**ABSTRACT:**

In this paper we introduce an approach for automatic recognition and reconstruction of building façade structure from oblique aerial images. Contrast to street-view image oblique aerial image has larger field of view but lower resolution, weaker texture and more noise. To overcome these shortcomings, our approach firstly analyses the horizontal distribution density to extract individual façade area from image. Then a hierarchical repetition detection method is employed to partition the façade and recognize structural elements. Finally, the geometry structure of each façade element is reconstructed jointly by all repetitive image tiles. Results show the potentials of the proposed approach.

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3. Becker, G. (2009). Procedural Modelling (IPM) method is received significant attention (Becker, 2009; Dai et al., 2012; Muller et al., 2007; Simon et al., 2012; Teboul et al., 2010). Different from PM, IPM discover structural rules from input data, then use these rules to reconstruct building models in the PM manner. IPM is

**KEY WORDS:** Oblique aerial image, Building façade, Partition, Hierarchical repetition, Joint reconstruction
regarded as a better roadmap for façade reconstruction than pure data-driven or grammar-driven methods which can combine observations and domain knowledge efficiently. While the key of IPM is how to derive reasonable rules from raw data. Although numerous methods have been proposed, it is far away from practical application on real-world images due to the facades’ prohibitively high complexity and noisy, incomplete measurements.

We aim at a reliable and high-quality façade reconstruction from oblique aerial image in urban area. Contrasting to street view image, oblique aerial image can provide larger view of ground area and higher efficiency of acquisition, this character of oblique images require a method to detect façade regions from patches of roof, ground and tree mixed in one image frame. Then oblique image has lower resolution and weaker texture, which requires a robust method insensitive to erroneous and incomplete measurements. Moreover, building façades in practical urban scene are various and complex. Traditional methods conduct building façade as regular arrangement of a single type window or balcony just like a checkerboard pattern. While real-world façade usually contains various types of windows and balconies which exhibit an amazing variety of irregular mixtures of grid structures. The ubiquity of these façades requires a new method supporting such complex façades modelling.

We propose a novel approach to reconstruct irregular building façade by hierarchical repetition analysis. Assuming building façade is composed of a perpendicular dominant plane and some auxiliary elements like different types of windows, balconies or oriels. The target of façade reconstructing is to recover the elements’ geometric structures and align them to proper position. To achieve the general objective, we attempt to tackle three main problems as following:

1. To detect individual façade dominant plane from oblique image.
2. To discover elements on façade and recover their spatial layout.
3. To reconstruct 3D geometry of each element.

In the next section, we apply a series of technique to solve these three problems and then integrate them into an automatic pipeline.

3. METHODOLOGY

According to previously mentioned idea, we design a three-stage pipeline to reconstruct irregular façade automatically from oblique images. The detailed implementation flow is described in Figure 1.

The whole flow of façade reconstruction is divided into three main steps: façade detection (grey blocks), façade partitioning (orange blocks) and façade reconstruction (dark green blocks).

Figure 1 The whole flow of façade reconstruction from oblique images (rectangle represents a processing node, parallelogram represents a data node).

3.1 Facade Detection

With larger field of view than street view image, oblique aerial image covers a wide scope of urban area which contains a variety of land cover such as buildings, roads, vehicles and vegetation. In the first step, we need to detect façade from oblique image automatically. Most existing work on façade identification adopt image classification technique, which relies on a series of well-designed procedure of feature selection and training (Ceylan et al., 2012; Liu and Liu, 2014). Considering that building in urban scene generally juts from the ground and the facade is mostly perpendicular, we design a simple way to identify facade by this 3D priori knowledge.

Firstly, Semi-Global Matching (SGM) method (Hirschmuller, 2005) is used to perform pixel-wise stereo matching to generate 3D point cloud from oblique images. Considering building façades are mostly perpendicular, the obtained 3D points on façades have approximate planar coordinates. We calculate their horizontal distribution density according to formula (1).

After that, the labelled façade points should be divided into individual façade and then the dominant plane for each façade should be extracted.
Assuming facade is generally perpendicular, we project all labelled facade points onto horizontal plane and cast the 3D points segmentation to a 2D straight-line fitting problem. We utilize a robust multiple structures estimation method (J-Linkage) to extract all straight line segments (Toldo and Fusiello, 2008). And then use the resulting lines and the maximum and minimum height of facade points to fit the parameters of 3D dominant planes. Subsequently, the dominant planes are projected to oblique image in order to label the corresponding facade image areas. Then a Transform Invariant Low-Rank Textures (TILT) method (Zhang et al., 2011) is used to ortho-rectify each facade image to the frontal view. Figure 2 shows the flow of facade detection.

Figure 2 (a) is a part of raw oblique image. (b) is the result 3D points by stereo matching, the points are colored by height ramp from blue to red. (c) shows the points colored by horizontal density. (d) shows the segmentation result of facade points, different color indicates different line segment, blue points are the outliers. (e) is the rectified facade image corresponding to the area marked by a yellow dashed box in (a) and (c).

3.2 Facade Partitioning

Considering that building facade in urban scene generally contains a lot of repetitive structures, we intend to utilize such property to partition the facade and eventually identify facade elements and their arrangement. However, this work is challenging due to poor-quality of oblique image and complex layout of facade. We hold the view that if the regular facade can be described by a simple repetitive pattern, the irregular also can be described by a series of simple repetitive patterns. Therefore, we design a hierarchical strategy to split the irregular facade into a set of simple repetitive patterns.

The building facade is expected to be partitioned into a set of horizontal and vertical slices. Different from the traditional method which partitions facade along horizontal and vertical directions simultaneously (Muller et al., 2007), we split facade once along each direction successively. According to prior knowledge of urban buildings, the horizontal (vertical) splitting places of facade should be placed where vertical (horizontal) edges are rare and horizontal (vertical) edges are dense. After each splitting, a group of image slices can be obtained. Then an image registration method is applied to these slices image to discover the similarity among slices. We use the gradient mutual information to measure the similarity which is proposed robust to noises (Dalal and Triggs, 2005). Then we label the repetitive slices and combine them into a new image. Subsequently, the image splitting and repetition detecting is executed again on the new image along the other direction. The processing is performed iteratively until each slice is small than a certain area. Our partition approach ensures every splitting is based on a certain repetitive pattern determined in last similarity detection. So the whole flow can partition facade hierarchically. By the iterative splitting, the whole facade is partitioned to a group of tiles. Assuming each facade element has a unique repetitive pattern, we classify all the tiles to individual cluster according to their labels marked previously. After that, we utilize similarity repetitive patterns to perform a global optimization toward alignment of repetitive tiles. Firstly, each tile in a cluster is selected as an image template and the template based image match is conduct on the whole facade image. The extreme points of each template matching are extracted and all these extreme points are combined together. Finally, the least-square adjustment is adopt to refine the coordinates of each tile.

Figure 3 (a) shows the result of facade splitting along horizontal direction. Blue lines indicate the segmentation position. (b) shows the result of similarity detection along horizontal direction. Similar slices are filled with the same color and the slice different from others is colored in red. (c) shows the result of vertical splitting on the similar slices determined in horizontal direction (green area in (b)). (d) shows the similar slices in vertical direction. (e) shows the result of the complete facade partition. Tiles in different cluster are painted in different
3.3 Facade Reconstruction

The geometry structure of facade element can be represented by a group of line features. In this section, we aim at recovering the wire-frame model for each element. The direct idea is to detect lines from image and group them together. We use a fast line segment detector named LSD to extract line segments (von Gioi et al., 2010).

Due to the low quality of oblique image, it is very common that line detecting in some image tiles cannot achieve desired result. Because repetitive tiles corresponding to an identical element, we integrate all the lines in repetitive tiles to reconstruct the element model. For each tile cluster corresponding to an element, the whole facade structure can be represented by a few element models. The coordinates of repetitive tiles are aligned in the previous step. We can use the relative position among tiles to map all lines in each tile to a unified reference coordinate frame. Then a two-step filtering process is performed to eliminate some non-structural lines. At first step, we suppose that element model is only consisted of horizontal and vertical lines (Manhattan assumption), so we discard non-horizontal and non-vertical lines with a criteria indicating the slope of line, denoted as $S$. We abandon those lines with $S$ less than a predefined threshold $\tau$ (0.0875 in our experiment, which means any line segment deviate more than 5° away from vertical and horizontal directions will be removed). Then the remainder lines which are nearby to each other (two pixels away on the orthogonal direction in our experiment), will be marked as a group of similar line segments.

\[
S = \begin{cases} 
|y_{\text{end}} - y_{\text{start}}| & |x_{\text{end}} - x_{\text{start}}| \\
|x_{\text{end}} - x_{\text{start}}| & |y_{\text{end}} - y_{\text{start}}| \\
|y_{\text{end}} - y_{\text{start}}| & |x_{\text{end}} - x_{\text{start}}|
\end{cases}
\]  

(2)

At the second step, a non-maximum suppression process is used to find the correct position and length of line segments. For each group of similar lines, we calculate the image gradient along the orthogonal direction of each line. Then a scan process is started along the direction of similar lines on each possible position, the pixels’ gradient value is accumulated within each scan line, the maximum absolute value of accumulation is assigned as the accurate position of the combined line. At last, we seek the point of intersection of all determined lines, and link the intersecting points on horizontal and vertical directions to construct a complete wire-frame model. The element reconstruction results of each processing step is shown in Figure 4. Figure 4(a) shows the result of line segment detection. Different colors indicate lines in different tile clusters, and the red lines do not belong to any cluster. In Figure 4(b), lines belong to the same cluster are mapping to a unified reference coordinate system and overlap together. Then in Figure 4(c), the overlapping lines are swept by a two-step strategy. Figure 4(d) shows the reconstructed wire-frame models of corresponding 4 tile clusters.

The wire-frame model of each element is then arranged on facade image according to the coordinates determined in section 3.2 (Figure 5).

4. CONCLUSION AND FUTURE WORK

In this paper, we have presented an automatic approach for the recognition and reconstruction of building facade elements from oblique aerial images. Our approach recognizes the facade elements via repetitive structure detection. A hierarchical image splitting and similarity detection method is proposed to partition complex facade. Supposing similar image structures belong to the same facade element, we propose a joint modelling method.
to reconstruct all repetitive structures to a uniform geometric element. Our approach is robust to low resolution, weak texture and noise. And the experiment shows that this method is effective to reconstruct complex facade models containing multiple elements.

However, due to our method partitions facade based on image gradient information, it may fail to distinguish wall and facade element if they have similar gradient. Therefore, further enhancement should be taken in future by introducing more high-level knowledge and constraints.

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