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# SGM-based seamline determination for urban orthophoto mosaicking

Shiyan Pang [a,b], Mingwei Sun [a,*], Xiangyun Hu [a,b], Zuxun Zhang [a]

[a] School of Remote Sensing and Information Engineering, 129 Luoyu Road, Wuhan University, Wuhan 430079, Hubei Province, China
[b] Collaborative Innovation Center of Geospatial Technology, Wuhan University, Wuhan 430079, Hubei Province, China

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ABSTRACT

Mosaicking is a key step in the production of digital orthophoto maps (DOMs), especially for large-scale urban orthophotos. During this step, manual intervention is commonly involved to avoid the case where the seamline crosses obvious objects (e.g., buildings), which causes geometric discontinuities on the DOMs. How to guide the seamline to avoid crossing obvious objects has become a popular topic in the field of photogrammetry and remote sensing. Thus, a new semi-global matching (SGM)-based method to guide seamline determination is proposed for urban orthophoto mosaicking in this study, which can greatly eliminate geometric discontinuities. The approximate epipolar geometry of the orthophoto pairs is first derived and proven, and the approximate epipolar image pair is then generated by rotating the two orthorectified images according to the parallax direction. A SGM algorithm is applied to their overlaps to obtain the corresponding pixel-wise disparity. According to a predefined disparity threshold, the overlap area is identified as the obstacle and non-obstacle areas. For the non-obstacle regions, Hilditch thinning algorithm is used to obtain the skeleton line, followed by Dijkstra's algorithm to search for the optimal path on the skeleton network as the seamline between two orthophotos. A whole seamline network is constructed based on the strip information recorded in flight. In the experimental section, the approximate epipolar geometric theory of the orthophoto is first analyzed and verified, and the effectiveness of the proposed method is then validated by comparing its results with the results of the geometry-based, OrthoVista, and orthoimage elevation synchronous model (OESM)-based methods.


## 1. Introduction

In the field of photogrammetry, rectified aerial images are usually stitched into a large image, and then cut into maps with a standard format. In the orthophoto mosaicking process, geometric and radiometric discontinuities are inevitably generated along the seamline in most cases (Soille, 2006). The radiometric discontinuities around the seamline can be minimized or corrected by methods proposed by Chandelier and Martinoty (2009) and Pan et al. (2010), but this is beyond the scope of this study. This study aims to avoid geometric discontinuities along the seamline.

For seamline optimization, Milgram (1975) initially selected the "best" seam points for each line by selecting the minimum gray difference between overlaps within a specified region; the resulting artificial edge at the seam point was locally smoothed. Subsequently, Yang et al. (1989) put forward a two-dimensional seam point search method that can considerably smooth artificial edges. Thereafter, Fernandez et al. (1998) presented a bottleneck shortest path algorithm for seam-based mosaicking of aerial photographic maps, which still takes the absolute value of the pixel-value difference as the cost. To further optimize the bottleneck shortest path, a greedy random adaptive search procedure (GRASP) was proposed by Fernandez and Mart (1999). Considering that the dissimilarity of the images is shown in terms of color and texture, Kerschner (2001) proposed a twin-snake model for selecting an optimal path with the lowest difference in a combination of colors and textures. A similar method can be found in Ai et al. (2011). Meanwhile, Soille (2006) developed an image compositing algorithm based on a mathematical morphology and its marker-controlled segmentation paradigm to position seams along salient image structures to diminish visibility in the output mosaic. Zhao et al. (2013) detected an optimal seamline along the boundaries of land cover objects by incorporating the watershed segmentation and the Dijkstra shortest path algorithm. Chon et al. (2010) presented a seamline selection method based on limiting the level of maximum difference and Dijkstra's algorithm with normalized cross correlation as the cost. Pan et al. (2014) first determined

* Corresponding author. Tel.: +86 13607144988; fax: +86 02768778010.
*E-mail address:* Mingweis@whu.edu.cn (M. Sun).

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the preferred regions according to the span of the segmented regions obtained by meanshift segmentation. Dijkstra's algorithm in differential cost was then adopted to achieve pixel-level optimization in the seamline selection. In addition, gray correlation (Zhang et al., 2009), image gradient (Pan and Wang, 2011), combination of appearance similarity constraint (e.g., color, edge, and texture), location constraint, and saliency constraint (Yu et al., 2012) were also used as costs in the succeeding research.

With respect to the construction of a seamline network, Yang et al. (2011) proposed a seamline algorithm based on the bisector, which can be applied to complex polygons and multiple images. By introducing the AVDO (area Voronoi diagrams with overlap) concept, Pan et al. (2009) presented a global-based seamline network generation method. Based on this method, Mills and McLeod (2013) carried out further research and proposed a method for optimal vertex placement for seamline network generation.

Considering that relying solely on the spectral information and its derived information (e.g., the gray difference, image gradient, edge, texture, normalized correlation coefficient, and saliency) on the overlap region as the cost for seamline selection, the case where the seamline is across the building object in the textureless region still exists. In recent years, seamline optimization algorithms that use external data have been proposed. Wan et al. (2013) presented a seamline generation method using vector roads. In this method, vector roads are overlaid with the extracted skeleton to build a weighted graph; the Floyd–Warshall algorithm is then applied to find the lowest cost path. A similar method can be found in Wan et al. (2012). The significant difference between the two is that Wan et al. (2012) used the Dijkstra's algorithm as the seamline optimization method. Ma and Sun (2011) proposed seamline finding for orthophoto mosaicking with LiDAR point clouds. In this method, Voronoi diagrams were adopted to generate the initial seamlines of the whole area. An improved $A^*$ algorithm was used to automatically make the seamlines avoid the identified obstacles by delineating black holes from filtered point clouds. To resolve the inconsistencies between the DSM and the orthophoto, Chen et al. (2014) proposed an orthoimage elevation synchronous model (OESM)-based seamline network generation method for urban orthophoto mosaicking using a digital surface model. In this method, OESM was first obtained by DSM and DTM; Dijkstra's algorithm was then used to obtain the seamline of two images, followed by the generation of a seamline network. The seamline optimization algorithm using the external data obtained better results. However, in most cases, no external data are available for mosaicking, significantly limiting the practicality of such methods.

Traditional orthophotos are obtained through the orthorectification technology using digital terrain model (DTM) and the orientation elements of the image. Any objects above the ground (e.g., buildings, trees) not included in the DTM are displaced perspectively. To avoid the seamlines from cutting these differently displaced objects, especially buildings in urban areas, our research approach to guide seamline determination has been initiated. In this paper, the areas with geometric differences in the overlapping orthorectified images are referred to as the obstacle areas.

Given the breakthrough of dense matching technology, the semi-global dense matching method (SGM) (Hirschmüller, 2008; Hirschmüller and Scharstein, 2009), as one of the most popular dense matching algorithms, can effectively overcome the effect of the shaded and texture-less areas. In addition, this method uses mutual information (MI) as similarity measurement, making it insensitive to deformation of image radiation, and allowing it to robustly and effectively obtain per-pixel disparity of the image pair. During the SGM process of the adjacent orthophotos, objects with different relief displacements show different values on the disparity image. Therefore, disparity information can be used to detect areas with relief displacements on the orthophoto, namely, obstacle areas, and then guide the seamline to avoid crossing these areas. Based on this idea, the current study presents a seamline optimization algorithm based on SGM. First, the approximate epipolar geometric relationship between the orthophotos is derived and proven. The approximate epipolar image pair is generated by two different methods for two different cases, where the elements of the exterior orientation are known and unknown. Second, the SGM algorithm is applied to the overlap of the approximate epipolar image pair to obtain its corresponding pixel-wise disparity. The disparity image is divided into obstacle and non-obstacle areas by setting the disparity threshold. Next, the Dijkstra shortest path method is used to obtain the seamline of the two orthophotos based on the detection of the obstacle area. Finally, a seamline network is sequentially generated for all orthophotos according to the strip information recorded in flight.

The main contribution of this paper lies in the following two aspects: (1) deriving and proving the approximate epipolar geometric theory of the orthophotos and (2) introducing SGM to detect the obstacle area, which can effectively avoid seamlines from crossing obvious objects on the DOMs.

This paper is organized as follows: Section 2 describes the proposed SGM-based seamline determination algorithm, where Section 2.1 is the derivation and proof of the approximate epipolar geometric theory of the orthophoto. Section 2.2 presents the detection of the obstacle area for both cases where the elements with exterior orientation are known and unknown. Section 2.3 introduces the construction of the seamline network of the orthophoto. Section 3 presents the experiments and the discussion, followed by the summary in Section 4.

## 2. Seamline determination based on semi-global dense matching

Obvious objects (e.g., buildings and trees) appear at different locations on the overlapping orthorectified images (Kerschner, 2001). In the disparity map, these objects correspond to areas with larger disparity. In this section, the SGM algorithm is used to obtain the disparity map of two orthophotos because the algorithm can obtain the per-pixel disparity values of two images. To obtain the disparity map using the SGM algorithm, the vertical parallax of the orthoimages must be removed by rotating the two orthorectified images; the rotating angle can be computed by their photogrammetric baseline. The consistency of the parallax direction of two orthophotos with the direction of their photogrammetric baseline is proven in the following sections. After detecting the obstacle areas (e.g., buildings and trees) on the orthorectified images, the Dijkstra shortest path method is used to obtain the seamline between the two orthophotos, followed by the construction of a seamline network for the whole project based on the strip information recorded in flight. Details of these specific principles and implementation process are provided in the subsequent sections.

### 2.1. Approximate epipolar geometric theory of the orthophoto

Assuming that the DTM around the object $P$ is a horizontal plane $E$, as shown in Fig. 1, where $S_1$ and $S_2$ are the projection centers of the two images, $H_1$ and $H_2$ are the flying heights of the images relative to $E$, $h$ is the height of the object $P$, $N_1$ and $N_2$ are the projection points of $S_1$ and $S_2$ on the horizontal plane $E$, $P_0$ is the projection point of $P$ on the horizontal plane $E$, and $P_1$ is the intersection of the ray $PS_1$ and the horizontal plane $E$, $P_1$ represents the position of the object $P$ on the orthorectified image and $P_2$ is similar as $P_1$ based on the orthorectification principle.