EXTRACTING BUILDING GEOMETRY FROM RANGE IMAGES OF CONSTRUCTION SITES

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Abstract. Modeling from range images offers promise for cost effective digital modeling of construction sites. However, most commercial software lack support for automatic alignment of range images and automatic geometry extraction – nor also do they deal with the time-dimension. This can hinder automatic digital modeling. In this paper, we describe a solution that addresses these drawbacks.

1. Introduction

Cost effective digital modeling of construction sites is essential for many real world applications; examples include construction project management (Tsai et al., 2006), construction progress monitoring (Shih and Wang, 2004), construction assessment and update (Cheok et al., 2000), and construction quality control (Akinci et al., 2006). For construction site modeling, the geometric description of the "as-built" condition is of importance (Cheok et al., 2000), though difficult to obtain. Construction sites are typically full of dynamically changing "amorphous" objects, for example, the state of excavation of the terrain, or of the half-completed wall. Such situations invalidate the usual VR or 3D modeling approaches (Retik and Shapira, 1999; Vaha et al., 1997), which are helpful for simulation and visualization, but require knowledge of geometry information in advance. Other difficulties include typically tens of thousands of items, dramatically varying shapes and sizes, requirements of non-intrusive access, etc.

Recent modeling-from-reality techniques popular in computer graphics and vision research, offers promise for this task. The basic approach is to capture multiple range images with partial overlapping regions, then align the range images (known as *registration*), and lastly extract the geometry from the registered range images for further manipulation. Advanced sensor-based defects management at construction site (ASDMCon), central to this paper, targeting defect identification at early stages of construction, employs the same idea for building and maintaining an integrated project model. In particular, we focus on the following aspects, which are either unsupported by most state-of-the-art commercial software, or require manual intervention: i) Alignment of different scans, typically requiring points or markers to be manually picked. ii) The time-dimension, critical for any review of the history of a construction site. iii) Extraction of geometry from range images, requiring users to specify both the subset of the range image and type of the expected underlying geometry, e.g., cylinder, sphere, etc. It is however important to note that the physical conditions of construction sites vary both spatially and temporally; e.g., wall data cannot be captured if the wall is hidden behind dense scaffolding. In this paper, we assume that a reasonable amount of data from the targeted objects can always be captured.

2. Related work

There is research on using range images to improve traditional techniques dealing with buildings and construction sites: Cheok et al. (2000) use terrain excavation as a proof of concept to demonstrate how LADAR can be used for real-time non-intrusive construction assessment and documentation in the form of 3D models; Shih and Wang (2004) use as-built range images to monitor construction progress by comparing the scanned images with a CAD model of the original construction schedule; Kwon et al. (2004) utilize sparse range point clouds and target objects to accelerate local 3D modeling of construction sites with human-assistance; and Geodert et al. (2005) create scaled models of target regions of construction sites for off-site investigation by integrating laser scans with rapid prototyping.

There is also relevant research in 3D computer vision. In modeling-from-reality, systems that directly use meshes incident with registered range images have been developed for various objects such as statues (Levoy et al., 2000), heritage sites (Ikeuchi et al., 2003) and underground mines (Huber and Vandapel, 2006). Stamos and Allen (2002) developed a system for modeling building exteriors utilizing parallel and orthogonal constraints. Parameterized geometry extraction is another form of object recognition. Faber and Fisher (2002) use knowledge-based architectural models as constraints to build geometric models with CAD model quality. Vosselman et al. (2004) explore techniques for recognizing objects as planes, cylinders or spheres in industrial plant and urban landscape contexts.

3. The ASDMCon project and Integrated Project Model

The ASDMCon project targets detecting defects as they occur, in order to reduce the subsequent rework cost and time. The approach is to perform frequent, complete, and accurate assessments of construction activities by examining the integrated project model (IPM) – a real-time digital model of construction sites. Advanced sensor technologies including range and embedded sensors are key to this model. Range sensors are capable of accurately capturing geometric data, while embedded sensors monitor non-geometric aspects, such as concrete strength and interior temperature. See Akinci et al. (2006) for other details.

The IPM comprises the as-planned, as-built, specification, and defect models. The as-planned model reflects the construction schedule, integrating data from the as-designed models and scheduling systems. It consists of a set of time-stamped as-designed components specified by its 3D geometry, identity, and type. An as-planned model at a given time point contains all components of the corresponding as-designed model scheduled to construct before that time. The as-built model contains product and process information based on data collected by range sensors, and the geometry extracted. The specification model is a computer-interpretable version of the construction requirements. Lastly, the defect model contains any product deviations identified by comparing the as-planned and as-built models.

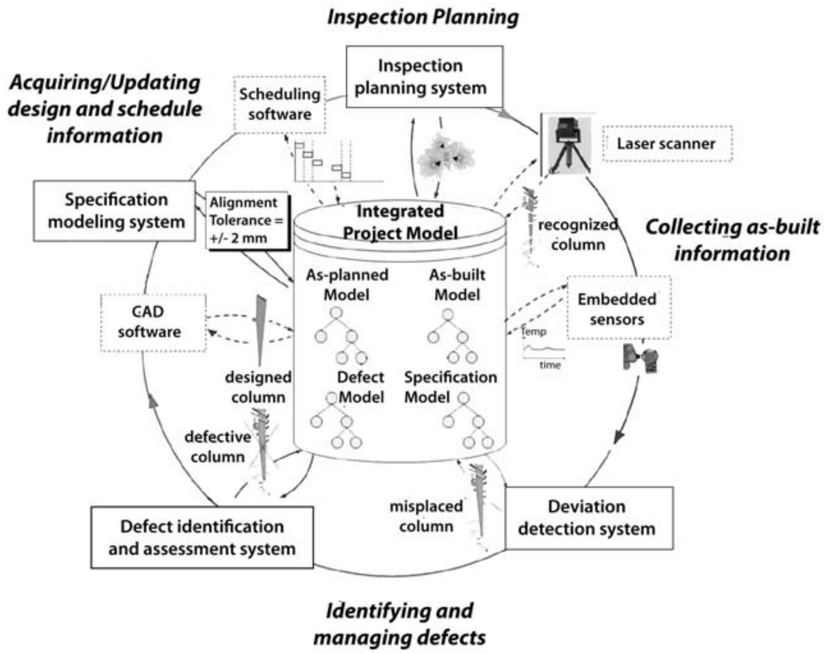

Figure 1. Framework for the ASDMCon project.

4. As-built point cloud model

As-built point cloud models are used to record construction activities. Each visit to the construction site is a time-stamped scan session. Typically, an as-built point cloud model consists of multiple scan sessions, each containing multiple scans. The scans are merged using a process of registration.

4.1 RANGE DATA COLLECTION

A Z+F LARA 25200 laser scanner was used to collect point cloud data. The Z+F scanner is able to scan 360° horizontally and 70° vertically, and capture both range and reflectance data for each point. It has a maximum range of 25 meters, and a data rate of 120,000 samples per second. Typically a scan session consists of about 30 scans over the course of a couple of hours, taking an average of 6 minutes per scan including spin-up time and interface navigation. Strategic points are chosen so as to maximize the number of components that can be inspected with minimal intrusion. Scanning a region can be performed quickly enough so that regional condition changes within a single scan session can be safely ignored.

4.2 RANGE DATA REGISTRATION

Each scan (3D point cloud) data is represented in a local coordinate system relative to the laser scanner. It becomes therefore necessary to register the session scans to a common coordinate system. There are a number of established methods for registration. The first is to specify three pairs of corresponding points; this approach is manual and slow. The second is to augment the target site with markers, which can be easily detected in the 3D point cloud data and aid registration; this approach, although relatively faster, still requires human input. Placing markers is either cumbersome or may be impossible in reality. The third approach is to augment sensors with a pose estimation system such as GPS, which records scanner position and orientation for each scan. This can then be further refined. This approach is fast, but initial pose estimation may be hard or even impossible to obtain in certain situations. Lastly, there are automated methods, which require that the scans, taken pair-wise, overlap to a certain level. This approach has proven fast and accurate in experimented environments.

We adopt a version of fully automated registration based on spin-images (Johnson, 1997), owing to the large number of scans to be registered. The following is a conceptual description of the approach; see Huber and Hebert (2001) for details. The basic problem in automatic registration is to find the neighbor pairs for each scan. The premise is that the local neighbor information of the same point from a correct pair is consistent in the overlapping region. If a descriptor for the local neighbor information of each point can be found, the problem becomes a search for scans with consistent descriptors. As there is a rigid transformation between pairs, the descriptor needs to be independent of rigid transformation. This can be achieved by an object-oriented coordinate system, which uses the normal and tangent plane of a point as a 5-tuple basis. Normals are computed from neighbor points. With this coordinate system, all other points of a scan can be described by two parameters; the perpendicular distance to the normal and the signed perpendicular distance to the tangent plane (Figure 2: left). A 2D bin is created with this 2D coordinate to accumulate the number of points falling in. By viewing this bin as an image, surface matching becomes a problem of image-based matching, which has been extensively studied.

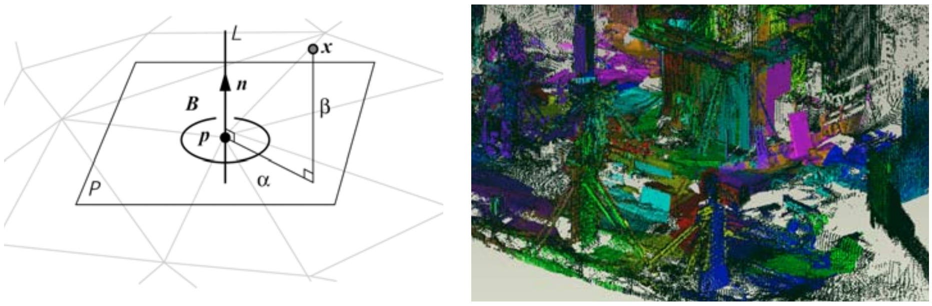

Figure 2. *Left*: An oriented point basis created at a vertex in a surface mesh, reproduced from (Johnson, 1997). *Right*: A registered as-built model overlaid with an as-design model.

This algorithm often finds the correct relative pose of a pair; however, it may fail for data-dependent reasons. Heuristics for visibility consistency used to eliminate incorrect results examine the consistency of the two surfaces along the line of sight from each sensor viewpoint. To ensure the overall optimization, a final global surface consistency is conducted, from which the absolute poses of each scan can be read directly.

Note that registration of the as-planned and as-built models cannot be automatic: the effect of the algorithm's optimization is to propagate differences throughout the whole model, which potentially alleviates true defects and creates false defects. Manually specifying three pairs of points seems a safer and more accurate way for registration (Figure 2: right).

5. 4D Visualization

An important motivation for digital modeling is to record and review construction activities over its lifetime. It is vital to visualize the IPM with a system supporting the time-dimension. However, most current commercial software for range images is specialized for modeling manufactured parts, with no concept of time. Another limitation is 3D navigation; manufactured parts are solid and have no need to be viewed from within. However, for construction sites, it is important to be able to look inside a multistory to inspect a piece of column on a given floor. Clipping the view to focus on a small region is important for detailed examination.

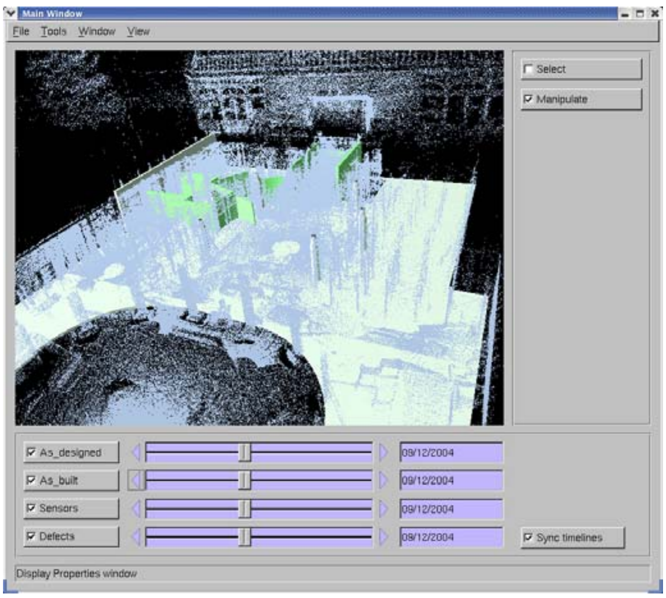

Figure 3. The main window of the Viz interface showing its timeline sliders.

Given the limitations of commercial software, we have developed a custom visualization OpenGL-based environment, named Viz. In particular, the as-planned model is treated as time-stamped "As-designed". The time stamp indicates either when to construct or optionally, if temporary, when to remove. "As-built" contains both registered time-stamped point cloud models and the corresponding geometry extracted. Embedded sensors are treated separately as "Sensors". Viz acts as a browser for users to retrieve, view, and analyze data at any point along the time-line specified by the construction schedule. Figure 3 shows the software's main interface window. It consists of a 3D viewer for displaying and interacting with the 4D models, and a set of timeline sliders, one for each class of data, by which the user can control the point in time that is visualized. The sliders can be synchronized to display the status of the site at a particular time, or the individual sliders can be independently adjusted to examine the components at various times.

6. Extraction of Building Geometry

A "raw" registered point cloud model can be useful; for example, distances between two points or angles defined by three points can be directly measured; with a co-registered as-designed model, defects can be manually identified with the aid of deviation coloring (Figure 4a), which colors the points according to the "nearest" distance to the as-designed model. However, in general, a point cloud model is too cumbersome to use; for the construction sites that we studied (with ranges of 10,000 ~ 150,000 square feet footprint), each data collection session produced about 20 ~ 70 laser scans, and each scan data store in the range of 25 ~ 300MB. Reverse engineering the point cloud models to parameterized geometry models becomes highly desirable for further manipulation.

A typical approach extracting parameterized geometry is to use object recognition algorithms. Object recognition in general is a "chicken-and-egg" problem. Most 3D object recognition algorithms convert the general object recognition problem into the problem of matching models from a database with representations of those models extracted from a point cloud model, and can only handle rigid-transformed 3D objects for which a precise 3D model is already known. Building components on construction sites are highly variable in both shape and size. For those "amorphous" objects, 3D models are unknown, or are known only as an approximation of the true shape. Further complicating matters is the unusually high amount of clutter in active construction sites; these include scaffolding, material storage, formwork, and other temporary structures. Our approach takes advantage of the availability of a co-registered as-designed model, which is implemented in two steps: as-built segmentation and geometry extraction.

6.1 AS-BUILT SEGMENTATION

Except in extreme cases, as-built components are close to their counterparts in the co-registered as-designed model. With the observation that the deviation between the as-built and as-designed are not too large, segmenting the as-built model is straightforward given a co-registered design model. Based on a simple nearest neighbor algorithm, points in the as-built model are associated with the closest as-designed component (measured in Euclidean distance). Outlier points further than a given threshold from any as-designed component are considered to be clutter. Larger deviations are more challenging. However, with knowledge of which as-designed components have as-built counterparts, spatial reasoning can determine candidate components corresponding to the large deviation part. Exhaustive search can ultimately assign an as-designed counterpart to it.

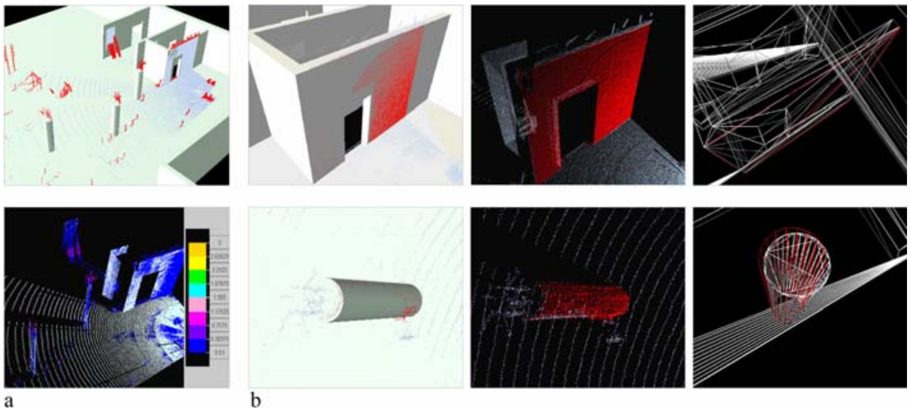

Figure 4. (a) *Top*: Clutter identified, shown in red. *Bottom*: Deviation color analysis of a scan. (b) *Top*: Fitting an infinite plane (Results: angles with X-Y- and Z-axes = 89.4438°, 0.5443°, 0.1146° respectively. Ground truth: is in Y-Z plane). *Bottom*: Fitting an infinite cylinder (Results: radius = 28.21cm. Ground truth: 25.53cm)

6.2 EXTRACTION OF BUILDING GEOMTRY

There are various systems for representing building component geometry: boundary representation; swept or extruded geometry; and CSG. However, most can be converted to either as a boundary-wise representation, which is viewed as the intersection of infinite planes or curved surfaces, or as a parameterized equation. Under the assumption that such information is available or is able to be inferred from the as-designed model, once the as-built counterpart of an as-designed component is identified, geometry extraction is a relatively easy task. For components that can be described boundary-wise, the problem reduces to fitting infinite planes or curved surfaces on the point cloud of the as-built counterpart, which is further segmented into smaller pieces using standard segmentation algorithms. For components that can be parameterized, the problem reduces to fitting a parameterized model. Figure 4(b) shows examples of fitting an infinite plane on the subset of point clouds representing a planar surface, and fitting an infinite cylinder on the point clouds to represent a cylindrical column.

7. Issues: implications for future work

There still remain several outstanding technical issues. First, we found differences in centimeter magnitude between the fitted results and ground truth – even after exploring a variety of fitting algorithms. For practical defect detection, we need to reduce tolerance to millimeter levels. Second, we observed overall offset or rotation effects when the as-designed model is overlaid on the registered as-built point cloud model. These effects, perhaps, due to accumulation of errors, can easily reach meter magnitude for larger-scale projects. Techniques to control model uncertainty are thus necessary for accurate modeling. Lastly, obscured data is common in any construction environment mainly due to clutter; we need more robust techniques to handle such situations. This, we believe, is knowledge-based.

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References

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C. and Park, K.: 2006, A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Automation in Construction,* 15**,** 124-138.

Cheok, G. S., Stone, W. C., Lipman, R. R. and Witzgall, C.: 2000, Ladars for construction assessment and update. *Automation in Construction,* 9**,** 463-477.

Faber, P. and Fisher, B.: 2002, How can we exploit typical architectural structures to improve model recovery? *3D Data Processing Visualization and Transmission.* Padova, Italy.

Goedert, J., Bonsell, J. and Samura, F.: 2005, Integrating laser scanning and rapid prototyping to enhance construction modeling. *Journal of Architectural Engineering,* 11**,** 71-74.

Huber, D. and Hebert, M.: 2001, Fully automatic registration of multiple 3D data sets. *IEEE Computer Society Workshop on Computer Vision Beyond the Visible Spectrum 2001.*

Huber, D. and Vandapel, N.: 2006, Automatic three-dimensional underground mine mapping *The International Journal of Robotics Research,* 25**,** 7-17.

Ikeuchi, K., Nakazawa, A., Hasegawa, K. and Ohishi, T.: 2003, The great buddha project: modeling cultural heritage for VR systems through observation *The Second IEEE and ACM International Symposium on Mixed and Augmented Reality.* Tokyo, Japan.

Johnson, A.: 1997, Spin-images: A representation for 3-D surface matching Pittsburgh, PA, Robotics Institute, Carnegie Mellon University.

Kwon, S.-W., Bosche, F., Kim, C., Haas, C. T. and Liapi, K. A.: 2004, Fitting range data to primitives for rapid local 3D modeling using sparse range point clouds. *Automation in Construction,* 13**,** 67-81.

Levoy, M., Pulli, K., Curless, B., Rusinkiewicz, S., Koller, D., Pereira, L., Ginzton, M., Anderson, S., Davis, J., Ginsberg, J., Shade, J. and Fulk, D.: 2000, The digital Michelangelo project: 3D scanning of large statues IN AKELEY, K. (Ed.) *Siggraph 2000, Computer Graphics Proceedings.* ACM Press, Addison Wesley Longman.

Retik, A. and Shapira, A.: 1999, VR-based planning of construction site activities. *Automation in Construction,* 8**,** 671-680.

Shih, N.-J. and Wang, P.-H.: 2004, Point-Cloud-Based Comparison between Construction Schedule and As-Built Progress: Long-Range Three-Dimensional Laser Scanner's Approach. *Journal of Architectural Engineering,* 10**,** 98-102.

Stamos, I. and Allen, P. K.: 2002, Geometry and texture recovery of scenes of large scale. *Comput. Vis. Image Underst.,* 88**,** 94-118.

Tsai, M.-K., Yang, J.-B. and Lin, C.-Y.: 2006, Synchronization-based model for improving on-site data collection performance. *Automation in Construction,* In Press.

Vaha, P., Kansala, K., Heikkila, R. and Kaisto, I.: 1997, Use of 3-D product models in construction process automation. *Automation in Construction,* 6**,** 69-76.

Vosselman, G., Gorte, B. G. H., Sithole, G. and Rabbani, T.: 2004, Recognizing structure in laser scanner point clouds. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences.* Freiburg, Germany.