3D Scan Information Management System for Construction Management

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Abstract: This paper presents an internet-based three-dimensional (3D) scan information management system (3DSIMS) that can be used as an interface to input, display, and inspect design as-built construction information. This system is mainly developed using 3D scan data. The function of the 3DSIMS is to integrate the scan data collected before, during, and after a scan scheme that is designed to capture as-built 3D records. The information included in this system consists of a scan scheme, scanned point clouds, construction records, and postscan processed clouds for the display, search, and comparison of scans made each week during the construction of a campus building. This study represents a long-term effort that has rarely been done before. A web page is used to deliver and share scan information. The feasibility of this approach is explained by the examples of dimension-related checks through as-built data.

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CE Database subject headings: Scheduling; Construction management; Information management.

Introduction

Construction site monitoring is an on-going process that records and inspects data for immediate or postconstruction analysis (Al and Salman 1985; Atkin 1986; Shih 2002). The monitoring of a site and corresponding activities defined by a schedule requires object identification and a thorough record of site occurrences. To achieve this goal, the activities and related objects have been represented in virtual reality (VR) or three-dimensional (3D) modeling to simulate tasks with better visualization (Vaha et al. 1997; Retik and Shapira 1999; Retik et al. 2002). Four-dimensional (4D) monitoring, which refers to a time-based simulation of schedule, focuses on a preconstruction study allowing for the better management of a site afterward (Haymaker and Fischer 2001). But, the preconstruction simulation does not necessarily take into account every incident that might occur involving the as-built parts of a building under construction. Although VR in construction has shown its feasibility in communication (Woksepp and Tullberg 2001), the comparison between original design and as-built models was seldom made mainly because there was no appropriate as-built form available.

4D technology simulates a construction process based on design data. The design data has to be compared with as-built data for quality control. A simulation system must be made by 3D data in order to check dimensions and configurations. However, a system that is made of an original design specification can only be used to predict the construction process. The as-built data does not exist during the design stage. Only as-built information verifies original design from real construction status. A system for as-built information management is as important as a simulation system, especially when 3D data should be made as the corresponding format of representation for construction components. The two systems should act as two-way data verification processes.

An efficient process of collection and representation of as-built information is needed. There was hardly a way to record an as-built construction status with geometric attributes presented as a whole. As-built information used to be retrieved by discrete measurements and image records. The collection of dimensions, which features fragmental representation of geometries, was a bottom-up process that was not feasible enough to describe an as-built configuration in terms of a computer format. To create 3D as-built models based on the discrete measurements requires too much effort. If the as-built models can be created initially, fragmental representation can be prevented and individual measurement can be retrieved in a top-down manner. Then, the as-built configuration can be viewed as a whole, and the dimensions can be inspected individually or be related cross parts.

Photogrammetry technologies were used to retrieve as-built geometries and to represent results as 3D computer models by pictures taken from different angles. As compared to manual measurement and input of data, photogrammetry is faster. Although photogrammetry was used in the preservation of archeology and architecture objects (Debevec et al. 1998; Hanke and Ebrahim 1999; Boehler et al. 2003), the number of objects and the level of details could make the modeling process inefficient.

Construction assessment using a laser range finder is also known as a nonintrusive scanning technology for data retrieval (Shih 2002; Tseng et al. 2002). Maximum scan distance varies from 100 m to 800 m (Gordon et al. 2001). Cases have demonstrated that a laser scanner is a useful tool in either accessing data at a construction site or measuring data for the interior bill of materials (Bailey 1999; Cheok and Stone 1999; Cheok et al. 2000). A scanner seems to be feasible for use with a ground

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profile at a large construction site with an accuracy of less than one centimeter, or for use at interior renovation sites to measure accurately enough for cost estimation. Being able to conduct scans of a large area and to inspect the dimensions of a small region at the same time would be an extension of a long-range laser scanner's functionality, and a combination of functions that takes advantage of both types of measurement accuracy.

Comparing to photogrammetry, combining laser ranging with commercial software can model existing facilities four times faster (Besuner and Springfield 1998). A range finder, that uses laser beams to locate the coordinates of a point on surface, has been applied in construction for a long time. Recent development of technology has enabled the tool to cover a large area for the continuous record of object configuration. For example, rapid local area sensing and 3D modeling was applied for better planning and control of construction equipment operation (Cho et al. 2002). The measuring efficiency is also increased. If each point takes about 5 s to aim to through a total station, a laser scanner that projects 999×999 points in 999 s would be 4,995 times faster for the same amount of laser points. The resolution of a scanworld can be increased by tiling scans with the highest resolution from left to right and from top to bottom. Once a scan is done, its corresponding computer format is stored as the model of point cloud. The cloud format can be transferred into polygonal model. The scanned point clouds, which are full-scaled 3D data initially, make the visualization of 3D as-built more straightforward, and the inspection of an object's dimension a nonintrusion manner.

In order to present the 3D scan information management system (3DSIMS) for construction, this paper is organized in the following order: Introduction, Research purpose, Scan data retrieval, System features (including subsections of Subsystems, 3DSIMS modules, The representation of 3D models, and Examples for geometric information retrievals), Involved parties (including a subsection of User responses), As-built data versus 4D models, Contributions, and Conclusion.

Research Purpose

The goal of this paper is to develop a 3DSIMS to share 3D as-built chronological construction records of point clouds for comparison and to visualize progress. The as-built information is primarily from the 3D scanner. The method of representation, the characteristics of data, and the effort are the objectives presented in this paper. The 3DSIMS has the following features:

1. To co-relate individual scans: Data retrieval using scans or created after scans are made can be used through the system from the remote end;
2. To manage a construction database: All scan-related information, such as uploaded files or forms, could be managed using the system database; and
3. To collect and display scan data.

Scan Data Retrieval

Instead of using a traditional discrete and point-based data survey, this study applied a long-range 3D laser scanner, *CYRAX* 2500 and *CYCLONE* software, as a survey device for continuous data retrieval. This system can generate a 999×999 matrix of laser dots about 4 mm in diameter. The distribution of dots is considered a continuous sampling of x, y, and z coordinates of a particular component (see Fig. 1).

Fig. 1. Cyrax 2500 3D laser scan system and the scan of the campus construction site

These items were checked or compared based on

1. Chronological records: Comparisons were made to the temporary structure about every two months based on weekly scans (see Figs. 2 and 3);
2. Construction stages: Checks were made for displacement between different levels of excavation; and
3. Specific construction situations: Checks were made to determine the difference before and after the removal of temporary structures or the effects of a sudden impact on a working platform caused by the movement of heavy machinery.

The collection of 3D coordinates enables the measurements of components in terms of location, distance, linearity, and flatness. Measurements made to point clouds were used to check if any unexpected displacement or deformation occurred to construction members for vertical, longitude, or horizontal movement. For example, an attempt was made to the joint of a temporary structural support for retaining walls during basement excavation. The joints, made by steel members, were scanned to reveal that displacement did occur. The displacement may come from coaxial stress passed from the retaining walls, impact of construction machinery, or simply a layout that did not initially follow the drawings. We also found a case in which the top surface of the steel beams at the same level changed at a place that was lower than the others during different stages of excavation. More examples are introduced in the subsection entitled, "Examples for Geometric Information Retrievals."

System Features

A scan scheme is the operation plan for scans that are to be made at a site. Associated information includes the records made before, during, and after scan operations, such as the data retrieved during scans and manipulated post-scan. The system collects as much data as needed in order to fulfill the needs of analysis, indexing, and search.

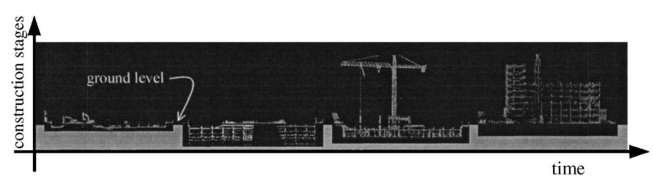

Fig. 2. Chronological records of the construction of the campus building

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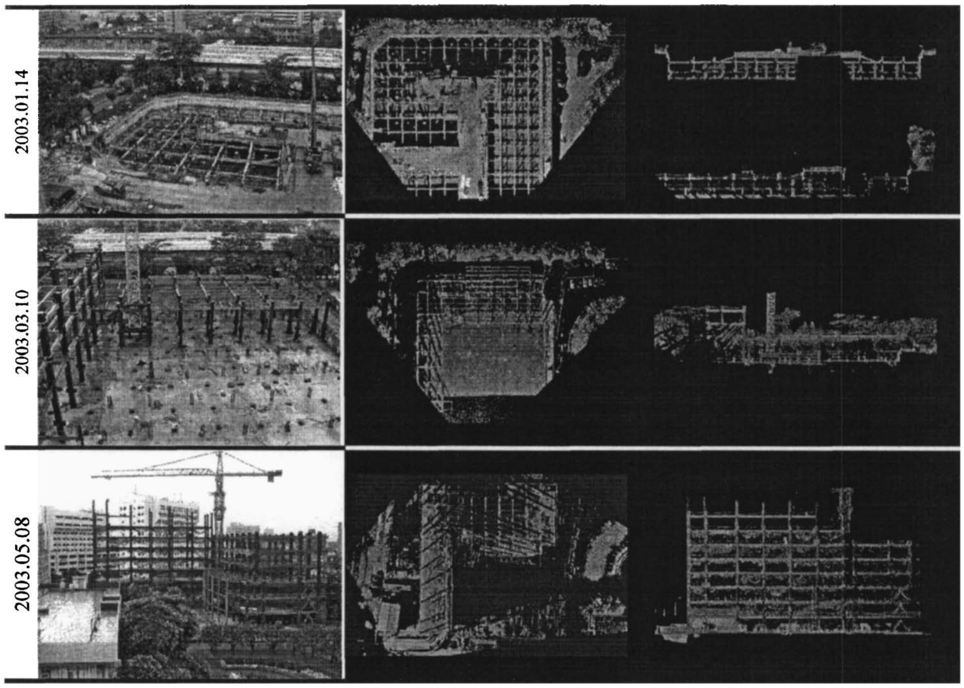

Fig. 3. Examples of images and scan data

The main features of the 3DSIMS are to provide a mechanism or an environment for

1. Uploading scan records, construction records, and scan files;
2. Uploading data created from postscan manipulation;
3. Browsing, inspecting, and querying of models, photographs, images, voices, and text; and
4. On-line comparison of the differences between as-built construction models and working drawings, or between as-built construction models that were scanned in different time periods.

Subsystems

The 3DSIMS is an Internet-based system that collects the information occurring before, during, and after the scheme is conducted. The collected information is used to inspect, compare, and inquire using a system provided interface. In order to fulfill these needs, the main framework is made by the subsystems and functions, such as the database management system, active server page, web page editing system, and file transfer function (see Fig. 4).

1. Database management system: Stores and manages scan-related data;
2. Active server page: Dynamically communicates between the web page server and database;
3. Web page editing system: Can be used on the web page server end and user end in browser mode, including HTML created by JavaScript, VBScript, ActiveX; and
4. File transfer functions: Transfer files between a drafting system and a scan system using a format, such as DXF, DWG, PTX, and PTS.

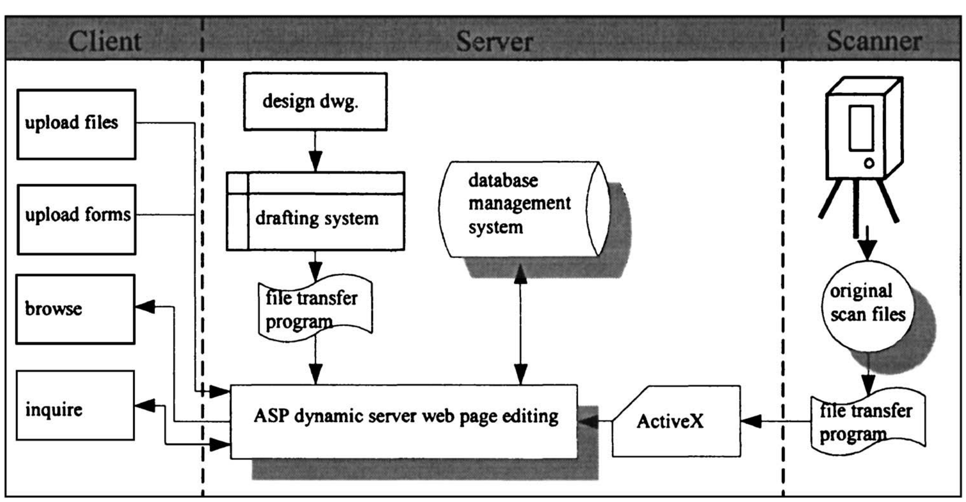

Fig. 4. System framework of 3DSIMS

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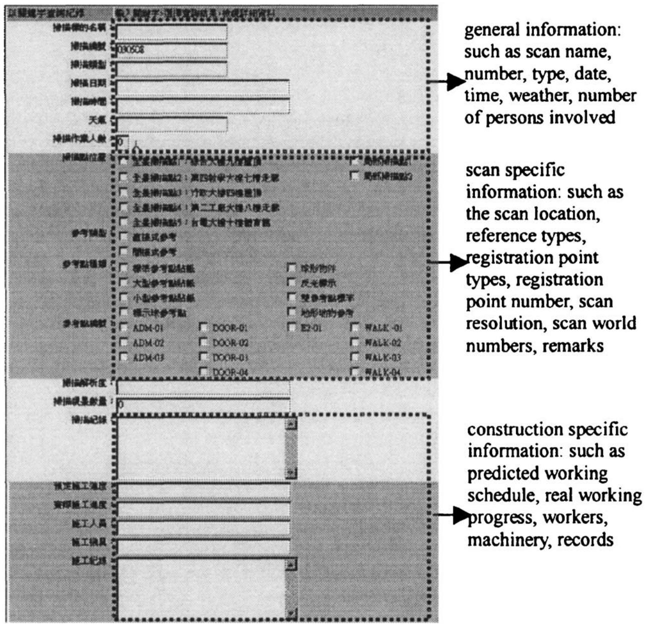

Fig. 5. Scan and construction record

3DSIMS modules

The 3DSIMS consists of four modules to handle scan and construction records, scan information, scan information inquiries, and comparisons for uploading, inputting, and record inquiries. The designed system, which was a first attempt, was a project-specific tool that can be extended to other projects. For example, check boxes, which were specifically used in this project for a reference point, have to be named on a project base. The naming manner for scans and scanworlds also has to be consistent in a new project.

1. Scan and construction records: This part of the system allows a user to create, edit, and delete records by uploading information. The records (see Fig. 5) consist of
   - General information: Such as scan name, number, type, date, time, weather, number of people involved;
   - Scan specific information: Such as scan location, reference types, registration point types, registration point numbers, scan resolution, scan world numbers, remarks; and
   - Construction specific information: Such as predicted working schedule, real working progress, workers, machinery, and records.
2. Scan information: This part of the system allows a user to input scan numbers, registration types, and data process

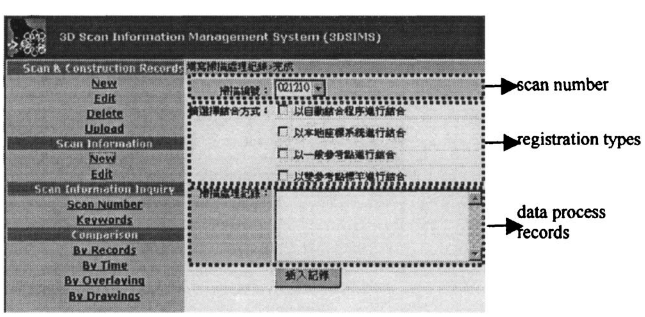

Fig. 6. Scan information

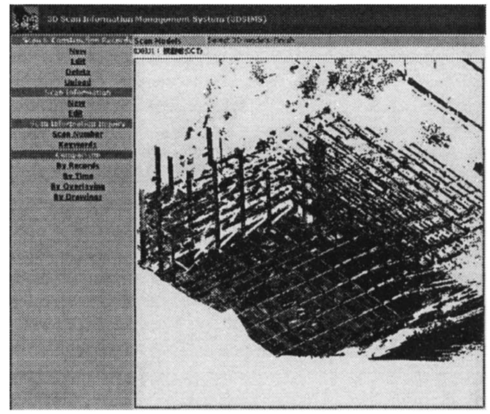

Fig. 7. Scan inquiry by number (2003.3.31)

records (see Fig. 6). The registration types include
   - Auto-registration: The least-effort registration process that is provided by Cyclone without registration points being scanned along with the subjects;
   - Local coordinate system: Specific points, whose x, y, and z coordinates are measured by theodolite, are included additionally for the purpose of high precision registration;
   - Registration points: Free-standing registration points provided by Cyrax 2500 for a normal registration situation; and
   - Double registration points: Two registration points are installed vertically on the same rod as a plumb indicator.
3. Scan information inquiry: Inquiries includes search and display. Inquiries involving scan information are made by scan number and keywords (see Fig. 7). The scan number represents the date when a scan was made. For example, "020523" would mean a scan that was made on May 23, 2002. If a "05" is keyed in, a list of scan records with "05" as part of identifying number will be searched and displayed.
4. Comparison: Comparisons of scan information is conducted using records, time, overlaying, and drawings.
   - Records: With this request, a single scan and construction record will be shown.
   - Time: A user can request 3D point clouds scanned at two different time periods in order to examine the differences between them (see Fig. 8). The OCT format is specifically prepared for browsing a large size file such as that produced by Octree software (Octree Corp. 2003, Bedford, N.H.). The clouds in such a format can be rotated, translated, and scaled as browsed.
   - Overlaying: The overlaying of clouds is a direct way to show the differences between two clouds. Fig. 9 shows an example of overlaid clouds that are each assigned different colors for better visual differentiation. Overlaying cannot be made automatically. Clouds have to be registered before being transferred into OCT format. Experience also shows that overlaying a focused region is better for identifying parts than overlaying the entire construction site.
   - Drawings: This part of the system is an extension of the cloud comparisons and provides structural drawings as references to as-built construction situations. Fig. 10 shows a cloud placed above, and a corresponding foundation drawing placed below. All related drawings, which are mainly in AutoCAD DWG format, are listed to the right.

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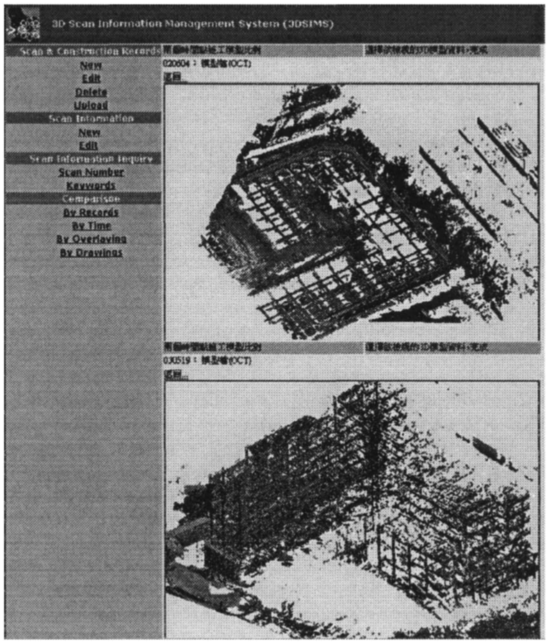

Fig. 8. Scans compared by time (2002.6.4 versus 2003.5.19)

Representation of 3D models

The 3DSIMS is an Internet-based system and part of its function is used to display 3D point clouds. The ability to browse 3D objects is usually subject to the bandwidth of the Internet, because scan data usually contains millions of dots with x, y, and z coordinates. Browsing the point cloud models is calculation consuming and the ordinary Internet display algorithm or supported format is not fast enough to enable a smooth display, especially when bandwidth is limited. Therefore, the cloud models have to be translated into an appropriate format before being inspected and managed.

This study used software called Octree Author to translate the format of scanned point clouds into a browser-efficient format. Octree technology differentiates a scene into indexed parts and only displays the parts of an object within a viewpoint, in order to accelerate display speed. At the users end, the browse plugin can be installed automatically. Octree Author takes the exported PTS and PTX file format from the Cyclone application and translates it into OCT format, which is embedded within HTML documents through ActiveX. PTS and PTX are text files of the x, y, and z coordinates and the intensity of each point, except that PTX provides four additional variables for storing the point retrieval process and scan sequence. PTX files can isolate each scan as an individual object to be edited separately. This character enables two point clouds in different colors to be overlaid under the same coordinate system. Colors help a user to distinguish one point cloud from another in an Internet browser.

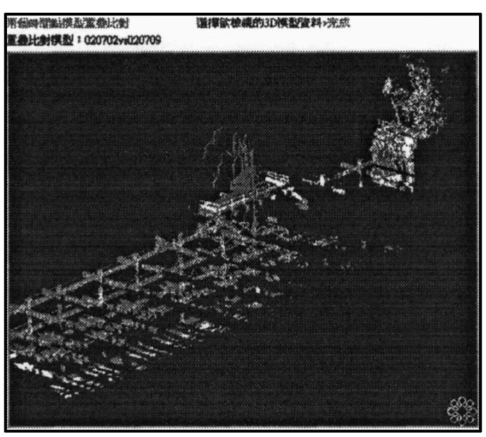

Fig. 9. Scans overlaid (2002.72 versus 2002.7.9)

Examples of Geometric Information Retrieval

Because the point clouds recorded 3D shapes with laser beams, the data stood for a formal representation of as-built shapes during construction progress. The 3D point clouds was an as-built building configuration in a full-scaled model that enabled the observation and measurement of geometric characteristics, for example, the observation of gradual configuration change over a period of time (see Figs. 2 and 3) and the measurements cross different parts. Additional measurement-related activities include dimensioning, defining relative locations, and displaying geometric attributes. A user can see the shapes and, in the mean time, conduct measurements.

Point-cloud-based measurements were made of the steel structure and building enclosure. Observation and measurements were also made of temporary facilities during the construction process, such as the retaining walls and structural support, scaffolds and dust curtains, temporary buildings, fences, working platform, tower crane, machinery, and safety installations. Some of the works are stated in the following sections.

Geometry-related attributes of the scanned data are categorized based on their appearances in one, two, and three dimensions, such as length, width, height, or their smoothness for finish works or bill of materials. Related works derived from the scanned data include checks for spacing, size, number, and the relationship with adjacent components. Fig. 11 shows a vehicle ramp with its slope that meets the requirement of building regulation. Dimension-related checks are usually measured associated with the standard deviation for stress-related (pressure, force, and fire) deflection or unexpected change of construction quality. The working platforms (see Fig. 12), which started from the southeast entrance and extended into the center of the site, was used as a place for machinery during basement excavation and for a short-term storage place for steel columns and beams. With the functions embedded within the 3D scanner program, a "patch" function was applied to the platform to check if the working plane was flat. The image to the right of Fig. 12 shows the boundary of the co-plane points of the platform along with a standard deviation of 0.024 m in this area. The patch shows the flatness of the platform and the sag due to the repetitive weight impact of machinery.

Building construction regulations require sites with protection fences, retaining walls, and scaffolds installed to prevent casualties, soil sag, and neighborhood building collapse. Item 150 and 152, Chapter "Design and Construction" in Building Technology Regulations, also require fences or equal-functioned protection facilities with a minimum height of 1.8 m installed around the site during new construction, renovation, modification, and demolition. Site scans showed that the fences around the campus site was about 2 m high. Fig. 13 shows that a height of 1.973 meter was measured at different locations. The image to the right of the Fig. 13 shows that the fences were installed inside the original campus fences. When the building was almost done, the construction fences were removed and were replaced by moveable fences that were 1.821 m high.

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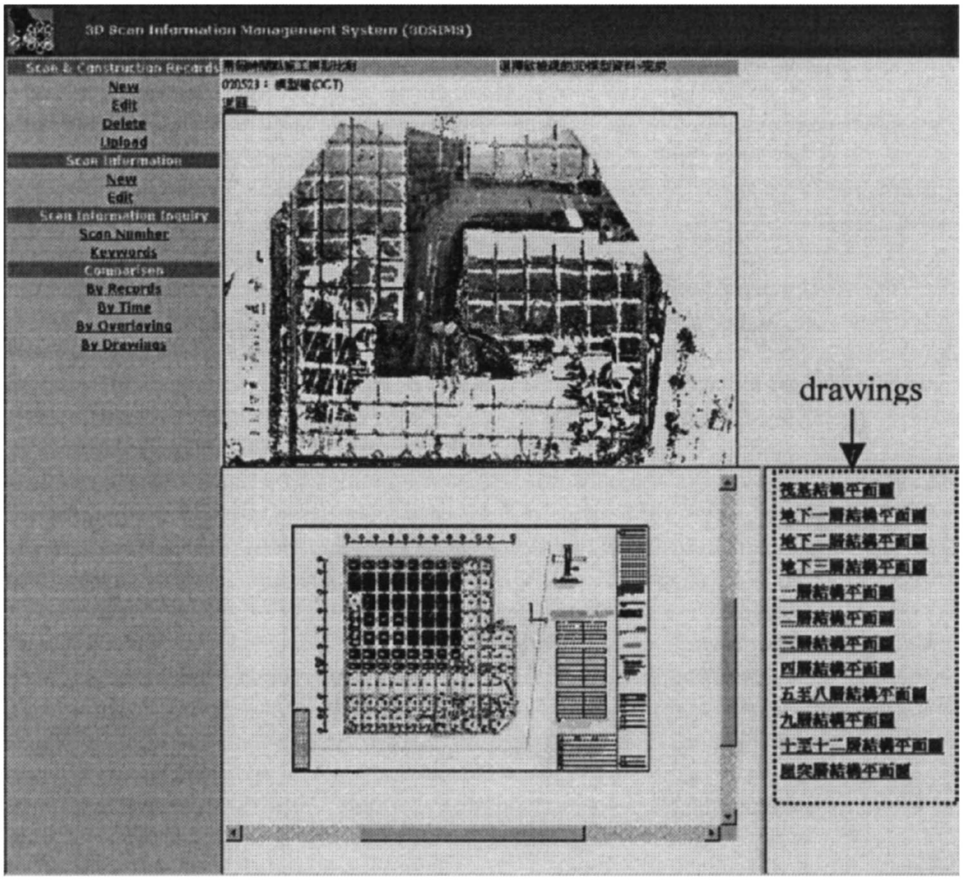

Fig. 10. Scan (2002.5.23) and drawing are simultaneously referred

Measurements were frequently made in confirming design specification for the places that cross different parts or locations difficult to reach. On 2003.12.13, the southeast part of the façade was almost done, cloud-based measurements were made to compare with design specifications. Fig. 14 shows that the clearance between two building zones varies from 1.635 m on the fourth floor to 1.792 m on the eighth floor. A difference of 0.157 m exists. Measurements of spacing for overhang parts were also made.

Questions were asked by the client (the university staff for charging construction jobs) and the design firm (the provider of original design data) to the construction company (site supervisors) regarding schedule progress. Three questions mostly addressed the delay of the original schedule, due to the shortage of steel supply during that period of time. The construction company presented a revised schedule to the university to reduce delay.

Involved Parties

3DSIMS can be used either as an individual information management system or as a link to a current construction management system as a subsystem, depending on how it is to be used. This system is designed to be used by four parties, for example, a scan team, a design firm, a construction company, and a normal user such as a client (see Fig. 15). The scan team might work for the design firm, the construction company, or any client who is involved in the construction project. The scan scheme is executed by a scan team at the work site and an internal programming team that determines the details of the scanning process.

The server end of 3DSIMS is located with the internal programming team, for easy and direct maintenance of the system. The framework of the 3DSIMS application by different parties is shown in Fig. 15. The contents created by different parties are specified as follows:

1. Design firm: The design firm has to prepare drawings for comparison with 3DSIMS in order to have some reference for analyzing the as-built scans. Currently, the system includes drawings of structural plans from basements to all floors and the roof. These two-dimensional drawings are made with drafting software, such as AutoCAD.
2. Construction company: A construction company can upload the working schedule, construction progress, and daily records to the 3DSIMS for inspection.
3. Internal programming team: This team is responsible for
   - System interface: This involves creating forms based on the items and specifications that are defined in the scan scheme, such as scan locations, registration types, and registration numbers to be used by related parties online.

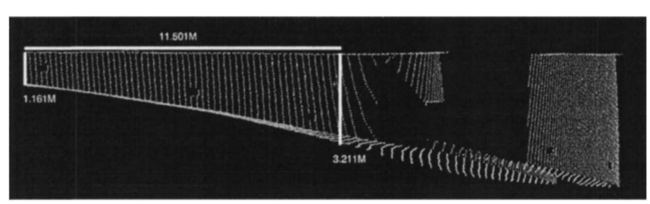

Fig. 11. Vehicle ramp and related dimensions

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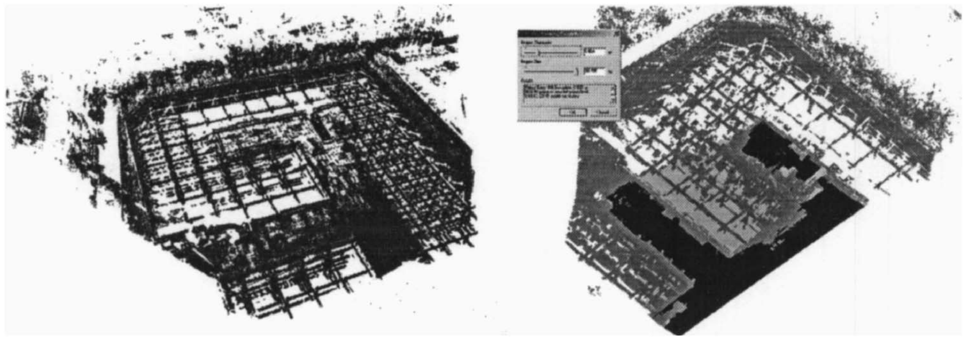

Fig. 12. Construction working platform (left) and the boundary of the co-planed points on the platform (right)

- Scan data: This involves illustrating overlaid point clouds as 3D models for comparison.

4. Scan team: This term usually works at the construction site to upload scan records by filling out the forms on the web pages. Uploaded files can include videos, images, or voices.

User Responses

Hands-on operations involve the client, construction company, and scan team. The responses of these three parties, given interviews, were as follows.

1. Client: Since this was a campus building, the staff in the construction and building maintenance section of the Office of General Affairs represented the client. Their responses were
   - Construction inspection: An ordinary video display would be sufficient for their comprehension of the construction progress. A network camcorder could display the site in a real-time manner more than the 3D scanner. Rotating point clouds through the Octree interface online appeared inconvenient to them. It seemed they preferred a more conservative approach using consumer electronics that they could control versus a 3D laser scanner that had to be operated with an additional task force outside their section.
   - Measurement function: The measurement function, which is provided by the browser to facilitate the inspection of bill of materials, was helpful.
   - Comparison: Areas where differences occurred between two clouds were more easily identified with overlaid clouds than with the clouds being placed side by side. Colors and text annotation would be helpful. We later separated the same area of cloud from the two clouds, assigned it with different colors, and then registered it. As a result, the registered clouds were divided into three colors: The shared part, the part existing only in Cloud A, and the part existing only in Cloud B. This allows for a better comprehension.
2. Construction company and supervisors from the design firm:
   - Cloud inspection: A department head or a project supervisor found it useful to control the construction schedule online.
   - Measurement function: The company could use this function to measure dimensions or inspect working tolerance. A special demand occurred when there was need to measure the span of a tower crane's arm in order to calculate its bearable load more precisely. Supervisors from the design firm could also benefit from the dimensions retrieved from the remote site for supervising design changes.
   - On-line comparison: This function was beneficial to construction management and for the discovery of construction errors. This was used mainly for dimension verification. A case showed that an offset of steel beams was found. It revealed a change occurred inconsistent with the drawings of temporary support during basement excavation. For the management's part, the point clouds contributed to the identification of built parts of the structure between two weeks. The activities that occurred in the open space in front of the building were also scanned as records to show the allocations of machinery, workers, and materials.
   - Construction records: For now, the 3D digital construction records of point clouds can be applied by the construction company and design firm for internal use. The idea of using 3D records as formal construction documents still needs to be regulated by the government to ensure its legitimacy.
3. Scan team:
   - Scan record input interface: Scan location and reference

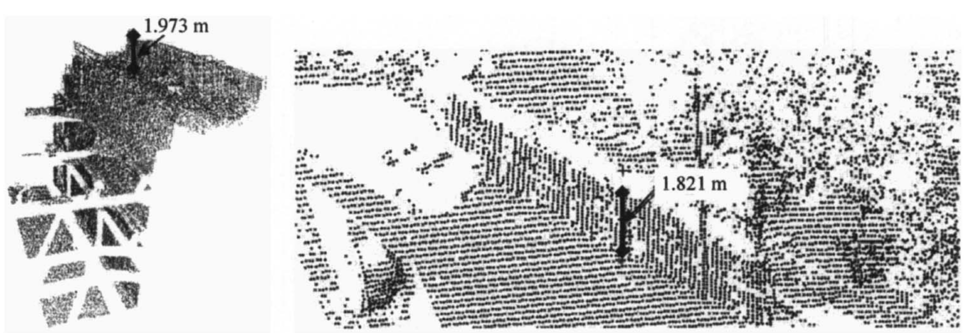

Fig. 13. Fences (left) and movable fences (right)

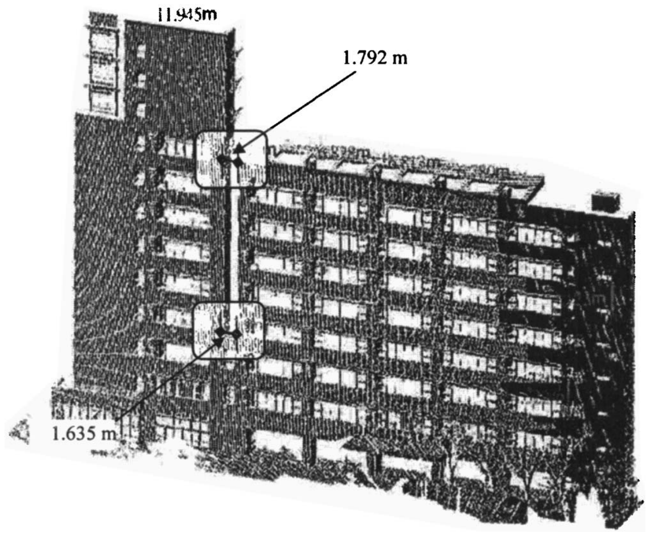

Fig. 14. Southeast part of façade and related dimensions

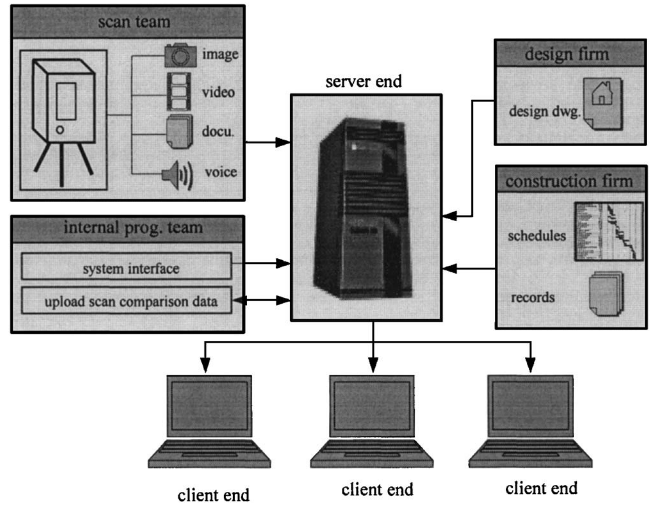

Fig. 15. System framework of 3DSIMS

points should be added online. In a scan operation, locations and points could be added as needed. Detailed reference information, such as coordinates, should be added as well. This browser interface was used specifically for a campus building construction. Since the selection of reference points was an important task that was planned ahead, any additional need or unexpected point designation should be discussed before being added into the web pages.

- Display of cloud model: Currently point clouds can only be displayed in two types of colors: A gradient gray scale and uniform color. If the original site image could combine clouds in true color, comparing two clouds would have been much more intuitive.
- Overlaying comparison: Registered clouds were separated at a distance due to an error occurring with the older version of Octree Author. This problem was fixed by the company in its latest update.

As-Built Data versus 4D Models

Current 4D technology does not include as-built data. There was no way to represent as-built geometric data in digital from as 3D computer models, until the laser range finder was applied. A former approach, which used a 3D design model to simulate schedule progress, was a "one-way" prediction from the original design to construction. The confirmation, which is made of as-built construction data from the other direction, was missing in a digital form with chronological records of whole building. The fragmented nature occurred in the current collection of as-built data made it impossible to view the entire building interactively in a 3D environment or even through Internet.

The 3D scan technology and 4D technology have existed before. Our work is different by combining these two technologies together to overcome the shortage of 4D (as stated in literature review) by providing the missing as-built information. Most of the as-built inspection was based on the on-site collection of information. The collected information was then compared like a 4D representation of progress.

The challenge in finding a way to collect the fragmented dimensions and to check a dimension that is difficult to get through the construction process is now solved by using 3D scan data. 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 the check for individual component was made.

The challenge in representing the as-built construction stages over a period of time and storing the as-built form as computer models is also solved by 3DSIMS. The traditional 4D approach, which shows the progress of parts being assembled or built over time, was an ideal representation of the construction process made by computer data in a virtual world. The records, which were made by real objects in the construction site, were hardly done because there could be too many objects presented simultaneously in a construction site. The real construction situation, which was usually beyond the representation of the 4D models, makes the reference of as-built construction from computer models unavailable. We found that there was nothing like 3D scan data to include as much as-built building parts as possible, and to make the data to represent as-built form in computer format.

Virtually, the differentiation of construction tasks and matching components can be as small as desired. However, in matching the as-built progress and 4D definition, there could be an intermediate level beyond the original scale of differentiation. For example, in reality, a job could be finished by a certain amount of percentage; the computer models created in four dimensions did not usually define a continuous level of details, for example, the area covered during pouring concrete. Scans, which record more faithfully, are more continuous in showing the changes in geometric appearance.

Contributions

With the application of the 3DSIMS, construction progress can be recorded. The benefit comes from the browser environment that serves the needs for data input and pared comparison. The browser enables the rotation, scale, and translation of 3D clouds interactively. The contribution is also made by the system, the methodology, and the long-term record of the as-built data. The effort, the characteristics of the as-built data, and the communication method makes the case study feasible and creates a new

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way of defining and representing as-built construction progress.

The full-scale point cloud proves that viewing the subject from different angles and conducting measurements is really promising. For now, the as-built construction progress in terms of objects, shapes, and dimensions can be digitized as computer models. The digital as-built models open up all kinds of possibilities in regard to schedule-related studies. The traditional one-way application of design data is now a two-way process with the availability of as-built data. The function of a current commercial product using 4D technology can be extended by including the comparison between as-built models and design models for two-way confirmation.

Conclusion

The 3DSIMS can provide input, display, and inspection design as well as as-built construction information. This system integrates scan data collected before, during, and after the scan scheme is finished. 3DSIMS was used on a campus building as a test of its feasibility of on-line functions by different parties. The responses showed it is feasible for remote monitoring of a construction site that enables a measurement function. Although the 3D digital construction point cloud records can be applied by a construction company and design firm for internal applications, using 3D records as formal construction documents still needs to be regulated by the government to ensure its legitimacy. In general, the application of 3DSIMS is a totally different construction experience. Its practical use in real construction cases also expands its research potential promisingly.

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