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A Surface Reconstruction Technique based on 3-D Triangulation Enhancement

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ABSTRACT

3-D reconstruction technique plays an important role in the applications for 3-D data acquisition, such as medical diagnosis, animation and virtual reality. Moreover, the 3-D triangulation process is one of the most important parts while reconstructing the smooth surface of a 3D object. The essential of 3-D triangulation is to find the intersection of the rays emitting from the correlated points on each image pair, but the emitting rays always don't intersect with each other owing to the error in process. So the obtained 3-D point is an approximated value and makes the reconstructed surface uneven. In the paper, we propose an triangulation enhancement method, which reduces the perturbation in the reconstructed data and filter out the error caused by spurious vectors in the process of correlation.

Keywords: 3-D geometry, correlation vector field, 3-D triangulation, multiply factor, 3-D stereo imaging system.

1. INTRODUCTION

The reconstruction of 3D object from stereo images has been widely investigated for various applications, such as medical diagnosis, virtual reality, and animation, etc. In the processes of reconstruction, 3D data are mainly determined by data correlation between two image frames and 3D triangulation from two correlated points. The correlation process is adopted to calculate the correspondence of data points of two image frames to generate correlated vector fields. According to the relation provided by the vector field, the triangulation process will produce 3D coordinates of an object. The concept of the technique is to restore the 3-D coordinates of an object by using the point correlation on two image frames and the extrinsic/intrinsic parameters[1]. The extrinsic parameters depict the location and orientation of the camera reference frame with respect to a world reference frame, whereas the intrinsic parameters describe the connection of the pixel coordinates of an image point and the corresponding coordinates in the camera reference frame. Whether the parameters are known or not, Trucco[1] classified the reconstruction problems into three cases: (1) intrinsic and extrinsic parameters are known, (2) only intrinsic parameters are known, and (3) no information on parameters. However, due to the error of correlation and calibration processes, it is still impossible to get a totally correct solution even if in case of (1). The phenomena of case(1) are the fundamental issue we should cope with. Our research aims to find an enhanced triangulation method, which could filter out the spurious vectors in the correlation vector field and reduce the 3-D error.

In Section 2, we describe the 3-D stereo imaging system based on the direct triangulation and an enhancement triangulation is proposed in section 3. Section 4 illustrates the experimental results and finally section 5 gives the conclusions.

2. 3-D STEREO IMAGING SYSTEM BASED ON DIRECT TRIANGULATION

2.1 Stereo imaging system

In the paper, a 3-D stereo imaging system with laser speckle projection is proposed to capture the stereo images and reconstruct the shape of a 3-D object(see Figure 1).

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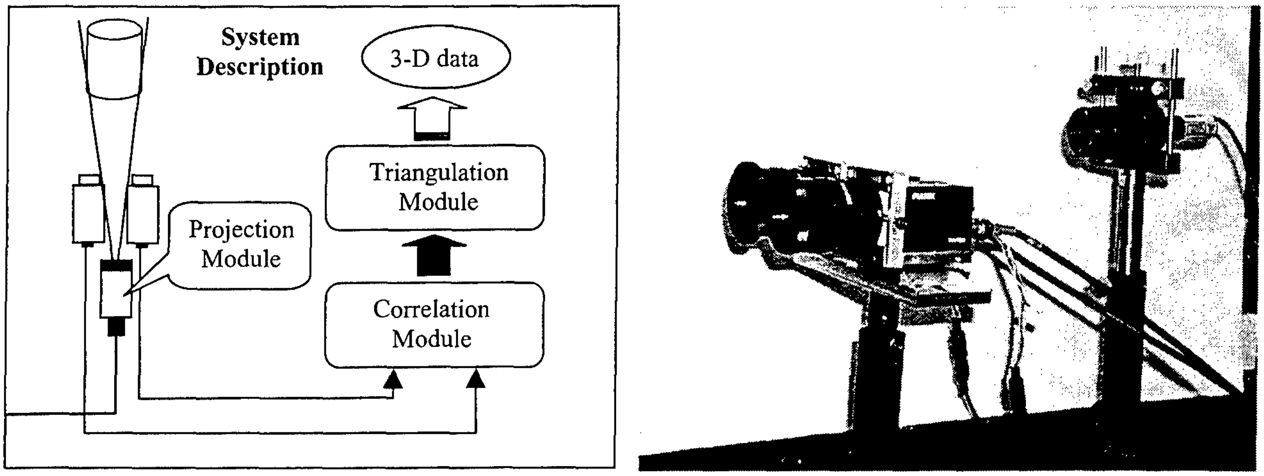


Figure 1 The 3-D stereo imaging system with laser speckle projection.

In the aspect of processing, a 3-D stereo imaging system contains three major modules: (1) projection module, (2) correlation module and (3) triangulation module. In the projection module, the randomized patterns are produced by letting laser beam pass through a diffuser and projected on the object surface, which provides the reference information for the correlation module. There are some criteria about how to select an appropriate speckle pattern for better correlation result([2]). Then, in correlation module, we compute the correlation by using the relation between the two image frames and build the correlation vector field, which describes the correlation of the points on left and right image frames. In order to get high speed processing, we adopt the method of compressed image correlation proposed by Hart([3], [4] and[5]). The method has been successfully applied to track the flow vectors in PIV images.

Finally, the triangulation module is adopted to calculate the 3-D coordinates from the vector field and reconstructs the 3-D object. The essential of triangulation module is to find the intersection of the rays emitting from the pair of correlated points. In ideal case, the 3-D rays corresponding to the correlation points on the image frames should intersect with each other at a point, P''(see Figure 2). However, in practical situation, the two rays will be skew in 3-D space without intersection. The triangulation error comes mainly from two error sources: (1) correlation error and (2) CCD calibration error. We identify three conditions by considering the two error sources:

- The correlation and CCD calibration is perfect and error free.
  The de-projection rays(L and R'') intersect at point P''(see Figure 2).
- The correlation is perfect but with CCD calibration error.
  The correlation pair is still (P_L ,P'_R), however, the de-projection ray R'' corresponding to P'_R moves to R' because of the calibration error(see Figure 2). The triangulation point P' is estimated from the shortest path between both rays.
- Both correlation and CCD calibration induce error.
  This is the most common condition. The correlated point in the right image frame shifts rom P'_R to P_R, moreover, the de-projected rays is Rand the triangulation point becomes P(see Figure 2).

In the paper, our system is based on the third condition since the the results of the correlation and calibration processes should bring error in real world. The computation of triangulation P is as following:

(1) Let ray L be αP_L and ray R be $T + \beta R^T P_R$, then the vector w, which is orthogonal to both rays L and R, is described as $w = P_L \times R^T P_R$. (Eq.1)

(2) Solve the equation

$$\alpha P_L - \beta R^T + \gamma w = T. \qquad \text{(Eq.2)}$$

Solving Eq.2 will determine the end points of the shortest path(s) between two rays, and the triangulation point P is the midpoint of the path s.

The correlation error dominates the 3-D triangulation error because the 2-D errors are enhanced while 2-D points in image frames are converted to 3-D rays. In section 2.2, the 3-D error caused by correlation error will be analyzed and discussed.

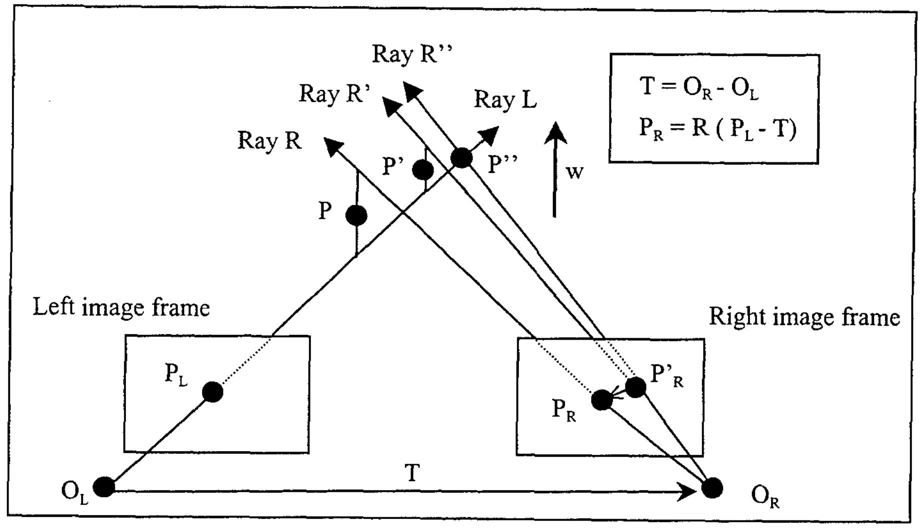


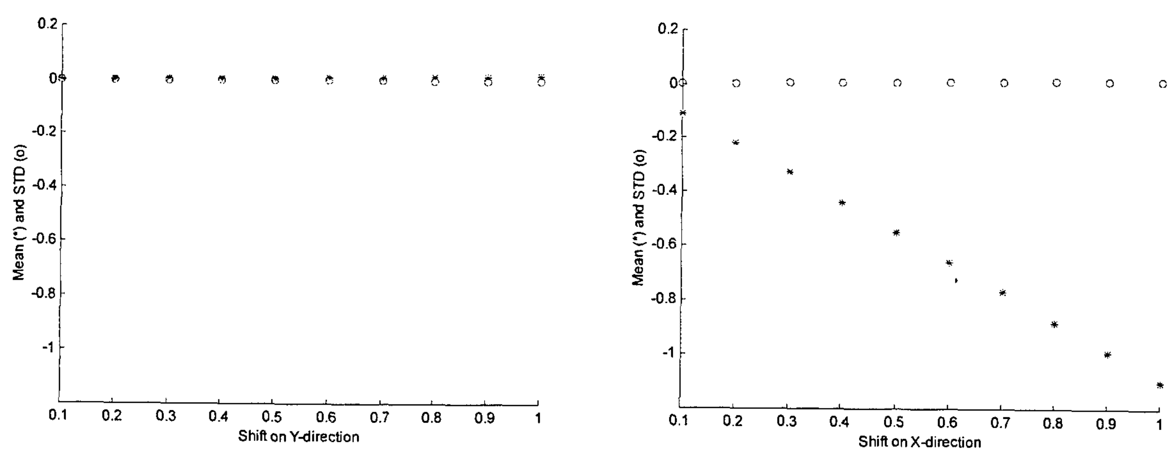
Figure 2 Three conditions in triangulation process.

2.2 Relation between 2-D shift and 3-D displacement

Many issuses affect the correctness of correlation, for example, the quality of the spackle projection, the slope of object surface, the CCD inherent disturbance, etc. We make an experiment to investigate and measure the effect on 3-D space when the correctness of corelation vector is corrupted by the issues:

Step 1. Take a set of CCD parameters obtained in the calibration process.
Step 2. Grid the left image frame and use the position of cross-intersection as the left point set(S_L).
Step 3. Assume the 3-D surface is z=0 and de-project S_L the 3-D point set($S_{3\text{-}D}$) by using the CCD parameters.
Step 4. Project $S_{3\text{-}D}$ to right image frame and get the right point set(S_R).
Step 5. Shift the right point set in x- or y- direction as the correlation error to calculate the influence on the coordinates of the triangulation point.

Figure 3 shows the relationship between mean/STD and x/y shift. Figure 3(a) illustrates that the 3-D displacement order is around 10^{-3} in the shift of y-direction and Figure 3(b) represents that the shift in x-direction has much displacement, the order is around 10^{-1}. Besiedes, since the STD is low in both, it depicts that the point on the image frame with the same shift has similar effect on 3-D displacement.



(a) (b)

Figure 3 Mean and STD on Z-direction direction.

From the observation, we conclude that the depth-shift ratio is 0.8~1.1 mm/pixel in x-direction, in other words, the z coordinate will shift about 1mm if the correction vector has pixel-level error. Of course, the depth resolution is dependent on the photogeometry of the stereo system, e.g. the distance between CCDs. If the distance between CCDs increases, then the depth resolution will increase. But it is unreasonable to enlarge the distance unlimitedly. In our system, the distance is approximately 60 mm.

3. THE ENHANCEMENT TRIANGULATION

The system based on direct triangulation method faces two major problems:

(1) The z-coordinates of the reconstruction surface are sensitive to the correlation error.

(2) Some spurious vector still survive after Correlation Error Correction(CEC) in the correlation process.

Problem (1) will be discussed in section 3.1 and section 3.2 gives an solution to problem(2).

3.1 Vector Mapping Method

Since the stereo system has two CCDs, the direct triangulation will enlarge the error while the 2-D correlated pair is converted to 3-D space rays. Little shift of correlation vectors induces larger 3-D depth error. A vector mapping method is proposed to directly convert the 2-D pixel coordinate (x, y) to 3-D space coordinate (X, Y, Z) by using three scale factors(K_X, K_Y, K_Z). This will reduce the 3-D perturbation caused ion from . The central part of the method is to compute the scale factors.

Figure 4 illustrates the computation of K_X and K_Y. Select a observation space where the object will be located, then calculate the scale factors K_X and K_Y by using the relationship between (X_2-X_1, Y_2-Y_1) and (x_2-x_1, y_2-y_1).

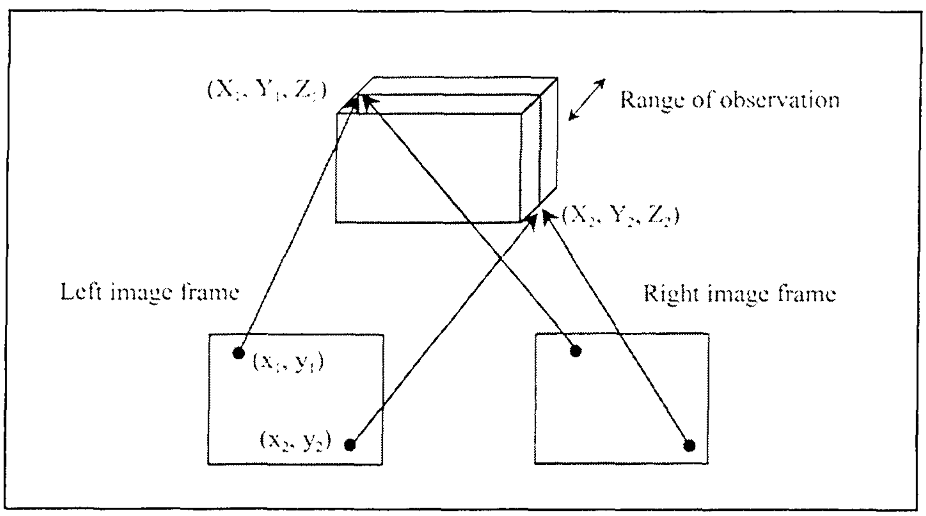


Figure 4 Computation of K_X and K_Y.

The length of the correlation vector is variant when a 3-D point moves with different distance from CCDs. According to the relation of the vector mean length related to the varied distance between the 3-D point and CCDs, K_Z is computed from the ratio of the mean length and distance. Surely, the value of K_Z should vary with the distance, however, K_Z will approximate a constant if the z-depth of the point is in a certain range. Here, we use a template to calibrate K_Z (see Figure 5). Firstly, we place the template at the position at Z=0, and compute the mean length($len(V_0)$) of the vectors in correlation vector field. Then we move the template to another position Z = *t*, also compute the mean length($len(V_t)$). K_Z related to position Z = *t* is calculated from $t / (len(V_t) - len(V_0))$.

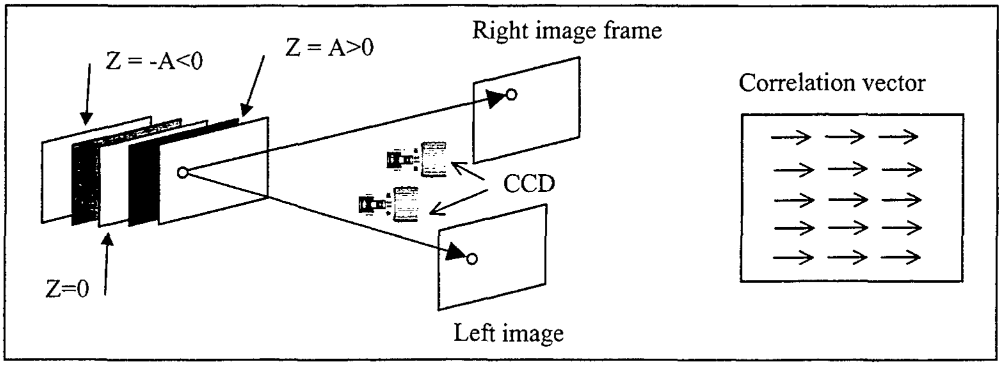


Figure 5 Calibration of K_Z.

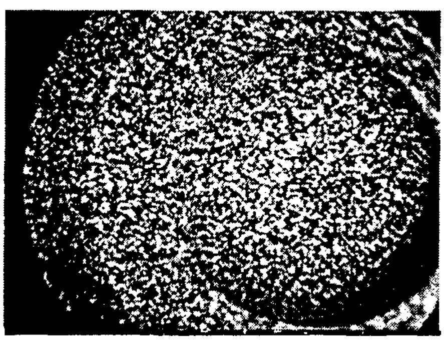
The relationship between 2-D pixel coordinate *(x,y)* and 3-D space coordinate *(X, Y, Z)* is formulated as

$$\begin{cases} X = X_S + kx * x \\ Y = Y_S + ky * y \\ Z = K_Z * (len(Vx) - len(Vx_0)) \end{cases} \quad \text{(Eq. 3)}$$

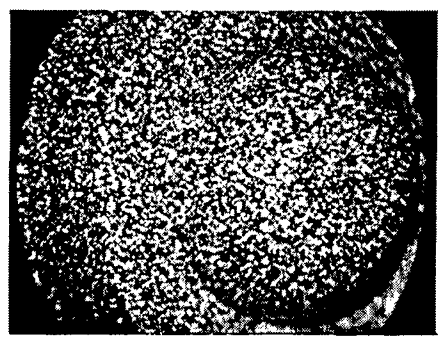
where X_S and Y_S are the initial position of 3-D space.

3.2 Distance Map

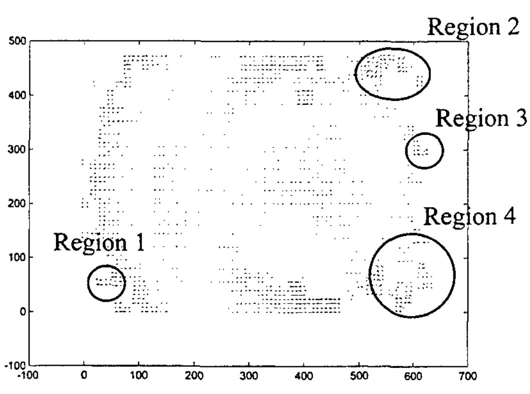
The 3-D rays of the correlated point pair often doesn't intersect with each other because of the corelation and calibration errors. The distance between two rays gives a direction about how to filter the spurious vectors. Figure 6 shows the experiment of computing the shape object of half-sphere.



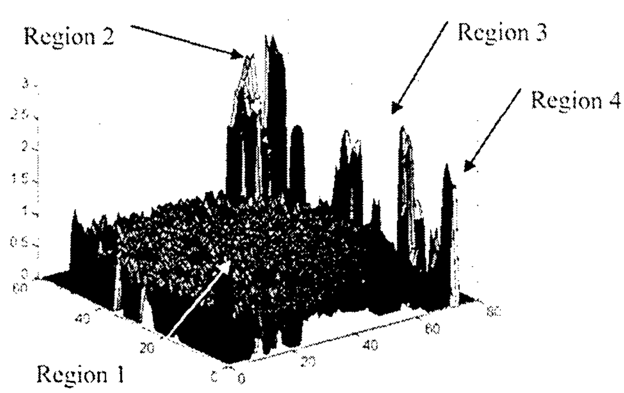
(a) Left speckle image.



(b) Right speckle image.



(c) Correlation vector field.



(d) Distance map.

Figure 6 Correlation vector field and distance map of the half sphere.

Figure 6(a) and 3(b) are the left and right speckle images of the half sphere. The correlation vector field corresponding to the two images is shown in Figure 6(c). According to the smoothness criteria, we find that maybe some spurious vectors occur in region1 to region4, where the vectors are obviously in the different direction. However, the vectors could possibly locate on the edge or peak of the object. We cannot make sure that they are exactly spurious vectors or not even if they pass the CEC process in the correlation module. But from the distance map(see Figure 6(d)) corresponding to the vector field, the related areas have significant high distance. In other words, there is a proportional relationship between distance map and correlation vector field, i.e., some position with large value in distance map represents the corresponding vector is spurious vector. This phenomenon provides a useful indication to identify the spurious vectors. We can filter out the spurious vector by observing the corresponding distance in the map.

3.3 Procedures Related to Enhancement Triangulation

Figure 7 illustrates the related procedures of triangulation enhancement. The method includes the generation of distance map exploited to filter out the spurious vectors and the calibration of multiple factors (K_X, K_Y, K_Z) applied to compute the 3-D coordinates of object.

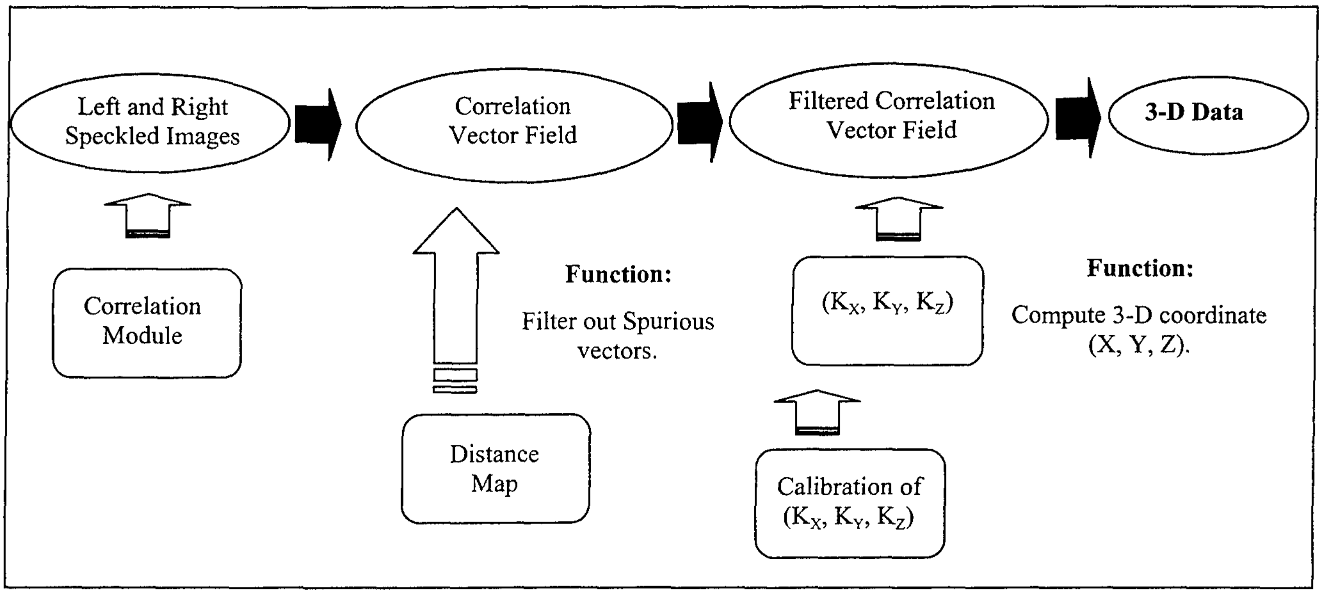


Figure 7 Stages of triangulation enhancement.

4. EXPERIMENTAL RESULTS

In the section, we compare the experimental results from direct triangulation and triangulation enhancement separately. The distance between two CCDs is 65 mm and the object is 550 mm from the CCDs. Figure 8 displays the left and right speckle projection images captured from the stereo system.

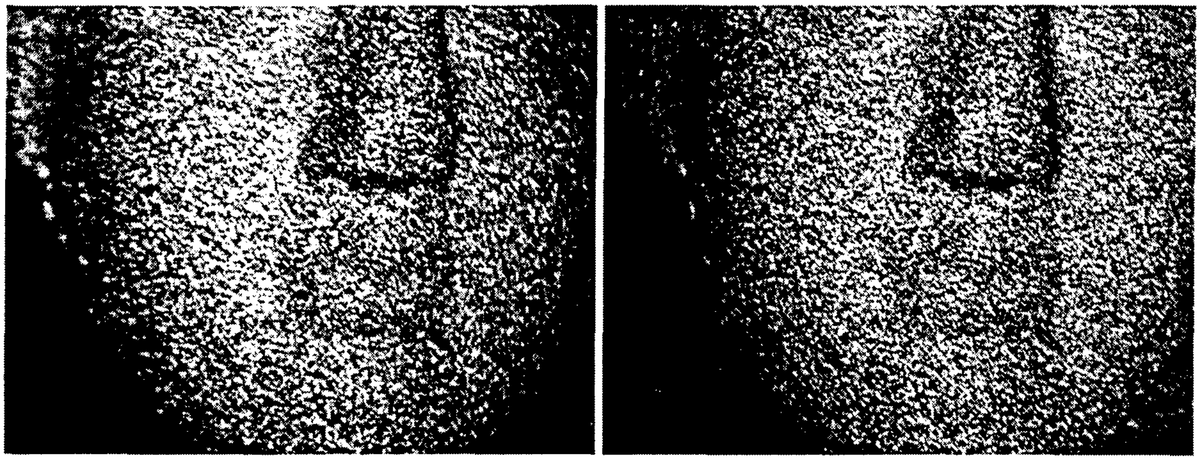


Figure 8 Left and right images of Venus Head.

Figure 9 is the result by using the direct triangulation method and Figure 10 shows the reconstructed surface through the method of triangulation enhancement.

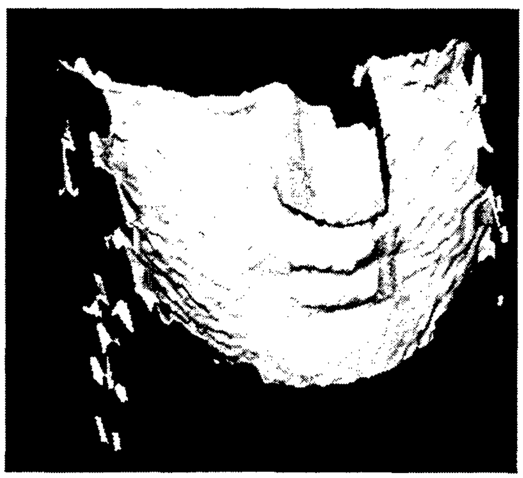


Figure 9 The reconstructed object from direct triangulation.

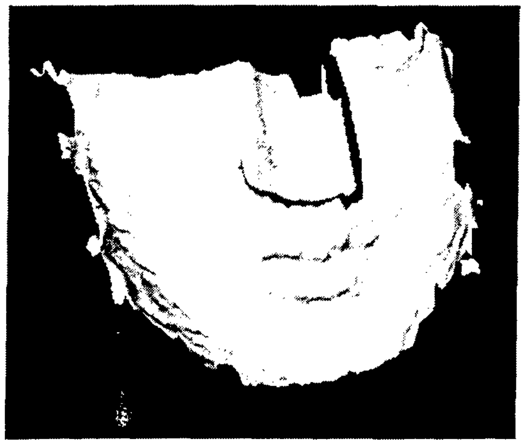


Figure 10 The reconstructed object from triangulation enhancement.

Compared Figure 9 with Figure 10, the surface points with large error are filtered after the enhancement, especially on the right cheek. Besides, the surface in Figure 10 is smoother than Figure 9, and the difference is particularly obvious on the left cheek. The reason is that the histogram of the spackled image is not very the same(see Figure 8), so the correlation errors in the part of left cheek are larger than other area of the face. The direct triangulation will enlarge the influence of the correlation error while converting 2-D image pairs to 3-D points, however, the triangulation enhancement has smaller perturbation in 3-D surface since it just reflects the correlation error.

5. CONCLUSIONS

In the paper, we propose a triangulation enhancement in a stereo imaging system. The proposed method gets smoother surface than direct triangulation by reducing 3-d error through vector mapping method, moreover, it filters out the spurious errors by exploiting the distance map. By observing the experimental results, we conclude that over 85% of the 3-D errors are influenced by correlation error. Therefore, the correlation algorithm on sub-pixel level should be improved to increase the correlation accuracy. Furthermore, the depth resolution is another important consideration; in the other words, the reconstructed surface will achieve better quality if the depth-shift ratio becomes lower. Our future work will focus on how to improve the accuracy of the correlation algorithm and increase the depth resolution.

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