Fast Area-Based Stereo Algorithm

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Abstract

Area-based stereo algorithms, as the most universal of all stereovision methods, have the potential to become widely used in many industrial sectors, but their relatively low speed halt the usage. This paper describes the method which can significantly increase computing speed. This new method is called false epipolar constraint. It is an addition to epipolar constraint which can reduce the set of possible corresponding points from whole image to single line [3]. False epipolar constraint in combination with epipolar constraint is able to reduce even this set. This method is most efficient in area-based stereo algorithms but it can be used in any application, where the epipolar constraint is used.

Keywords: epipolar, stereo, computer vision

1 Introduction

Stereovision is the part of computer vision inspired by nature. All higher life forms have two eyes to perceive and navigate in the 3D world. We can assume that the same can be done by computers. Thanks to the recent fast progress in digital camera technology, we have an appropriate input. All we need is an efficient algorithm. In the simplest model, we have two pictures of the same scene taken from the different positions and we want to extract as much 3D information as possible from them.

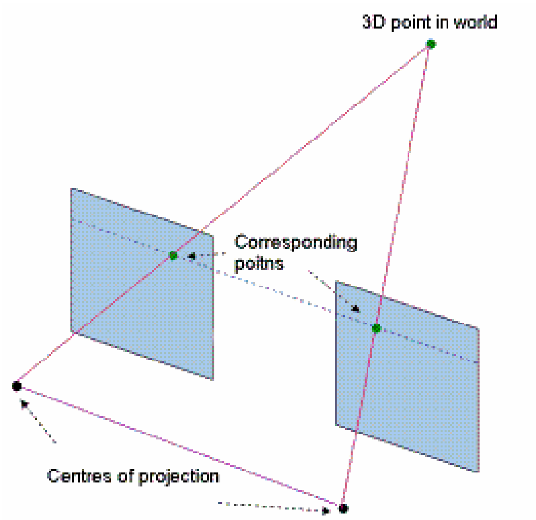

Figure 1: Corresponding points as projections of a 3D point into the stereo pictures.

This information can be retrieved from the different positions of the corresponding points in images (see Figure 1). The essential task is to find the corresponding points. This is the critical phase of all stereo algorithms because the highest possible speed and accuracy is often required. The aim of this paper is to speed up the process of corresponding points detection. Also the accuracy of the process is slightly increased. Up to now several methods have been introduced to increase the speed of the area-based algorithms [3][4][5]. None of them is significantly related to this method, but most of them can be used together with this method to further speed up the algorithms.

2 Area-based stereo algorithms

Since corresponding points are the images of the same real point in the taken scene projected into both pictures, we can assume that their surroundings in both pictures will be quite similar. Area-based methods use this similarity for corresponding points detection [5]. It is computed from the difference in local neighborhoods (usually a constant size square) of the points. Computing the similarity of two points is the elementary step in the method and cannot be speeded-up. The main question is where to look for the corresponding point in the picture. The naive area-based algorithm chooses a point from the first image, and run through all the points in the second image to find its corresponding point. To accelerate this inefficient process, some constraints can be applied to tell the algorithm, where to search for the corresponding point.

The most efficient method is inferred from the Epipolar Geometry and is called accordingly, the epipolar constraint. For stereo pictures there is a unique matrix called a fundamental matrix [4]. When F is the fundamental 3x3 matrix, the equation

$$\mathbf{x}^T F \mathbf{x'} = 0$$

is valid for every corresponding points **x** from the first image and **x'** point from the second image. The projective coordinates **x**=(x, y, 1) and **x'**=(x', y', 1) of image points are used. The epipolar constraint derived from this equation imply that for each point **x** from the first image there is an epipolar line given by equation $\mathbf{x}^T F=0$ in second image. The corresponding point to **x - x'** is located on it [2]. Thanks to this constraint, we don't need to search whole picture for corresponding point, we can look for it just on the epipolar line.

3 False Epipolar Constraint

A new constraint as an addition to the epipolar constraint will be presented in this section. Thanks to this method, the provable area on epipolar line with corresponding point can be highlighted. The area can differ from 1/3 to 1/10 size of the original epipolar line. As a result, algorithm does not need to search for corresponding point on the whole epipolar line but only on this smaller section. Obviously this can speed-up whole process significantly and increase the accuracy because some incorrect correspondences may be eliminated from the searching area.

3.1 Method Realization

The method is based on the existence of so-called False Fundamental Matrices. While correct fundamental matrix should be computed from accurate corresponding points, false fundamental matrixes are computed from error input deliberately. They can be computed by the method commonly used for numerical computation of fundamental matrix known from epipolar geometry. The 8-point algorithm proposed by Longued-Higgins in 1981 [6] can be modified to compute false fundamental matrices. In my work 9-point modification was used. The structure of the original algorithm [1]:

1) As an input we have 9 pairs of corresponding points already detected in the pictures.

2) Equation $\mathbf{x}^T F \mathbf{x'}=0$ can be rewritten as:

   $x'xf_{11}+x'yf_{12}+x'f_{13}+y'xf_{21}+y'yf_{22}+y'f_{23}+x f_{31}+yf_{32}+f_{33}=0$

   where **x**=(x,y,1) ; **x'**=(x',y',1) are the projective coordinates of corresponding points and $F=(f_{ij})_{i,j=1..3}$ is the fundamental matrix.

3) After substituting all 9 corresponding points into this equation, we will get 9 equations with 9 unknown variables.

4) Solving this system (by SVD-decomposition for example [7]) will lead to fundamental matrix.

To get a false fundamental matrix, we have to do only simple input modification. We must change the coordinates of all 9 original points

$\mathbf{x}=(x, y, 1)$ to $\mathbf{x}_\varepsilon=(x+\varepsilon_1, y+\varepsilon_2, 1)$

and their corresponding points

$\mathbf{x'}=(x',y',1)$ to $\mathbf{x'}_\varepsilon=(x'+\varepsilon'_1, y'+\varepsilon'_2, 1)$

where ε_1, ε_2, ε'_1, ε'_2 are relative small numbers dependent on picture resolution. We can consider to bound ε_1, ε_2, ε'_1, ε'_2 in intervals described in Table 1.

Resolution	Interval
640x480	<-1, 1>
800x600	<-1.5, 1.5>
1024x768	<-2, 2>
1280x1024	<-2.3, 2.3>

Table 1: Interval – resolution dependencies for corresponding point changes.

It is important that for each point these variables are different and are distributed through the interval uniformly. The simplest way is to choose the variables randomly from the interval. Another solution is to predefine these variables, or design a function to compute them. Example of one possible function:

$$\varepsilon_1 = \cos(2\pi / 9 * i)*d$$
$$\varepsilon_2 = \sin(2\pi / 9 * i)*d$$
$$\varepsilon'_1 = \cos(2\pi / 9 * i + \pi/2)*d$$
$$\varepsilon'_2 = \sin(2\pi / 9 * i + \pi/2)*d$$

where ε_1, ε_2, ε'_1, ε'_2 are the modification variables for i^{th} point (i=1..9). Variable d is the highest bound of interval described in Table 1.

Algorithm with this input modification will compute false fundamental matrix F' (fundamental matrix with slightly changed input). This matrix has some important properties:

1) Corresponding point for **x** should be located near false epipolar line given by equation $\mathbf{x}^T F'=0$.

2) False epipolar line should have different direction than the original epipolar line.

From these two properties, we can see that the corresponding point should be located near the intersection of both lines (see Figure 2). This intersection can define an area in epipolar line, where we can search for corresponding point. Size of the area depends on current task or algorithm requirements. By increasing the area size the reliability of algorithm is raising but also the computing time.

Figure 2: A light line is the epipolar line and a dark one is the false epipolar line. The corresponding point is located near their intersection.

3.2 Method Extension

The critical question is: How far the corresponding point is located from the epipolar lines intersection? In most cases it is only few pixels far away, but there are usually some specific areas in the image, where intersection is more distant from the point. Existence and location of these areas is caused by the selection of particular nine points for matrix computation, but it is hard to predict these areas just from this selection. Another problem appears when the false epipolar line and the original epipolar have similar directions. Corresponding point is always located in some distance from false epipolar line. As the angle of false epipolar line with correct epipolar line is decreasing (lines are becoming parallel), this distance is causing intersection moving away from the correct corresponding point. The best solution for these problems is to apply more false fundamental matrices at once. Some degrees of freedom were added using the algorithm from previous chapter – in computing the variables ε_1, ε_2, ε'_1, ε'_2. Different methods or functions can be used to compute these variables. Several different matrices can be computed this way from the same set of points so that no additional data are required for this extension. More matrices will guarantee a greater chance that at least one of the intersections is located near the corresponding point. We can also eliminate false epipolar lines which are in a low angle with original epipolar line. During the testing 5 - 10 false fundamental matrices proved to be sufficient to solve the problems. The algorithm was modified to find a left-most and a right-most intersection of the false epipolar lines with the epipolar line. These two boundaries will give us interval, where the corresponding point could be located (see Figure 3). The interval can be increased by some fraction to prevent any omission of the corresponding point. Intersection of a single false epipolar line with the "correct" epipolar line is either on the left or on the right side from the corresponding point. Let's consider that it is on the left side. This matrix was computed thanks to ε_1, ε_2, ε'_1, ε'_2 parameters modification to corresponding points as described in the previous section. False fundamental matrix computed by using negated parameters: $-\varepsilon_1$, $-\varepsilon_2$, $-\varepsilon'_1$, $-\varepsilon'_2$ generates epipolar lines intersection on the other side (right side). Corresponding point should be located between these intersections. This assumption is valid in the majority of the picture area, but there can be some specific locations where the intersections are on the same side. Therefore the use of more false fundamental matrices can increase the reliability. Unfortunately, there still can be present some areas with corresponding points pinpointed incorrectly in the picture, as described in section 5 (False Epipolar Constraint as Week Constraint). Possible solutions are described in section 6 (Future Work).

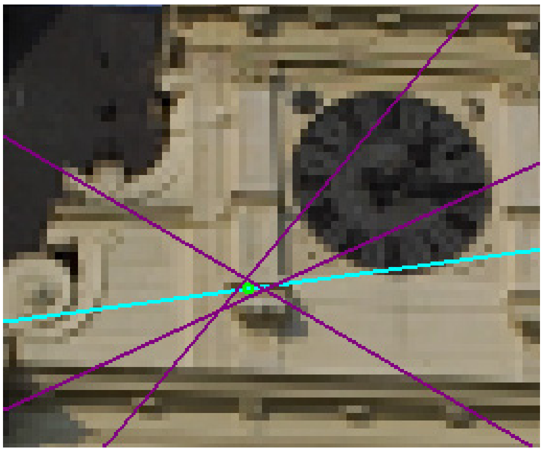

Figure 3: Three dark lines represent three false fundamental matrices used together. Light corresponding point is located between leftmost and rightmost intersection.

4 Testing Results

For testing purposes a simple area-based algorithm was implemented. This algorithm is able to compute similarity of two locations from intensity values of local point's neighborhood. Two pictures and relevant fundamental matrix are required as an input. If the matrix is missing, algorithm can compute it from nine points together with false fundamental matrices. User is able to select whether he wants to use epipolar constraint and false epipolar constraint for corresponding points detection. Also the method extensions described in previous section were implemented.

The aim of the experiment was to compare the speed of corresponding points detection while using the epipolar constraint and the speed of detection with addition of the false epipolar constrain.

Resolution	EC [s]	EC+FEC [s]
400x300	15	10
800x600	31	11
1200x900	59	13
1600x1200	97	16

Table 2: Time needed for detecting 500 corresponding points is recorded. EC - only epipolar constraint was used; EC+FEC - results of using additional false epipolar constraint is displayed, both for different image resolutions. (tested on Athlon 2000+, 512 MB RAM)

As we can see in Table 2, speed increases significantly when false epipolar constraint is used for high resolution images. The computational acceleration is based on points set reduction. About 0.95% of the second image area has to be searched for corresponding point when only epipolar constraint is used. With false epipolar constraint, it is only about 0.08% of picture. This reduction is so big, that the dependency of algorithm speed and the image resolution becomes insignificant.
The speed of algorithm is slightly dependent on the number of used false fundamental matrices. The more matrices are used, the larger is the searching interval. This dependency is displayed in Table 3.

Number of matrices	5	6	7	8	9
Searching area size (% of picture)	0.071	0.076	0.079	0.080	0.081

Table 3: Dependency of average searching area and number of false fundamental matrices.

It is also obvious that the reliability of successful point detection is increased by false epipolar constraint. However this property is hard to test, as it is varying case to case. For example when there are many similar objects on the picture, reliability can increase considerably. (see Figure 4).

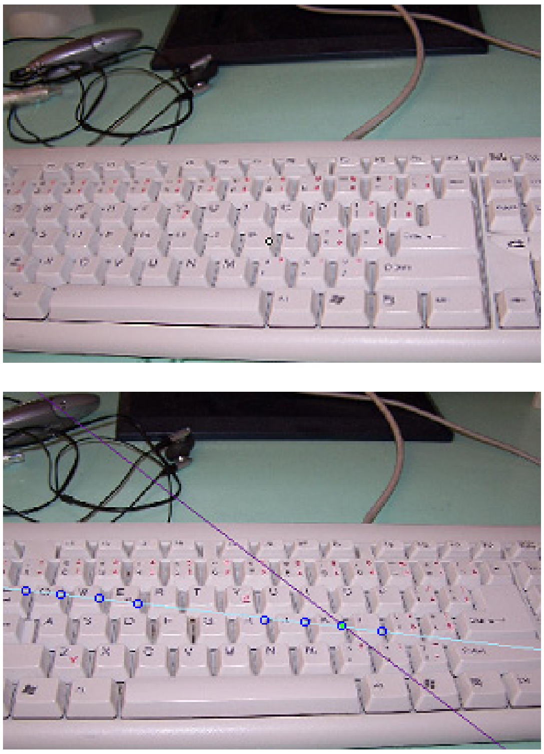

Figure 4: A light epipolar line is running through many similar locations in this picture (marked in circles). Usually this can cause incorrect detection, but false epipolar constraint was used here to pinpoint correct location (dark line).

5 False Epipolar Constraint as Weak Constraint

Even after method's extensions, which increase the reliability of algorithm, false epipolar constraint should be considered as weak constraint (it is not always valid). The assumption that we can pinpoint the location of corresponding point will ultimately fail in cases when the positions of points adjacent in first image are too discontinuous in second image. (see Figure 5). False epipolar lines intersections on epipolar line for these points will remain continuous in second picture and will be close just to one location. As a result, all points in one of these locations will have pinpointing intersection in other (incorrect) location, thus will not be detected correctly. Which location will be pinpointed depends on the set of 9 points, form which the false fundamental matrix was computed. This problem can be possibly solved or avoided in the future. It occurs only when objects are relatively close to both cameras. Up to now it restricts the usage of the method to near-baseline stereo with cameras close to each other. Increasing the searching area on epipolar line will also solve this problem because the larger area will reach both locations.

Figure 5:
Points in the border of two objects marked in first picture have too discontinuous correspondences (marked in second picture as two circles). Intersection will be only inside one of these locations for points from both objects.

6 Future Work

False epipolar constraint has a potential to become a practical method useful in many stereovision algorithms. The first program, in which this method was used is described in section 4 (Testing Results) and the method extensions were consequently derived during the testing. With extended usage of this method another modification could be implemented. One of them could be the solution of the weak constraint problem described in previous chapter. As mentioned before, the location of intersection is dependent on the set of 9 points. This problem can be avoided by computing multiple false fundamental matrices, each from a different set of points. This modification can possibly solve most cases, but as a result, the computing time will increase, because the searching area in epipolar line will be more extensive.
Focus of this paper is on area-based algorithms. It should be noted, that false epipolar constraint can be used in any algorithm, which uses also epipolar constrain. For example, the feature-based algorithms are using epipolar constraint to match corresponding points or to discover incorrect correspondences. False epipolar constraint can improve both speed and accuracy of these tasks.

7 Conclusion

When the false epipolar constraint is used properly, it can significantly speed up the corresponding point detection algorithm. This method allows the area-based stereo algorithm to run several times faster then before and with increased accuracy. I believe that also this constraint can be one of the methods that will help the stereo algorithms to become the most universal and widely used distance measuring method.

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