Passive Stereo Matching Algorithms -A Review

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Abstract

Binocular stereo vision is an important measurement method widely used in the field of machine vision, which has the advantages of high precision, simple structure, high measurement efficiency and non-contact. The main task of binocular stereo vision is to get two images of the same scene by two cameras in different positions, then get the initial disparity map via stereo matching, and finally optimize the previous disparity map. Starting from the background and research significance of stereo matching technology, this paper first introduces the basic principle of binocular stereo vision, then explains the four steps of stereo matching. And finally reviews the research status and existing problems of passive stereo matching algorithms.

Keywords

Stereo Vision; Stereo Matching; Adaptive Support Window; Disparity Optimization.

1. Introduction

Vision is an important means for human beings to observe and understand the world. About 75% of the information obtained from the outside world comes from the visual system [1]. Through vision, human beings can perceive the size, light and shade, color and other characteristics of external objects, and obtain a large amount of information from a small amount of information in the relevant environment. With the development of digital technology, human beings can obtain images from the surrounding environment through mobile phones, cameras, cameras and other devices. However, how to make the machine simulate human eyes to further process and analyze the collected image information, and identify and measure the target objects is a challenging research direction in the field of machine vision.

Binocular stereo vision is an important form of machine vision. It uses two cameras to obtain the left and right images of the measured object from different views, and obtains the three-dimensional geometric information of the object by calculating the position deviation between the corresponding points of the image, which is called disparity. The three-dimensional information obtained by this method has the advantages of simple structure, low cost and non-contact. Traditional binocular stereo vision system includes four steps: image acquisition, camera calibration, stereo matching and 3D reconstruction. Stereo matching is to find the matching point of each pixel from the left and right image pairs, and finally get the disparity map with strong reliability and high accuracy. The quality of the disparity map directly affects the results of the subsequent three-dimensional reconstruction, so stereo matching is the core content of binocular stereo vision research, and the research of stereo matching is very important for many visual applications.

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2. Basic principle of stereo vision

2.1 Disparity constraints

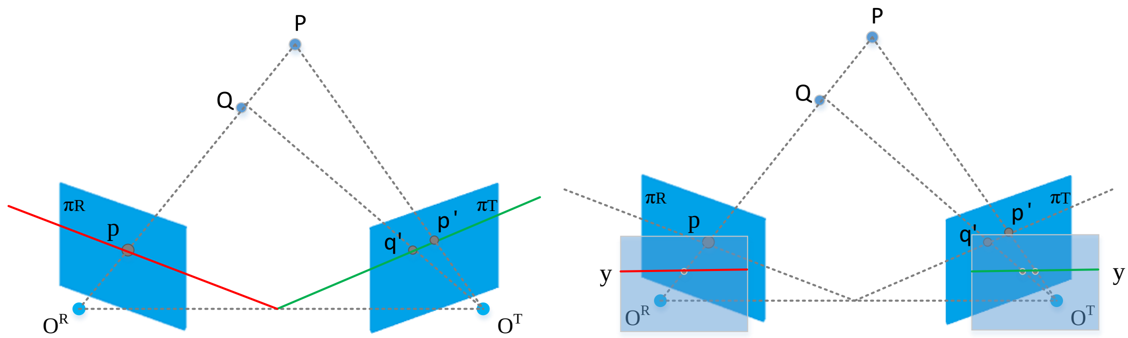
Stereo matching is a process that the camera takes images of the same object at different angles, and then uses the principle of triangle measurement to establish a direct disparity relationship between the left and right images to get the disparity map. Dense disparity map is the basis of subsequent three-dimensional reconstruction. In order to increase the accuracy of stereo matching, researchers put forward a variety of constraint assumptions.

(1) Epipolar constraint: the polar plane is the plane where the object and the centers of two cameras are located. The polar line is the intersection of the polar plane and two images. The epipolar constraint describes that the projection points on the two images must be on the same core plane.

(2) Uniqueness constraint: in order to avoid one to many matching and many to one matching, there is only one correspondence point in the reference image.

(3) Sequence consistency constraint: according to the geometric characteristics of opaque objects, the points on the three-dimensional space object are mapped to the two-dimensional plane, and the points on the reference image and the target image are arranged on the epipolar line in the same order.

As shown in Figure 1 (a), the point P is the object to be measured, the projection of P on the plane π R and π t is the point P and P ′, the plane composed of P, or and OT is the polar plane of point P, and the intersection line of plane π R, π T and the polar plane is the polar line, as shown by the red and green line segments in the figure. If we want to get the distance between P point and plane π R or π T, we need to determine the projection P and P 'of P point on two planes, and measure the distance between or and OT, the focal length of camera used for shooting, parameters and other data. When the epipolar equation is determined, the calculation range of the corresponding point of P is simplified from two-dimensional plane to epipolar line segment. In practical calculation, the stereo matching model is often idealized. As shown in Figure 1 (b), plane π R and π T are abstracted as two identical parallel cameras. Based on the constraint assumption of stereo matching, the position information of the point on the object P will not change in the order of mapping to plane π R and π T, and there is only one matching point corresponding to point P in the target image, Then the calculation of disparity is transformed into the difference between the abscissa of two points of the search point and its matching point.



(a) (b)

Figure 1. Diagram of stereo matching

2.2 Three-dimensional reconstruction via trigonometry

Binocular stereo vision is to imitate the human method of using binocular perception distance, by analyzing the two-dimensional images of the same object taken from different angles, calculate the three-dimensional depth information of the object. Different from the human eye in the same horizontal line to observe the object, the camera used to shoot binocular stereo matching image can be two cameras placed at an appropriate angle to shoot, or the same camera can shoot twice at different angles.

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The measurement model of stereo matching consists of two cameras keeping the polar lines parallel, and the optical axes of the two cameras are required to be parallel. As Figure 2 shows, suppose that the internal parameters of the two cameras are the same and the focal length is f, the projection and coordinates of P on the left and right planes are respectively and, the distance between the optical centers of the two cameras is the baseline distance b, and the depth of point P is Z.According to the triangle similarity principle, we can get the following conclusions:

$$\frac{B}{Z} = \frac{(B+x_R)-x_L}{Z-f} \tag{1}$$

It is further simplified as follows:

$$Z = \frac{B \cdot f}{x_L - x_R} \tag{2}$$

$$Z = \frac{B \cdot f}{d} \tag{3}$$

where $x_L - x_R$ is the disparity d. After the disparity of each pixel is obtained, the disparity map of the whole reference image can be obtained, and then the depth information of the object to be measured can be recovered. Therefore, it is a key step in stereo matching to get the matching points of the pixels in the reference image in the target image.

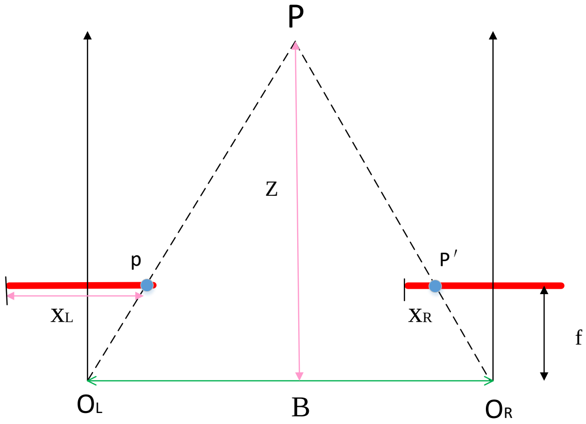
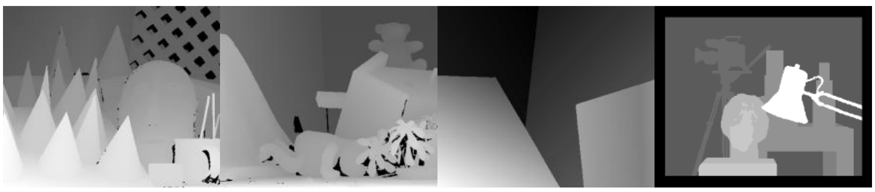


Figure 2. Three-dimensional reconstruction model via stereo matching

(a) Reference image

(b) Target truths



(c) Ground truths

Figure 3. Middlebury image pairs and standard disparity maps

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2.3 Evaluation criteria of stereo matching result

In order to evaluate various stereo matching algorithms, the images in Middlebury image library [4] are generally used to verify the effectiveness of the algorithm at home and abroad. These image pairs have been epipolar corrected, and the standard disparity map is provided to compare with the disparity map of the algorithm, so as to objectively evaluate the efficiency of stereo matching algorithm. Figure 3 shows the left and right image pairs and standard disparity map of cones, Teddy, Venus and Tsukuba.

In order to compare the matching results of algorithms quantitatively, the commonly used index is the mismatch rate, which is defined as follows:

$$P = \frac{1}{N}\sum_{(x,y)}(|d_C(x,y) - d_T(x,y)| > \delta) \tag{4}$$

Among them, N represents the total number of pixels in the matched image, $d_C(x,y)$ represents the theoretical disparity value of (x,y) the pixel obtained by some algorithm, $d_T(x,y)$ represents the real disparity value of (x,y) the pixel in the standard disparity map, and δ represents the allowable error range.

3. Passive stereo matching process

According to the conclusion of zechstein and Szeliski [5], local matching can be divided into four steps: matching cost calculation, matching cost aggregation, disparity selection and disparity optimization.

3.1 Cost calculation

The calculation of matching cost is to measure the similarity between the corresponding pixels of the reference image and the target image. The specific calculation method is as follows: firstly, taking the reference image as the benchmark, the target image moves a certain pixel every time on the corresponding horizontal epipolar, and stops when the moving range is equal to the maximum disparity search range. After the calculation, the difference between the matching image pairs is obtained, and the matching cost is the minimum The corresponding pixel is the corresponding pixel.

There are many methods to calculate matching cost, such as sum of absolute differences (SAD) [6], sum of squared differences (SSD) [7], zero mean sum of absolute differences (zsad), normalization cross correlation (NCC) [8,9], zero mean normalization cross correlation (ZNCC), etc.The formulas of common similarity evaluation functions are listed as follows:

(1) Sum of Absolute Differences(SAD)

$$C_{SAD}(x,y,d) = \sum_{x=-m}^{m}\sum_{y=-m}^{m}|I_L(x,y) - I_R(x',y')| \tag{5}$$

Where I_L is the left image, that is, the reference image, which I_R means the right image, that is, the target image. The size of the target window is (2m + 1) × (2m + 1), $I_L(x,y)$ and $I_R(x',y')$ represent the corresponding gray values in the reference sub area and the target sub area respectively.

(2) Sum of Squared Differences(SSD)

$$C_{SSD}(x,y,d) = \sum_{x=-m}^{m}\sum_{y=-m}^{m}|I_L(x,y) - I_R(x',y')|^2 \tag{6}$$

SSD algorithm has the same principle as SAD algorithm, but its similarity measurement formula is slightly different.

(3) Zero-mean Sum of Absolute Differences(ZSAD)

$$C_{ZSAD}(x,y,d) = \sum_{x=-m}^{m}\sum_{y=-m}^{m}|(I_L(x,y) - \bar{I}_L(x,y)) - (I_R(x',y') - \bar{I}_R(x',y'))|^2 \tag{7}$$

Compared with SAD algorithm, ZSAD algorithm eliminates the influence of gray mean value, so the robustness of the algorithm is higher than sad, and the disparity image is better than sad because it retains more details.

(4) Normalization Cross-correlation(NCC)

$$C_{NCC}(x,y,d) = \frac{\sum_{x=-m}^{m}\sum_{y=-m}^{m}[I_L(x,y)I_R(x\prime,y\prime)]}{\sqrt{\sum_{x=-m}^{m}\sum_{y=-m}^{m}I_L{}^2(x,y)\cdot\sum_{x=-m}^{m}\sum_{y=-m}^{m}I_R{}^2(x\prime,y\prime)}} \tag{8}$$

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The advantage of NCC algorithm is that it has strong anti noise ability and high matching accuracy in the weak texture region with little gray change. The results of NCC are usually controlled in the range of [- 1,1].

(5) Zero-mean Normalization Cross-correlation(ZNCC)

$$C_{ZNCC}(x,y,d) = \frac{1}{\Delta f \Delta g} \sum_{x=-m}^{x=m} \sum_{y=-m}^{y=m} [\bar{I}_L(x,y) - I_L]\,[I_R(x',y') - \bar{I}_R] \tag{9}$$

Among them, $\Delta f = \sqrt{\sum_{x=-m}^{x=m} \sum_{y=-m}^{y=m} [I_L(x,y) - \bar{I}_L]^2}$ $\Delta g = \sqrt{\sum_{x=-m}^{x=m} \sum_{y=-m}^{y=m} [I_R(x,y) - \bar{I}_R]^2}$, $\bar{I}_L$ it represents the average gray level of all pixels in the reference window and $\bar{I}_R$ the average gray level of all pixels in the target window. Although the form of this function is quite different from NCC, its anti noise ability is the same as NCC.

Different matching cost calculation methods have their own characteristics, and the matching accuracy of images with different features is also different. Choosing an appropriate matching cost function for cost calculation is a key step in stereo matching.

3.2 Cost aggregation

In order to evaluate the similarity between two pixels based on the initial cost calculation, the pixels around the matching point are used to describe the pixels to be matched. Therefore, in the process of cost aggregation, how to reasonably use the information of the surrounding pixels is the key problem to be considered in this step. Common cost aggregation methods are window selection method [10] and adaptive weight method [11, 12].

Window selection method is divided into fixed window method and adaptive window method [13,14]. Fixed window is to determine the rectangular window to be matched by setting a fixed window radius. Because the pixels in the same window are not selected, the cost aggregation of pixels with different features will be introduced, which will affect the matching accuracy. Moreover, if the fixed window is too small, it will produce a large mismatch in the weak texture region, and if the fixed window is too large, it will produce a large mismatch in the disparity discontinuity region. In order to improve the matching accuracy of weak texture region and disparity discontinuity region, relevant researchers proposed adaptive window method, which mainly includes two ways: adaptively changing the length and width of rectangular window and window shape according to the information of surrounding pixels. For the pixels in the same matching window, the closer the pixels are to the center pixel, the higher the degree of similarity between the pixels and the center pixel, and the greater the degree of influence they have on the center pixel in the matching process. Giving different weights to the pixels with different degrees of influence can improve the matching accuracy [15, 16].

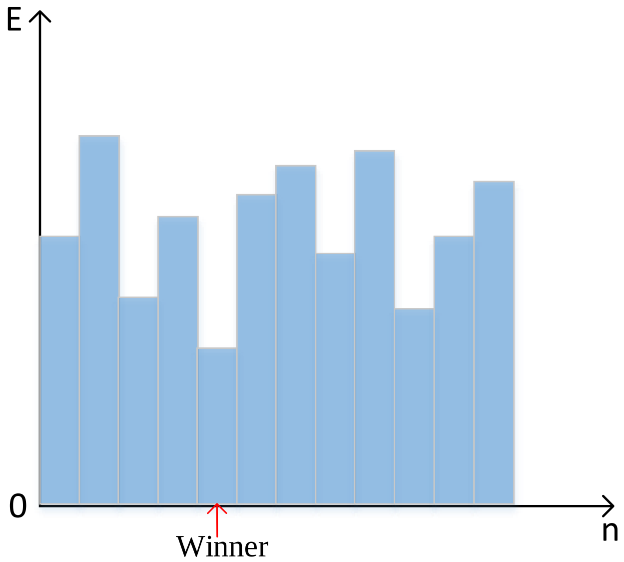

Figure 4. WTA diagram

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3.3 Disparity selection

After the above two steps, in order to obtain the disparity map, we also need to select the disparity. We usually use the strategy of (winner takes all, WTA) [17], and select the smallest generation value as the disparity value of a pixel among all the cost aggregation calculated by a pixel. Suppose the disparity range is 0 to n, $E_0, E_1 \dots E_n$ is the matching cost of a pixel in the range of difference, then the point where the minimum matching cost $E_\lambda(\lambda \in [0,n])$ is taken as the final matching point. The schematic diagram is shown in Figure 4:

3.4 Disparity optimization

The purpose of disparity optimization is to optimize the initial disparity image obtained in the previous step, and improve the quality of the disparity image by eliminating the wrong disparity value, so that the disparity value is more accurate and reliable. At present, left right is the most commonly used method to eliminate mismatches After the first stereo matching, the reference image and the target image are exchanged, that is, the target image becomes the reference image, the reference image becomes the target image, and then the stereo matching is performed again to get another disparity image. If the disparity value of the same pixel in the two matching is less than a certain threshold, the uniqueness constraint is satisfied, and it is retained, otherwise it is eliminated, The formula of left and right consistency check is as follows:

$$D_p = \begin{cases} D_{dp}, if|D_{LR} - D_{RL}| \le \delta \\ D_{invalid}, otherwise \end{cases} \tag{10}$$

Among them, D_p is the final disparity value, D_{LR} is the disparity result of the first stereo matching between the reference image and the target image, D_{RL} is the disparity result of the second stereo matching after the interchange of the reference image and the target image, δ is the threshold value. In addition to the left-right consistency check, iterative gradient descent and fitting a curve [18,19] and (locally consistent) methods are often used to improve the quality of disparity map.

4. Research status and problems of passive stereo matching algorithm

4.1 Global matching algorithm

Global matching mainly uses the global constraint information of the image to construct the global energy function, and then optimizes the global energy function to obtain the dense disparity map. The global energy function is expressed as follows:

$$E(d) = E(data) + E(smooth) \tag{11}$$

Among them, is the data item, which is used to judge the similarity between matched pixels, is the smoothing item, which is used to judge the continuity between adjacent pixels. Dynamic programming [20], graph cut [21] and confidence propagation algorithm [22] are representative global matching algorithms.

In 1992, the dynamic programming algorithm was proposed by belhumeur P.N [23]. Its essence is to find the minimum path on the corresponding scan line of the left and right images. The algorithm has high computational efficiency, but the mismatching of single pixel will affect the subsequent pixel matching, so the strip defect of dynamic programming has always been a concern. For this defect, many scholars have proposed different improved algorithms. In 2005, veksler et al. [24] aimed at the problem of vertical consistency in scan line search, in the matching process, dynamic programming was used to replace the traditional single scan line, and combined with tree structure. Experiments show that the algorithm has a good improvement in accuracy and computational efficiency. In 2008, Zhang Haofeng [25] and others proposed a stereo matching algorithm that combines dynamic programming with left-right consistency to eliminate the false matching points, and then get the final disparity map, which solves the problem of high false matching rate caused by dynamic programming to a certain extent.

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In order to overcome the problem of horizontal fringes in disparity map generated by dynamic programming algorithm, Roy [26] combined graph cut algorithm with stereo matching algorithm in 1998. Experiments show that the graph cut algorithm can effectively solve the problem of disparity discontinuity near the epipolar line of dynamic programming algorithm, but the disparity map generated by this algorithm has the problem of edge blur. Zhang Lingtao et al. [27] used the local algorithm as the prior value of graph cut method, deleted a large number of irrelevant points and edge values, and retained the disparity value in a certain range. The experimental results show that the algorithm can reduce the time consumption and ensure the quality of disparity map in the edge area. Li [28] et al. Proposed that the reference image be divided into non overlapping regions, and the minimum energy value of the segmented region is used to replace the minimum energy value of the pixel level of the traditional graph cut method. Experiments show that the algorithm has good matching effect in the disparity discontinuous region and the image boundary. Zhao Wenjie [29] used the results of image segmentation, combined with the initial disparity map and the mean filter, to assign the same disparity value to different regions. The experimental results show that the accuracy and calculation speed of disparity map have been greatly improved.

Belief propagation algorithm was first proposed by pearl in 1988. Since 1999, it has been widely used in various fields of computer vision to solve the optimization problem of graph structure with rings, and good results have been obtained [30]. In 2003, sun et al. [31] abstracted the stereo matching problem as three coupled Markov random fields (MRFs). After introducing two robust functions, the maximum a posteriori probability (map) of the Markov random fields was obtained by using Bayesian propagation algorithm (BP). Experiments show that the algorithm has good performance. Felzenszwalb et al. [32] in order to improve the speed of belief propagation algorithm and reduce the memory requirement of belief propagation, and use the multigrid method to iterate on a small amount of fixed information, the experiment shows that the speed of the algorithm has been greatly improved. Di Jin et al. [33] proposed a new Markov random field (MRF) method, using BP algorithm to infer model parameters. The experimental results show that the matching result of belief propagation algorithm is smoother than graph cut method, and the operation speed is faster. Liu Zhongyan [34] and others improved the matching based on single pixel, and realized the matching algorithm based on belief propagation by using the matching based on image block. The experiment shows that the algorithm has good matching effect, and the matching speed and accuracy are improved.

4.2 Local matching algorithm

Local matching algorithm is more and more concerned in recent years because of its fast matching speed, simple structure, mature algorithm and easy to realize. According to the different matching elements, the local matching algorithm can be divided into three-dimensional matching algorithm based on region, feature-based stereo matching algorithm and phase based stereo matching algorithm.

The focus of region based stereo matching algorithm is how to find the matching window in the right image according to the similarity condition. Kanade et al. [35] select the appropriate window size according to the local gray and disparity changes. Compared with the fixed window matching algorithm, the matching quality of this method has been improved to a certain extent, but the time efficiency of the optimal window selection is low. Zhou Xiuzhi et al. [36] improved the problem that the statistical error form of disparity range estimation in the algorithm proposed by Kanade et al. [35] is more complex. Experiments show that the algorithm has lower complexity and stronger adaptability. Zeng Zhifan et al. [37] proposed a new adaptive window matching algorithm using eight identical windows to select appropriate support regions in eight directions. Experiments show that the algorithm has good matching results in rich and weak texture regions.

In order to solve the problem that the region based matching algorithm is easily affected by illumination and occlusion, and the matching window is difficult to select, a feature-based stereo matching algorithm is proposed. The main work of the algorithm is to extract the point, line, edge and other features of the image, and then obtain the disparity value. Researchers at home and abroad have carried out a lot of research in this field. Moravec et al. [38] proposed the first method to

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calculate stereo matching directly by taking the gray value of pixels in different directions of pixel points as characteristic values. This method is called Moravec operator. Osman paraktuna[39] and others propose a stereo matching based on edge lines. Firstly, the edge lines are extracted from the left and right images, and the position, direction and position of the edge lines are used as the matching criteria for stereo matching. Liu Zhengdong et al. [40] in order to obtain high-precision disparity map, edge feature points are obtained by using the label set of disparity, and the feature points are introduced into the error function of radial basis function, which reduces the possibility of forming mis matching. In addition, some scholars combine a variety of feature points for stereo matching [41, 42].

Phase matching algorithm is a method proposed by schaffalizky et al. [43]. The core idea of this method is that the local phase between the matched pixels in the left and right views is equal. First, the local phase is selected as the matching element, and then the reasonable constraint conditions are added in turn for image matching. Common phase analysis methods include phase correlation method [44] and phase difference frequency method [45]. Phase based stereo matching algorithm has strong anti distortion and is insensitive to noise. It can better reflect the image structure and other information, and the processing speed is fast. However, it is difficult to find the equal phase points. Xu Yi et al. [46] proposed phase matching based on Wavelet and dynamic programming. Meng Yanqi et al. [47] proposed a sub-pixel phase stereo matching algorithm based on region segmentation to solve the problem of large measurement error caused by depth discontinuity and boundary shadow mismatch in binocular grating projection measurement. The algorithm reduces the average height relative error at the boundary shadow and depth discontinuity, and effectively improves the accuracy of phase stereo matching, which is of great significance to improve the accuracy of current 3D measurement technology.

5. Conclusion

The research of stereo matching technology has been developing for nearly 60 years. Stereo matching algorithm is also improving. However, it is still necessary to study how to improve the matching efficiency of weak texture region, how to obtain dense and reliable disparity map for high-resolution images, how to obtain disparity map quickly and accurately to make it work in scenes with high real-time requirements. In the future, we need to study the stereo matching algorithm from the following aspects:

(1) The efficiency and accuracy of occlusion, weak texture, no texture and disparity discontinuous region matching algorithm are improved. When shooting the same object from different angles, the two images will have different scenes, which will cause complex occlusion problems; most images have weak texture, no texture and discontinuous disparity area, which makes stereo matching difficult. How to improve the matching accuracy and efficiency of these areas is one of the problems that stereo matching should continue to study.

(2) Improve the stereo matching efficiency of high resolution image. With the continuous improvement of the performance of cameras, digital cameras, scanners and other equipment, the resolution of the images we get is also higher and higher, which puts forward new requirements for the accuracy, efficiency and reliability of stereo matching.

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