefulness in solving one single construction aspect which is the reversed working process of design verification by as-built data. There are still many other tasks in construction that have to be tested in order to fit the new technology and format into the current working process.

Some fundamental issues are related to a successful comparison:

- Description of schedule: If the working schedule was not specified or missing, a detailed comparison can still be made. However, if the reference base of the original design is missing, a detailed comparison cannot be specified even when point clouds are presented. In fact, we can consider that a schedule is never detailed enough to describe construction activities completely, as stated in the introduction. The missing description, no matter how trivial or important, would need to be represented. An overlapping comparison is an explicit way of representing the undefined part of a schedule with geometric information sufficient for quality control. The on-site occurrences are provided by the clouds and are presented as long as scans are made.
- Referencing scans: Enlarging the scan boundary can be helpful. For more information in referencing the relative location of two clouds, neighbourhood houses or fixtures can facilitate a better registration. An environment scan has now been used in many construction projects to define the existing facilities around a working area. As mentioned before, the scans provide a source of information that was not included in the schedule before. The missing description and as-built environment geometries create an explicit way to represent the undefined part of a schedule as well.

Experience shows that the cloud overlapping function and photos were mutually beneficial in identifying the differences between two scans. The former was most straightforward in pointing out where the exact location was in relation to the origin.
or any useful reference point in the whole construction site. We frequently checked photos afterward to confirm new additions that were ignored at first look. Although overlapping photos taken from the exact same location and orientation may lead to similar comparison effects, the images are not sufficient to define the boundary of changes or to check the attributes feasible for a 3D inspection of geometries.

It took about two hours to conduct three scans each week. In order to have a satisfactory inspection, the comparisons should be made by scans from multiple directions, higher resolution, and the least time lag. A 3D scan is similar to a picture-taking process in many ways. Both processes involve time lag between shots when only one device is used. Scans cannot include hidden objects. Multiple scans are like multiple exposures of a photo. Although it is unlikely every inch of a construction site needs to be photographed, a certain amount of time and effort is needed to achieve that goal. Based on our experience, scans made from 50 m away can cover almost all the activities in a building enclosure and a small amount of interior activities that can be observed through the openings. Although scans made from a distant location were not feasible for the identification of small parts like nails, the removal of construction forms or the addition of fire coating can be identified.

5 \textbf{BENEFITS FROM OVERLAPPING POINT CLOUDS}

The challenge from previous studies was to find a way to collect fragmented dimensions in order to create an integrated form of as-built data that is suitable for comparison. With the application of a 3D scanner, as-built building forms are retrieved as a whole. The dimension is no longer just an individual measurement of a single component in a bottom-up process. Instead, it is conducted across components as a top-down process with the whole configuration of a building recorded before a check for individual components is made.

Overlapping point clouds provide advantages for the verification, quantification, and creation of construction data as follows.

- Verification of rapid change: When two clouds overlap, new items of addition or removal can be identified between the two scans immediately and explicitly.
- Quantification of construction-related items: Cloud overlapping leads to the identification of displacement. The amount of changes in terms of sideways shifts or distorted angles due to construction load or unexpected impact can be measured to check if the value falls within safety tolerance.
- Design verification: Point clouds were imported into AutoCAD or MicroStation and overlapped with the construction drawings. The overlapping of different data formats that represents two different stages in construction help point out differences rapidly. Registration against construction drawing can be seen from the examples of interior scans of pipes and overlaying with drawings in a plan view (Figure 2). Design changes occurred as the installations of pipes were shifted sideways. Uncorrected changes may cause
future problems in finding actual location of subjects. The amount of offset represented in 3D is more helpful than the plan view of final drawings.

![Figure 2 The overlapping of interior scans and pipe drawing](image)

- **Link between real world and virtual world:** One of the advantages in creating 3D as-built models is the presentation of that data integrated with locations to match 3D spatial representation in the real world. The computer represents a replica of the real world reaching a level of as-built form.

- **Availability of central as-built database:** An integrated as-built central database is now provided in order to work reversely by retrieving dimensions from it before checking design specifications.

3D as-built scans, by no means, are different from photo records by nature. Comparing virtual construction progress with as-built progress was made in previous research in terms of 3D models (Shih and Wang 2004). This paper emphasizes the differences between two stages in an “as-built” form specifically. Instead of taking pictures of the construction site, the scans are used as the real 3D representation of the site. The scans provide more 3D characteristics than photos. The overlay analysis was executed as part of the program function. The analysis automatically shows the two scans and overlapped parts. Just like the fundamental difference between 2D drawings and 3D models, the 3D scans represent the 3D as-built geometry in particular.

### 6 CONCLUSION

Point clouds were overlapped to reveal the differences in construction progress. Although certain restrictions applied, the overlapping test provides one of the most comprehensive methods in checking the differences of as-built progress through digital format by far. While a schedule is never detailed enough to describe construction activities completely, an overlapping comparison is an explicit way of representing the undefined part of a schedule with geometric information sufficient enough for construction inspection and record keeping.
REFERENCES


