Complex Correspondences in Straight Line Stereo Matching

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Abstract Partial occlusion and fragmented lines will result in the various cases of straight line correspondences, such as one-to-one, one-to-many or many-to-many ones. However, the complex correspondences, such as one-to-many and many-to-many ones, are usually ignored or cannot be established completely in the existing methods. Here, the essence of the complex correspondences will be analyzed. Based on the two characteristics of a straight line, which are introduced by regarding a straight line as a set of collinear points, the compatibility between the complex correspondences and the uniqueness constraint of point correspondence is proved and a new uniqueness constraint of correspondence for matching lines is proposed. Based on the analysis of the complex correspondences, a new concept of line feature group is defined to describe a set of integral correspondences among straight line features from different images and then a new algorithm for establishing all the correspondences completely is described simply. The experimental results with real stereo images illustrate that the complex correspondences among straight lines are actual cases and can be established effectively.

Keywords straight line; stereo matching; occlusion; fragmentation; complex correspondence; uniqueness constraint; feature group

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Introduction

Stereo matching based on features is one of the basic problems studied for a long time in computer vision and photogrammetry, which is devoted to establishing correspondences between the features extracted from different images of a scene viewed from different viewpoints. Straight lines are the primary descriptors in the artificial scene and straight line stereo matching is met in various fields such as 3-D reconstruction, 3-D object recognition and 3-D motion tracking, etc. Many methods were proposed to attempt solving the problem of straight line stereo matching. First, with calibrated images the epipolar constraint is employed to reduce 2-D search space to 1-D [1-3], besides which maximal disparity range [4] and the photometric similarity [5] are also employed commonly. Second, various binary constraints are employed, such as uniqueness, gradient of disparity, or...
dering and topology, etc., by which the match pool size can be further pruned [6–8]. Third, the hierarchical schemes are proposed to improve the matching correctness by means of richer information of straight line groups consisting of multiple straight lines [3,4]. In addition, if multiple images of the same scene viewed from various viewpoints were usable, the trilinear constraint or the quadrilinear constraint is used to disambiguate the potential correspondences [5,9].

However, from a large number of existing literatures, it can be found that there are few methods announcing that the straight line correspondence problems had been solved effectively under the appearance of partial occlusion and fragmented straight lines. It is one primary trouble that the projection of one 3-D straight line may be probably segmented into two or more parts, which would invoke more complex correspondences than one-to-one ones, such as one-to-many and many-to-many correspondences.

To solve such problems, some methods grouping straight lines before matching were proposed. Horaud [1] described a method for grouping straight lines by means of topological relation consistence of straight lines between two images. Kim [2] and Noronha [4] employed a hierarchical perceptual grouping strategy. Both methods allow establishing one-to-many or many-to-many correspondences among fragmented straight lines. Demirci [10] presented a matching algorithm that could establish many-to-many correspondences between the nodes of two noisy, vertex-labeled weighted graphs. This algorithm does not aim at one special type of features. Shapiro [11] explored the problem of many-to-many correspondence for region matching. However, for the problem of matching straight lines, the method how to define the relationships between straight lines is critical and the relationships among them in various images probably vary, especially for wide-view stereo images. The two algorithms above do not apply to matching line directly.

Based on the analysis for complex correspondences in section 1 and the applicability of uniqueness constraint in the problem of straight line stereo matching in section 2, this paper will propose a new concept of straight line feature group and devote a new algorithm in section 3 for establishing various correspondences completely, where the complex correspondences would be included, among straight lines extracted from the stereo images. In section 4 the algorithm of straight line stereo matching proposed in this paper will be applied on the real stereo images. Lastly, some conclusions are given.

In the following, for the sake of convenience, a straight line extracted from an image is abbreviated to a line if no special announcement is proposed.

1 Complex correspondence in line stereo matching

1.1 The complex correspondence

The complex correspondences to establish in this paper are considered as correspondences between two line sets other than between individual lines, in which one line of one line set is allowed corresponding to more than one line of the other line set. Some existing methods based on line groups also announced that they could establish the aforementioned one-to-many and many-to-many correspondences. Such methods can broadly fall into two categories. First, lines are grouped into some specified 2-D geometry shapes according to the topological relationships between them, and then the line groups in one image are assigned to another line group in other images. The line groups usually contain richer matching information than individual lines, so matching line groups can acquire more support to reduce the uncertainty of correspondences. It seems that the methods can build the complex correspondences; however, any individual line in the line groups corresponds to no more than one line, as is resulted from the uniqueness constraint for individual lines. Second, correspondences for fragmented lines are considered. If multiple adjacent collinear lines were considered as different parts of the same projection of a 3-D line, they would be treated as an integrality to match other lines. The established one-to-many or many-to-many correspondences by these methods are real complex correspondences. However, grouping lines in one image is unstable and furthermore it cannot solve the badly worse fragmentation and the complex correspondences with noncollinear lines that will be introduced in the subsequent section.
1.2 Why complex correspondences exist

The one-to-one correspondence is most common in feature matching problems and then most existing feature matching methods consider the uniqueness constraints as effective means to eliminate the incompatibility among various feature correspondence hypotheses. The uniqueness constraint is true for point features or some area features, whereas it may be violated in the problem of line stereo matching. The violation is brought out by two factors. One is partial occlusion in projecting 3-D lines and the other is fragmented lines resulting from nonideal line extracting. The two factors will be analyzed in detail as follows.

1.2.1 Partial occlusion

The occlusion from other spatial objects or self-occlusion will result in partial or complete loss of the lines in images, which will weaken the strength of the similarity between corresponding lines and break up the one-to-one correspondence between them. The influence of partial occlusion usually falls into two categories.

1) The rupture of the projection of a 3-D line

Suppose that the interior of a 3-D line were occluded in one camera, its projection onto this camera would be divided into two or more parts, which would usually be regarded as individual projections.

2) The combination of the projections of two or more 3-D lines

According to the theory of perspective projection, the conjoined noncollinear 3-D lines in the same plane that passes through the optical center of one camera will be projected into one 2-D line in the corresponding image, while the 2-D lines in the other image are noncollinear. It is shown in Fig.1 that $O_1$ and $O_2$ are the optical centers of left and right cameras respectively and the left image and the right image are denoted by $I_1$ and $I_2$, respectively. $L_1$, $L_2$, and $L_3$ are 3-D lines. The 2-D lines in $I_1$ and $I_2$ are their projections, and the dashed lines are the projective ray from their endpoints. In Fig.1 (a), a one-to-many correspondence is present, in which $L_1'$ namely the common projection onto $I_1$ of $L_1$, $L_2$, and $L_3$, corresponds to the three lines such as $L_1'$, $L_2'$ and $L_3'$, namely the individual projections onto $I_2$ of $L_1$, $L_2$ and $L_3$ respectively. In Fig.1 (b) a many-to-many correspondence is present, in which $L_1$, the common projection onto $I_1$ of $L_1$ and $L_2$, and $L_1''$, the projection onto $I_2$ of $L_1$ and $L_2$, correspond to $L_2'$, the projection onto $I_2$ of $L_3$, and $L_3'$, the common projection onto $I_2$ of $L_2$ and $L_3$.

![Fig.1 Combination of the projections of two or more 3-D lines](image)

1.2.2 Fragmented lines

Idealistically the lines extracted from images are consistent with the projections of the 3-D lines, namely projective lines. However, the images may be probably disturbed by noise so that the projective lines cannot be extracted integrally and correctly with any existing line extracting algorithm. It is possible that an individual projective line is extracted into more than one segment, and furthermore the results extracted from various images may differentiate with each other probably. Consequently the one-to-many and many-to-many correspondences are imaginable.

2 Uniqueness constraint vs. complex correspondence

2.1 Characteristics of a line

In the existing line stereo matching methods, lines
are regarded as the match elements, namely they are indivisible. Actually, a line can be considered as a set of collinear points and then it possess two characteristics such as being extensible and being divisible. Because all the points in a line are collinear, the points that are invisible due to partial occlusion or fragmentation can be estimated by extending the visible points directly, as is defined by being extensible. By the characteristic of being extensible the loss of a line from occlusion or fragmentation would be complemented by means of the corresponding line in another image. This is the reason that by means of line matching the reconstructed 3-D lines are more complete than their projections in any image. In addition, a line is considered as a point set and then it can be divided into two or more subsets of the set, which correspond to different parts of the line. These parts are connected together, although they seem separate. This is the characteristic of being divisible, which is often ignored.

2.2 Applicability of uniqueness constraints in line stereo matching

Uniqueness constraint is an effective binary constraint to disambiguate correspondence hypotheses in feature matching. It is based on the supposition that the features to match were indivisible elements and then not more than one feature corresponds to one feature. However, according to the aforementioned characteristic of a line being indivisible, the uniqueness constraint for lines sometimes is violated, as has been proved in section 1.2.

The existing application of the uniqueness constraint in line stereo matching was motivated by the uniqueness constraint of point features correspondence in stereo matching. The uniqueness of point features correspondence is determined by visibility of the 3-D points in various images and is satisfied when the 3-D object is nontransparent. Consequently, a line as a point set is considered satisfying the uniqueness constraint naturally. If the correspondence between two lines is considered as a transform between two point sets, it usually can be regarded as a one-to-one map only from a subset of one point set to a subset of the other point set other than from one integral point set to the other integral point set. It is more reason-
A line feature group is a nonempty set of lines both in the image $I_1$ and the image $I_2$, which satisfies the following properties:

1) Correspondence. For any line in the image $I_1$ ($I_2$), the set must contain not less than one of its corresponding lines in the image $I_2$ ($I_1$).

2) Compatibility. Any two lines in the image $I_1$ ($I_2$) do not intersect with any same epipolar line in the image $I_2$ ($I_1$) simultaneously.

3) Integrity. For any line, the set must contain all its corresponding lines.

4) Continuity. If the set is arbitrarily split into two non-overlapped non-empty subsets, there is no less than one line in any set such that its corresponding lines are contained in the other subset.

From the above definition, it can be seen that all the lines in a line feature group form an integral correspondence and may include more than two lines possibly because that an imaginable complex correspondence is no longer the one-to-one relationship. In our algorithm, a line feature group will be an element to describe a correspondence instead of a match pair composed of two lines. In any line feature group the correspondence among lines is definite, so if only all the line feature groups are acquired exactly, all the correspondences among lines in various images can be established.

On the basis of the concept of a line feature group, a new algorithm for establishing various correspondences completely is proposed. The steps of the proposed algorithm are simply listed as follows. The detail will be described in another paper because of the limited length in this paper.

1) To build all potential line match pairs between any two lines of various images and measure the strength of every correspondence according to some constraints such as epipolar constraint, similar photometry characteristic, etc.

2) To generate all line feature group hypotheses using the potential line match pairs according to the properties of the compatibility, integrity and continuity of a line feature group. A relationship graph is built, in which nodes are the potential line match pairs and in which an edge is set up between any two nodes if the lines in the two nodes are compatible and contain a common line. Therefore, it can be proved that based on the given correspondence hypotheses from the potential line match pairs the maximal cliques of the graph satisfy all the properties of a line feature group and the line set in every maximal clique is regarded as a line feature group hypothesis.

3) To choose the optimal line feature group hypotheses. First, the stability of every line feature group is measured. Second, according to the uniqueness constraint, the compatibility relationships between any two line feature group hypotheses are built. If two hypotheses do not contain any common line, they are determined compatible, otherwise incompatible. Lastly, the set of hypotheses are chosen as the optimal ones if they are compatible with each other and their integrated stability measure has a maximum value.

4) To determine correspondences between any two lines according to the optimal line group hypotheses.

### 4 Experimental results

In this section, we present experimental results from two pairs of real stereo images, where the first pair of images is close-range images and the second pair of images is aerial images. We applied the stereo matching algorithm just described on them. For convenience of computation, all the images are arranged in the horizontal epipolar lines, and for convenience of publication, all the images are zoomed. The algorithm based on Kalman filtering proposed by Wen[12] is employed to extract lines from the images (lines shorter than 15 pixels are filtered out). In all the images illustrating line matching results, the black lines, red lines, blue lines and green lines describe, respectively, the unmatched lines, one-to-one correspondence, one-to-many correspondence, and many-to-many correspondence. The lines denoted by one same number reside in one line feature group.

Fig.2(a) and 2(b) show a pair of close-range stereo images overlapped with the extracted lines from them. The images, which have the size of 600×400, are acquired by a stereo camera in an office. In the two views, partial occlusion is very noticeable and the disparity range is large. In the results shown in Fig.2 (c) and 2(d), 94 sets of correspondences are obtained, in which there are 13 sets of one-to-many correspon-
dences, and 10 sets of many-to-many correspondences, most of which arise from the fragmented lines. The 51st and 52nd line feature groups illustrate the many-to-many correspondences due to partial occlusion, while the 19th and 24th line feature groups illustrate the one-to-many and many-to-many correspondences among the extracted lines similarly with the case in Fig. 1(a).

Fig. 2  The match case for close-range stereo images.

In aerial remote sensing images occlusions usually appear only in areas containing dense buildings with considerably different heights. When occlusion between different buildings is absent, the self-occlusion of the buildings becomes the primary problem. In Fig.3(a) and 3(b) a pair of joined buildings’ stereo images is used to test our algorithm. The images are provided by ETH Zurich, which have the size of 340 ×320 and are acquired by a camera mounted on a helicopter in Zurich. In the result shown in Fig.3(c) and 3(d), the 19th line feature group is a many-to-many case arising from self-occlusion, which is similar with the case in Fig. 1(a). In a scene including the buildings with gable roofs, similar cases usually appear. Except for the 19th line feature group, the remaining one-to-many correspondence cases arise from fragmented lines, such as the 3rd, 5th, 20th, 52nd and 54th line feature group, etc. By the method just mentioned, the correspondences are acquired correctly and completely. The process of lines stereo matching is usually followed by reconstructing the 3D structure. To acquire the complete and correct 3D information, the correct ratio and complete ratio of the matched lines should be treated equally. However, the complete ratio is usually ignored in the existing evaluation methods. In Table 1, the “Line number” describes the number of lines extracted from the left and right image and the “true match number” describes the number of lines whose corresponding lines are extracted partially or completely in the other image, which is given by manual search. The content from the 4th column to the last column shows the performance of our algorithm, which describes respectively the number of all matched lines, the number matched correctly, the number matched falsely, and the number missed. The “Correct ratio” is equal to the ratio of the “Correct number” divided by the “Match number by our algorithm”, and the “Complete ratio” is equal to the ratio of the “Correct number” to the “True match number”.

(a) Left image

(b) Right image

(c) Left lines matched

(d) Right lines matched
Here no other line matching algorithms are realized to compare with our algorithm. From the above results we can see that the complex correspondence is real, while no algorithm but ours claims that it dedicates itself to solving this problem. Therefore, in the experimental results, we illustrate better performance of our algorithm by distinguishing different cases of correspondence with different colors. The capability for building the complex correspondence argues explicitly that our algorithm is valuable.

In the process of choosing optimal line feature groups, we employ a greedy algorithm to search a wholly optimal solution, which adds up the computational cost remarkably. On a PC with 1.7 GHz CPU and 1 GB RAM, the experiment on the aerial images spends 4.6 seconds and the other experiment on the close-range images spends more than 2 minutes. This cost is beyond most similar algorithms. A conclusion can be drawn that the time in the process of grouping lines is trivial, while most time is spent on the optimization. In future research we shall employ a more effective optimization algorithm to make the whole process of matching lines faster.
5 Conclusion

We proposed the concept of the complex correspondence in line stereo matching and analyzed its causation. To discover the essential relationship between the complex correspondences and the uniqueness constraint of correspondence, the characteristics of a line, namely being extensible and being divisible, are analyzed by regarding a line as a set of collinear points. Based on the new understanding with a line, a new uniqueness constraint of correspondence for matching lines is defined and an algorithm is simply introduced. It can be seen from the experimental results that the complex correspondences among lines are actual cases and the lines involved in them are usually critical for describing the shape of an object. The complex correspondences should be paid more attention to in the subsequent line stereo matching algorithms.

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