

BUILDING ROOF RECONSTRUCTION BY FUSING LASER RANGE DATA AND AERIAL IMAGES

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ABSTRACT:

The objective of this study is to present an efficient and robust method of building roof reconstruction by fusing laser range data and aerial images through CSR (Construct-Shape-Refine) procedures. The algorithm starts by extracting 3D line features from laser range data by using the semi-automatic 3D line feature extraction engine. After 3D line features are extracted and regarded as input data for the CSR algorithm, then the procedures of building roof reconstruction are performed in the following algorithms of geometric inferences: (1) constructing the topological relationship of 3D line features that belong to the same building roof by using the special intersecting property of 3D line features projected onto plane; (2) shaping the initial building roof by means of adjusting the 3D line features, and compensating missing parts, if any, by the shortest path algorithm and reporting whether or not the investigated building roof is completed; (3) as a final stage, refining the building roof automatically or semi-automatically by integrating 2D line features observed from the images through geometric inference processes. The experiments show that the proposed CSR algorithm provides a workable platform for building roof reconstruction by fusing laser range data and aerial images.

1. INTRODUCTION

3D reconstruction of city model has recently been a popular research topic in Digital Photogrammetry (DP) as well as Computer Vision (CV) community. The indispensable process of 3D city modeling is to construct building models. Traditionally, the generation of building models is mainly performed by measuring the conjugate points on aerial stereo-pair images. However, line features, of higher-order information and easier detected than point features, are the main evidence for building hypotheses and an excellent feature primitive for building reconstruction if gone through proper photogrammetric approaches (Schenk and Csatho, 2002). As far as the data sources are concerned, line features can be extracted or measured from aerial images, topographic maps, and laser range data (also termed LIDAR point clouds or LIDAR data in this study), etc. LIDAR system, among which, has emerged as a new technology in the past decade for obtaining the surface data potentially revealing detailed scene geometry, which, as compared to aerial images that contain abundant spectral information and scene information, renders an promising alternative for feature extraction and building reconstruction. Besides, vertical component accuracy is far better than horizontal component in airborne LIDAR system while photogrammetric means usually suggests the opposite result due to restricted base/height geometry. It is therefore found that the LIDAR point clouds and aerial imagery data possess mutually independent advantages, suggesting a complementary potential if they are appropriately fused. Rottensteiner and Jansa (2002) proposed a bottom-up algorithm of fusing LIDAR data with aerial images for handling polyhedral buildings of arbitrary shape without any prior information about the building outlines. Seo (2003) presented an integration method based on fusing LIDAR data with aerial images to increase the level of automation in building recognition and reconstruction. Ma

(2004) proposed a scheme of building reconstruction by fusing LIDAR data sets with aerial images based on polyhedral model, where aerial image data are meant to improve the geometric accuracy of the building model. Chen et al. (2006) proposed fusing LIDAR data with aerial images to detect building regions followed by a reconstruction strategy of Split-Merge-Shape processing.

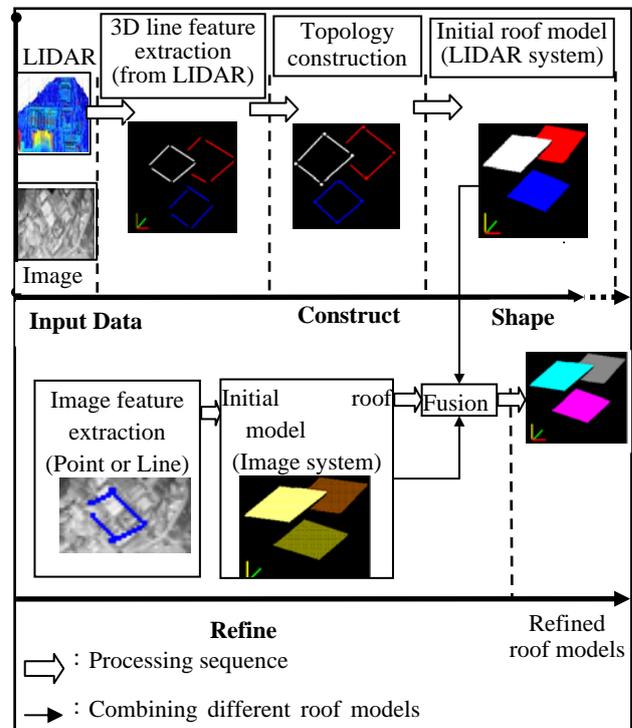


Figure 1. The workflow of CSR approach

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Due to the flexibility for extracting 3D line features from different data sources and the advantage of data fusion, the authors proposed, in this study, a scheme comprising **Construct-Shape-Refine (CSR)** three steps and developed a line feature-based geometric inference algorithm by fusing 3D line features with 2D image lines for building roof reconstruction. Figure 1 illustrates the flowchart of the proposed CSR method for the generation of 3D building roof models.

2. 2D AND 3D LINE FEATURE EXTRACTION ENGINE

At current stage where the accuracy of line features is not the main concern, we consider simple but reliable extraction tools for acquiring 3D line features from imagery and laser range data, respectively. The algorithm starts by extracting 3D line features from laser range data by using the semi-automatic 3D line feature extraction engine, which contains three major procedures: (1) interpolating the dispersed laser point clouds into regular grid data, then forming the range images; (2) automatically extracting 3D line features by using Canny operator with Hough transform; (3) considering the reliability for extracting these 3D line features, a user interface which fuses the human intervention was implemented to select the best 3D line features obtained in last step and to make up for the deficient parts that resulted from automatic extraction, if any. The effectiveness of the above design can be illustrated through the demonstrations of Figures 2 and 3, where the blues lines present the 3D line features extracted by image processing and the red one is the feature selected by a user. For those line features of building roof that miss in the detection, the operator would undertake manual measurements, as the green line shown in Figure 3. By way of the semi-automatic extraction, complete 3D line features of building roofs out of LIDAR point clouds can be obtained, as those black lines in Figure 4 illustrate.

As for 2D line feature extraction from aerial imagery, the (2) and (3) steps for 3D line features extraction are utilized.



Figure 2. Manual selection of extracted 3D line features

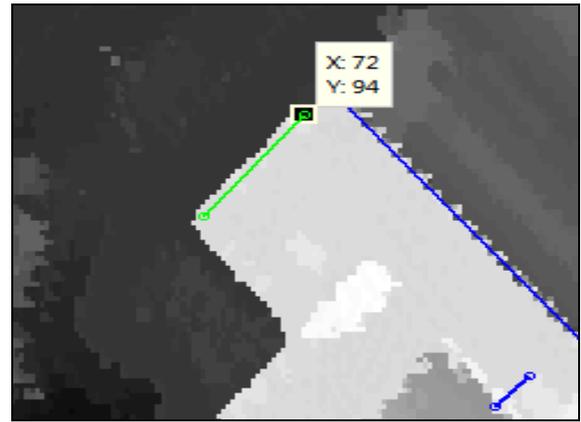


Figure 3. Manually measure the 3D line feature

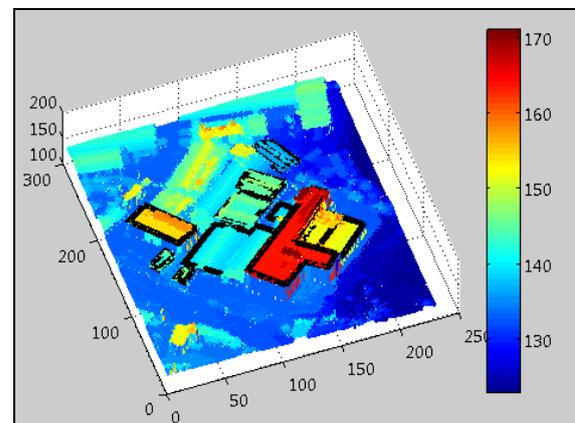


Figure 4. 3D line features superimposed on LIDAR DSM

3. CSR METHODOLOGY

After 3D line features are extracted and regarded as input data for the CSR algorithm, then the procedures of building roof reconstruction are performed through the following geometric inferences: (1) constructing the topological relationship of 3D line features that belong to the same building roof by using the special intersecting property of 3D line features when projected onto a plane; (2) shaping the initial building roof by means of adjusting the 3D line features, and compensating missing parts by the shortest path algorithm, if any, and reporting whether or not the investigated building roof is completed; (3) refining the building roof automatically or semi-automatically by integrating 2D line features observed from the images through 2D and 3D geometric inference processes. The function of the automatic mode is not only to find the building boundaries from images by using the distance, angle and topological checks in images and object space, but also adjust the 3D line features obtained either from laser range data or aerial images; on the other hand, in the semi-automatic refined mode, there are three modules that are separated by the feature types of measurements, namely point-based, line-based and hybrid mode. The point-based model is the traditional photogrammetric approach for building reconstruction where the first step is to measure the conjugate points in the corner point order, either clockwise or counter-clockwise, then execute the point-based intersection followed by connecting the roof corners through a CAD design. The line-based mode is nevertheless based on line

feature measurements which offer higher flexibility for measurements. The hybrid model is the most flexible method for measuring the geometric features in image space by offering both point and line features measurement selection.

The CSR approach is detailed in the following sections.

3.1 Construct

3.1.1 Determination of Junction Points: The core idea behind the **Construct** procedure is the characteristic of intersection of the 3D line features when projected onto XY-plane (Jaw and Cheng, 2007): When extended, a 3D line feature will be suspended when running into other 3D line features and thus candidate junction points are determined, as seen in Figure 5.

In order to obtain the correct intersection of 3D line features that correspond to building corners, two thresholds of geometric inference are imposed: **(1) Distance threshold:** The distance threshold is set taking account the random error of measurement and then used to filter out the improper junction points by buffering the end points of the line feature. **(2) Topological threshold:** When adjacent buildings get too close, the above distance check is inadequate to guarantee appropriate junction points. A topological check (Jaw and Chen, 2007b) is therefore implemented to identify those ambiguities. Figure 6 shows the result after applying the aforementioned thresholds and Figure 7 depicts the algorithm of junction point determination.

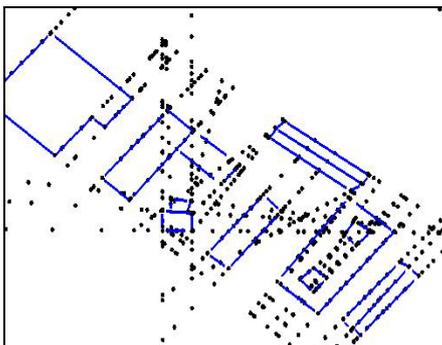


Figure 5. Candidate junction points before applying thresholds

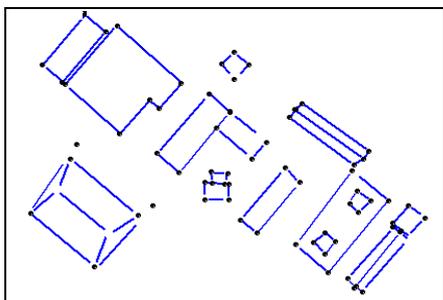


Figure 6. Junction points after applying thresholds

Input: 3D line features of building roof
Output: Reasonable Junction points
do 3D line feature projected onto XY plane.
do calculating the candidate junction points.
do the distance check and confirm if there is only one junction point in this direction of 3D line features
if YES
 Find the reasonable junction points. Output the result.
ELSE
do the topological check. Output the results.

Figure 7. Algorithm of thresholding junction points

3.1.2 Grouping the 3D Line Features and Constructing the Topology: After obtaining the proper junction points, the 3D line features that belong to the same building, each highlighted with different colors as shown in Figure 8, can be grouped by introducing the concept of cluster analysis, which is also utilized in establishing the topology of roofs within the same building.

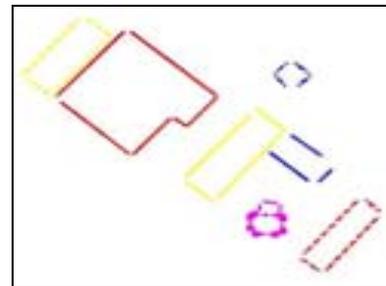


Figure 8. Grouping 3D line features

3.2 Shape

At the shaping stage, the model of Conditions Adjustment with Additional Parameters (as seen in Equation (2)) is used to estimate the 3D coordinates of roof corners. Realizing that one 3D line features can be expressed by two plane equations, as in Equation (1), the 3D coordinates of roof corners are treated as unknown parameters and solved by employing least-squares adjustment

$$\begin{matrix} a_1 X + b_1 Y = 1 \\ a_2 Y + b_2 Z = 1 \end{matrix}, \quad (1)$$

where a_1, b_1, a_2, b_2 are the observations;

X, Y, Z are the unknown parameters of roof corners when considering the intersection of two 3D line features.

$$B_{c \times n} e_{n \times 1} + A_{c \times u} \xi_{u \times 1} - W_{c \times 1} = 0_{c \times 1} \quad e \sim (0, \Sigma = \sigma_0^2 P^{-1}), \quad (2)$$

where A, B matrix are obtained by taking partial derivatives of unknown parameters, observations, respectively, with respect to Equation (1);

W represents the discrepancy vector;
 e stands for error vector;
 ξ is the unknown parameter vector;
 Σ is the covariance matrix of the observations while
 σ_0^2 is the variance component;
 c, n, u are the number of conditions, observations,
 and unknown parameters, respectively.

To compensate for hidden parts, if any, our approach hypothesizes the hidden parts by tracking the higher edges of the neighboring building using *Floyd-Warshall*, the shortest path algorithm (Cormen *et al.*, 2003). As demonstrated in Figure 9, the hidden parts (black dot lines) of the lowest buildings (colored black) are eventually compensated.

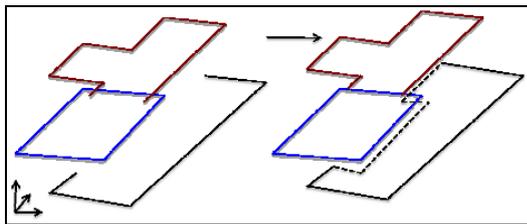


Figure 9. Compensation of hidden parts

3.3 Refine

Two modes were considered for the refinement procedures. One is automatic mode and the other is semi-automatic mode designed for whenever meeting extraction and/or reconstruction deficiency. The details of two modes are illustrated as follows.

3.3.1 Automatic mode: Having 2D line features available, automatic refinement considers the following steps: (1). Validation of building boundaries by imposing 2-D and 3-D geometric inferences in image space and in object space, respectively; (2). Merging and adjusting 3D line features of building boundaries from aerial images through adjustment computation. (3) Fusing initial building models from different sources (LIDAR system with image system). Figure 10 shows the proposed scheme for automatic refinement mode (Jaw and Cheng, 2007a).

3.3.2 Semi-Automatic Mode: In order to implement the process of building roof reconstruction in a more efficient as well as reliable fashion, point-based, line-based and hybrid user-interface modules (Jaw and Cheng, 2007b) are designed as follows:

Point-based: At point-based mode, the traditional approach of photogrammetric intersection by sequentially measuring the conjugate corner points in, at least, a stereo-pair is adopted. Then the corners determined by photogrammetric method are fused with those derived from 3D line features, ending up with refined roofs.

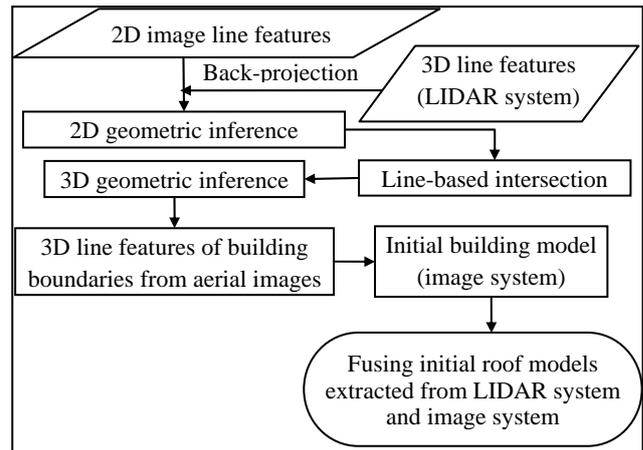


Figure 10. The proposed scheme of automatic refinement mode

Line-based: The approach of line-based module is similar to point-based one except that line features, instead of point features, are measured. 3D line features collected in this mode are the result of the intersections of conjugate 2D line features. Then the initial roof models of image system are formed by using **Construct-Shape** process. After that, refined roofs are determined by fusing initial roof models resulting from image system and LIDAR system.

Hybrid module: The hybrid module provides the most flexible method for measuring the features. Demanded by the users when taking the measurements, point features, line features, or the combination of both can be measured. Again, once 3D line features are formed upon measurements, the **Construct-Shape** processes are followed for acquiring the initial roof models of image system. Then fusion of different roof models is undertaken for improving the roof quality.

4. EXPERIMENTAL RESULT

Reconstructing building roof models were tested by fusing LIDAR data sets with aerial imagery. The test area is in Hsinchu, Taiwan. The LIDAR data sets were collected in 2002 by airborne laser scanning system while the images with a scale of 1:5800, B/H=0.225, were taken almost the same time as acquiring the LIDAR data sets. Figure 11 and Figure 12 depict the LIDAR DSM and aerial images, respectively, of the test area. The black lines in Figure 11 are 3D line features extracted from LIDAR DSM by 3D line feature extraction engine. Figure 13 gives the results of initial roof models from LIDAR system, Figure 14 displays the results of refined roof models through CSR processes, where the red, blue and green roofs were obtained by point-based, line based and hybrid module, respectively, while the yellow roof was reconstructed by the automatic refinement mode. In addition, the white roofs show the results reconstructed purely based on images (that were missing from LIDAR data sets). Due to the lack of external reference data, we calculated the fitting error of LIDAR point to the roof obtained through CSR approach as a kind of quality indicator and 20cm of fitting error was found. To report the reconstruction accuracy, we actually looked at the theoretical accuracy of corner points through the adjustment output.

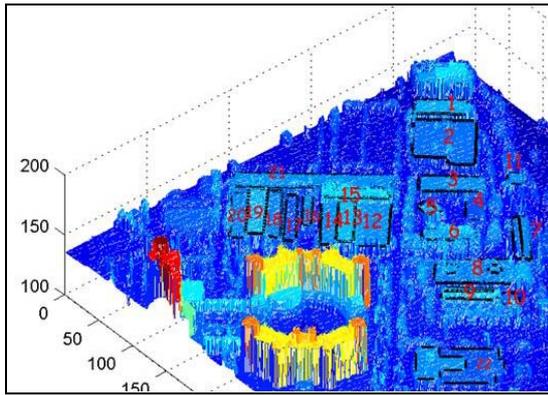


Figure 11. LIDAR DSM and 3D line features of the test area



Figure 12. Aerial image of the test area

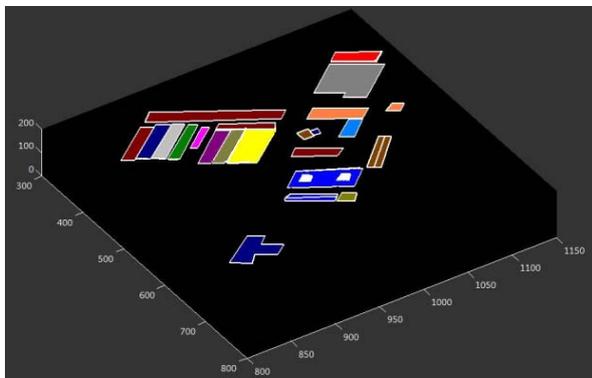


Figure 13. Initial building roofs from LIDAR system

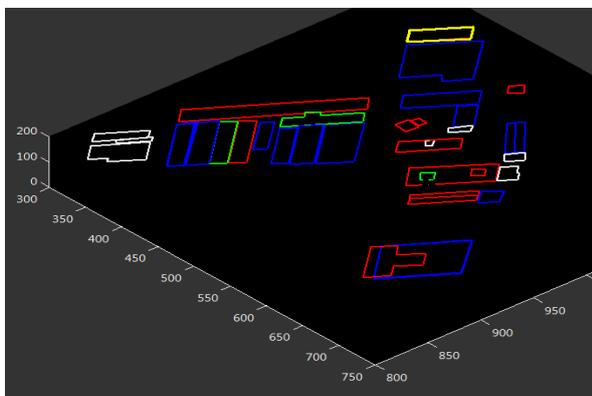


Figure 14. Refined roof model

The following cases demonstrate the advantages of the proposed scheme:

Compensation: Figure 15(a) versus (b) and (c) versus (d) are the examples of compensating the fully missing and deficient 3D line features out of LIDAR data by adding the image measurements utilizing the user interface.

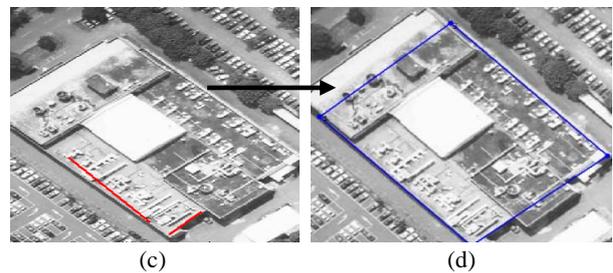
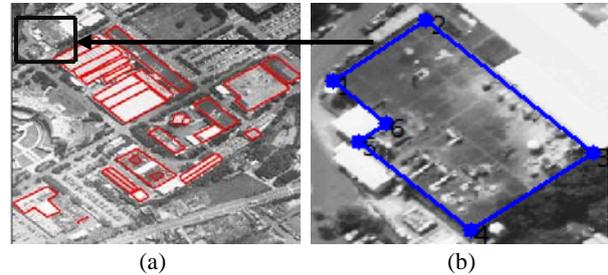


Figure 15. Compensating the missing and deficient parts

Update: If there exists change between LIDAR and imagery (assumed to be the latest data) data sets, the result of building roof reconstruction from LIDAR data can be updated by fusing aerial images. Figure 16 (a) versus (b) depict the update effect.



Figure 16. Updating the building roof model

Enhancement of Reliability: Sometimes due to the inaccuracy of LIDAR data, the result reconstructed by fusing LIDAR data with aerial images may seem unsatisfied, though rendering high precision revealed from the adjustment report. A user interface would provide a visual inspection environment for determining the most proper employment of line features.

Improvement of Theoretical Accuracy: According to the theory of error propagation, the precision of building roof corners will be improved by fusing different data sets as compared to the situation when only single data is available. Table 1 provides the precision of roof corners before and after the CSR approach. Notice that there are two corners obtained from LIDAR data and four corners from aerial images. In this case, the precisions of corners 1 and 2 are improved and corners 3 and 4 are updated.

Corner no (LIDAR)	Corner precision (unit: m) before fusion			
	σ_x	σ_y	σ_z	σ_{xyz}
1	± 1.57	± 1.65	± 0.30	± 2.30
2	± 1.70	± 1.62	± 0.28	± 2.36
Corner no (Image)	Corner precision (unit: m) after fusion			
	σ_x	σ_y	σ_z	σ_{xyz}
1	± 0.42	± 0.39	± 0.28	± 0.64
2	± 0.43	± 0.38	± 0.26	± 0.63
3	± 0.44	± 0.39	± 0.76	± 0.96
4	± 0.41	± 0.37	± 0.80	± 0.97

$$* \sigma_{xyz} = \pm \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

Table 1. The precision of corner points before/after fusion

5. CONCLUSION

This study identifies itself with several significances listed as follows:

- (1). Construct-Shape algorithm gains great efficiency for obtaining the initial 3D building roof models when provided with 3D line features.
- (2). The geometric quality of building roof models can be improved at the Refine stage by data fusion, especially when making use of the complementary sources, such as laser range data and imagery in this study.
- (3). The designed interactive operating environment that enables the 3D and 2D line feature extractions out of laser range data and imagery, respectively, is valuable especially when faced with incomplete or incorrect reconstruction due to the deficiency of automatic systems or data sets, where manual measurements would make up for those insufficiency.

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