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A graph-based optimization algorithm for fragmented image reassembly

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ABSTRACT

We propose a graph-based optimization framework for automatic 2D image fragment reassembly. First, we compute the potential matching between each pair of the image fragments based on their geometry and color. After that, a novel multi-piece matching algorithm is proposed to reassemble the overall image fragments. Finally, the reassembly result is refined by applying the graph optimization algorithm. We perform experiments to evaluate our algorithm on multiple torn real-world images, and demonstrate the robustness of this new assembly framework outperforms the existing algorithms in both reassembly accuracy (in handling accumulated pairwise matching error) and robustness (in handling small image fragments).

1. Introduction

Fragmented image reassembly recomposes a group of picture fragments into the original complete image. It is a geometric processing problem that has important applications in many fields such as archaeology and forensics. For example, archaeologists need to spend a lot of efforts to recompose fractured ancient paintings to restore their original appearances; forensic specialists manually compose damaged documents or pictures to recover the original evidence that are broken by humans. Developing robust geometric algorithms for automatic image reassembly can reduce the expensive human labors and improve the restoration efficiency, and hence is highly desirable.

Existing automatic reassembly algorithms can be generally divided into two categories: color-based approaches and geometry-based approaches. Color-based methods mainly use the color information to predict the adjacency relationship of the fragments and guide the matching [1–3]. These algorithms are usually efficient, but they sometimes suffer from composition accuracy and may fail when the textures of different fragments are similar. Geometry-based methods reassemble the fragments by matching their boundary curves [4–7]. They can more accurately align adjacent fragments along their breaking regions, but they are sometimes slow and can easily get trapped in local optima then fail to reach the correct result. Therefore, incorporating both the geometry and color information in the reassembly computation could make process more efficient, accurate, and reliable. This paper presents a novel 3-step composition algorithm, as illustrated in Fig. 1.

1.1. Pairwise matching

The first step is called the pairwise matching, which aims to identify adjacent pairs and compute their initial alignments. Geometry-based pairwise matching methods rely on analyzing the shape of the boundary curve contours; color-based pairwise matching methods match fragments using their color information. Our integrated algorithm (1) extracts the border of each fragment and represents it as a curve contour, (2) clusters such a curve contour into multiple segments based on both color and geometry, and (3) matches contour segments to suggest

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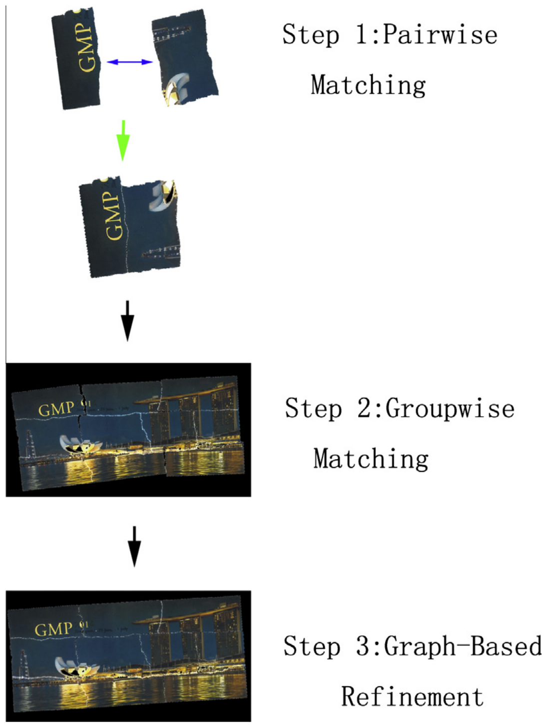

Fig. 1. The pipeline of our 3-step reassembly algorithm.

the potential alignment between adjacent fragments. This *pairwise matching* algorithm will result in a set of possible matching between identified pairs of fragments, some of which are correct while some are not.

1.2. Groupwise matching

The pairwise matching produces redundant matches, which we intentionally generate in order to tolerate erroneous adjacency identification due to noise and local minima. A global groupwise matching can better filter out these false matches. Extensive examination of this is a combinatorial optimization problem and is NP-hard. Many previous works use a best-first search strategy (i.e., to explore a graph by expanding the most promising node) with backtracking to solve this problem. In our work, the global composition is formulated as a novel graph-based searching problem, solving which will give us a more reliable global reassembly of multiple fragments.

1.3. Composition refinement via graph optimization

Groupwise matching can compose the fragments globally. However, the result is dependent on the composition sequence, and the alignment errors will be accumulated which may even cause a failure in the reassembly (i.e., fragment intersection, see Section 6 for details). We derive a graph optimization algorithm to reduce the global matching errors between adjacent fragments.

The main contributions of this work are as follows:

1. We integrate both geometry and color information in pairwise matching computation to obtain more reliable alignment between adjacent fragments.
2. We propose a graph-based algorithm that performs groupwise matching to better handle the errors resulted from pairwise alignments and obtain correct adjacency information of all the fragments.
3. We develop a variational graph optimization in the end to reduce the accumulated errors to refine the reassembly and achieve a global optimal result.

2. Related work

2.1. Local pairwise matching

The essence of fragment reassembly is to find the relative transformations between adjacent fragments. In the procedure of 2D images composition, fragments can be modeled and aligned using their boundaries, which are 2D curve contours. Therefore, pairwise matching often reduces to a partial curve matching problem, which is mainly solved in existing literatures via either geometry-based or color-based approaches.

Wolfson [8] approximates the curves as the polygonal shapes and solves their matching by finding the longest common substring, through a geometric hashing. This algorithm is fast and effectively employed in many puzzle solving methods. However, this algorithm may fail in many cases such as when the boundary of the image fragments are damaged, thus is inadequate for solving general image reassembly problem. Kong and Kimia [4] resample the boundary curves by a polygonal approximation, then compute a coarse alignment by dynamic programming, finally, use a dynamic programming again to obtain the fine-scale alignment. In [5], the authors calculate the curvatures of each curve and use a dynamic programming algorithm to match the curvature. However, since computing the curvatures reduces to the second order derivative, this method is sensitive to noise. In [6], the local shape features of the curves are extracted and matched to introduce the local reconstruction. In [7], a shape feature, referred to as the turning function, is estimated for each boundary curves and used to discover the matching of fragment pairs.

The texture or color information of the image fragments is another useful clue in computing local pairwise matching. In [1], the authors try to calculate the pairwise matching by finding the largest common substring with the similar color and curvature information. Their algorithm mainly focuses on the pairwise matching. In [2], the color/texture features are extracted and an FFT-based registration algorithm is utilized to find the alignment of the fragment pieces. In [3], color histograms are calculated to identify the adjacency of the fragment pairs and a Smith–Waterman algorithm is proposed to discover the matching contour segments of the adjacent images.

After local pairwise matching, a matching score is assigned to each pair of matched fragments. Higher score indicates better alignment given certain matching criteria. A widely used registration techniques called Iterative Closest Point (ICP) [9] can then be performed to further refine the alignment. Alternatively, many variants of ICP [10]

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