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Introducing locally affine-invariance constraints into lunar surface image correspondence

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ABSTRACT

This paper aims to solve the keypoint correspondence problem in lunar surface images, a typical correspondence task under point ambiguity. Point ambiguity may be caused by repetitive patterns, cluttered scenes, and outliers in the images, which makes the local descriptors less discriminative. In this paper we introduce locally affine-invariance constraints on graphs to tackle the keypoint correspondence problem under point ambiguity. The key idea is that each point can be represented with the affine combination of its neighbors. It is suitable for our problem because it is not only invariant to scale and rotational change, but also more resistant to outliers. Specifically, we introduce the locally affine-invariance constraints into the subgraph matching problem and the common subgraph matching problem. The locally affine-invariance constraint is not directly applicable on common subgraph matching due to its dependency on awareness of selected keypoints. This problem is approximately addressed by solving a series of reliable matching identification and rematching problems. In the experiments, we first apply the proposed method on standard graph matching datasets to evaluate its effectiveness on general correspondence problem under point ambiguity, and second validate the applicability on the lunar surface image dataset.

1. Introduction

In many computer vision tasks, such as image stitching [1], 3D reconstruction [2] and object detection [3,4], one of the core steps is to establish reliable correspondence of points between two images. Local descriptor based point correspondence methods may be the most popular methods, especially when equipmented with scale and rotation invariant local descriptors [5]. However, under some circumstances such as the lunar surface, there are various factors that make the point matching problem difficult. The first factor is repetitive patterns which may confuse matches. Secondly, outliers may exist in both point sets that have no corresponding points in the other. Both factors make the points ambiguous in the matching problem. Matching under point ambiguity frequently arises in planetary image analysis [6] and cluttered scenes [7,8].

Matching under point ambiguity calls for constraint on the mapping. To tackle this problem, many existing point matching algorithms model keypoint matching problem as a graph matching problem and utilize geometrical constraint on the mapping. Distance and orientation are the most commonly used features for enforcing geometric consistency [9–11]. However they are sensitive to scale, orientation, and outliers [12]. To make the constraint invariant to scale and orientation change, high order affinities have been utilized. Triplets similarity is used in [13], and [14] uses a tensor-based algorithm to solve the high order correspondence problem. Unfortunately, these methods usually require higher computational and space complexity. The graph matching based scheme is first utilized to deal with the lunar surface image keypoint correspondence problem in [6]. It formulates the correspondence problem as subgraph matching problem and adopts a probabilistic graph matching algorithm. The assignment probability is ranked to find specified number of best assignments. Such a two-step scheme may be inappropriate because even both steps are optimally solved, the final matching solution may not be the optimal [15].

In this paper, to tackle the task of lunar surface keypoint correspondence, an effective constraint, i.e., locally affine-invariance constraint, is introduced into the graph matching framework. The locally affine-invariance constraint is robust against repeated patterns, affine transformation, and outliers while does not incur higher computational complexity. The optimization is NP-hard. It is efficiently solved with a novel path-following based algorithm.

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The three main contributions are: (1) the locally affine-invariance constraint is introduced into graph based lunar surface image keypoint correspondence problem, and a novel objective function is constructed such that the similarity of corresponding points local structure is preserved and the dependency on local feature is further alleviated, (2) a novel path following algorithm is generalized to solve the optimization problem and a normalization process is proposed to regulate both the balance between pairwise and locally affine costs, and the optimization process, (3) to tackle the inapplicability of locally affine-invariance constraint on common subgraph matching problem due to the dependency on the awareness of selected nodes in the correspondence, an algorithm is proposed which iteratively identifies reliable matches and solve rematching problem with affine representation cost built upon the reliable matches.

The remainder of this paper is organized as follows. Related works are introduced in Section 2. Then the common subgraph model of the lunar surface image correspondence problem is built in Section 3. The locally affine-invariance constraint based matching algorithm is introduced in Section 4. Experiments are reported in Section 5 and Section 6 concludes the paper.

2. Related works

Two groups of correspondence algorithms, appearance descriptor based correspondence and graph matching based correspondence, are reviewed below. In particular, we focus on the papers which cope with ambiguous matches and outliers.

2.1. Appearance descriptor based correspondence

Key point correspondence can be solved by using a set of local interest points. Scale-invariant feature transformation (SIFT) [5] is a frequently used appearance descriptor for key point correspondence. It has been shown to be invariant to rotation and scale, and robust to local geometrical distortion. Other popular descriptors include speeded up robust features (SURF) [16], maximally stable extremal regions (MSER) [17], binary robust invariant scalable keypoints (BRISK) [18], and etc. Though local features are often effective for many key point correspondence problems, they often fail to cope with outliers and ambiguous patterns. An improvement strategy is the NN-ratio decision criterion which computes the ratio between the distance to the closest neighbor in the feature space and the distance to the second-closest one [5], and considers the matching to be ambiguous if the ratio of the closest distance to the second closet distance is large. The algorithm [19] improved the SIFT feature with global context to cope with the ambiguity caused by repetitive patterns. However, although these works have improved the performance of appearance descriptor, relying on local features alone is usually insufficient for key point matching in complex circumstances.

2.2. Graph matching based correspondence

Incorporating local pairwise geometrical constraints is an effective way to improve the performance of appearance descriptor based algorithms. When pairwise constraints such as distance and orientation are used, the key point correspondence problem can be formulated as a graph matching problem. However, the problem is known to be NP-hard, and therefore many approximate matching algorithms have been proposed as introduced below [20,21].

Spectral matching is an efficient approach for graph matching. The eigen-decomposition method proposed in [22] is known to be the first spectral graph matching method. It can solve the matching of two equal sized graphs with limited robustness. Another popular approach using pairwise constraint is spectral matching [9]. Specifically, the affinity matrix $\mathbf{A}$ is constructed based on unary and pairwise similarity, then the graph matching problem is approximated with the rank one approximation of $\mathbf{A}$, and solved with spectral method. Works that improve on spectral matching include reweighted random walk matching [23], balanced graph matching [24], probabilistic graph matching [13]. Graduated assignment [25] solves a series of one-order Taylor series approximation of the original objective function with power iteration followed by soft-assign operator. The soft-assign operator is controlled by a controlling parameter which pushes the result to a final discrete solution.

One drawback of the spectral method is that the matching problem is solved with a two-step scheme, i.e., the problem is first approximately solved in continuous domain and then projected back to discrete domain. In contrast, a path following algorithm is proposed in [26] by constructing a sequence of relaxation of the original optimization problem. Each relaxation is solved using the result of the previous as initialization and result is pushed to discrete solution in a gradual manner. Thus the constraints are employed more effectively. This path following algorithm is further improved in [15,27,28]. Ref. [29] also naturally imposes the discrete mapping constraint in the optimizing process by employing L_1 norm of the solution. An iterative approach is proposed to return an approximate discrete solution that sufficiently satisfies the constraint.

Besides pairwise constraints, other spatial relations are also used. If nonrigid deformation is present, the pairwise feature may not be preserved, especially for severe scale changes and deformation [30]. Other local geometrical constraints show better robustness such as the ones used in [30–32,4]. The binary quantized distance is used to represent the symmetric neighborhood relationship in [30]. This representation can be better preserved under scale change compared with absolute distance. Similar neighborhood preservation assumption is adopted in [31]. The outlying matches that disrupt the relationship are iteratively eliminated to derive two isomorphic neighborhood graphs in two images. Ref. [32] uses cyclic string edit distance to compute the difference of local spatial order of a correspondence, and designs a filtering strategy to rule out matches that give rise to large local spatial disorder. Local embedding is another powerful tool to describe local geometrical structure. One of the original works on local embedding is the locally linear embedding (LLE) [33] in the unsupervised learning field. The idea behind this method is to reconstruct each point with the linear combination of its k neighbors. The idea is generalized to graph matching problem in [4] by constraining the linear combination to locally affine representation, which is invariant to scale, translation and affine transformation. The l_1 norm of the representation error is then used as objective function of a subgraph matching problem in an object detection application, which is solved in a linear programming framework.

3. Graph matching model for lunar surface correspondence

The key points to be matched are extracted from the lunar surface images (SIFT is used in this paper). The key points in each image are modeled as a graph $\mathcal{G} = \{V, E\}$, where V is the vertex set with each vertex denoting a keypoint in the image and E is the edge set. Each edge carries a weight vector denoted as $w(ij)$ with $(ij) \in E$.

For a pair of lunar images, graphs are constructed as $\mathcal{G}^1 = \{V^1, E^1\}$ and $\mathcal{G}^2 = \{V^2, E^2\}$ with $|V^1| = M$ and $|V^2| = N$. It is assumed that $M \le N$ without loss of generality. We denote the vertex coordinate matrices of V^1 and V^2 as $\mathbf{P} = [\mathbf{p}_1, \dots, \mathbf{p}_M]^T \in \mathcal{R}^{M \times 2}$ and $\mathbf{Q} =$