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A depth estimation method based on geometric transformation for stereo light microscope

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Abstract. Stereo light microscopes (SLM) with narrow vision and shallow depth of field are widely used in micro-domain research. In this paper, we propose a depth estimation method of micro objects based on geometric transformation. By analyzing the optical imaging geometry, the definition of geometric transformation distance is given and the depth-distance relation express is obtained. The parameters of geometric transformation and express are calibrated with calibration board images captured in aid of precise motorized stage. The depth of micro object can be estimated by calculating the geometric transformation distance. The proposed depth-distance relation express is verified using an experiment in which the depth map of an Olanzapine tablet surface is reconstructed.

Keywords: Stereo light microscope, camera calibration, depth reconstruction, geometric transformation distance

1. Introduction

Three-dimensional (3-D) micro measurements are widely used in research areas of biomedicine [1,2], industrial inspection [3], positioning micromanagement [4], materials science [5] and etc. For micro size measurements, microscopes are frequently used. Extremely high precision can be achieved using expensive microscopes such as scanning electron microscopes, fluorescence microscopes and laser scanning confocal microscopes. However, one of their shortcomings lies in that they may interface or kill observed living specimen. Moreover, due to their low imaging rate, they are not to observe moving specimen [6]. Ideal candidate for biomedical research, is stereo light microscope (SLM), could observe specimen visually with barely interference. However, due to its complex optical imaging structure, narrow vision, shallow depth of field and large optical system deviation, difficulty in accurate calibration of SLM constrains its application in micro measurements.

Generally, it is assumed that the optical imaging structure of left and right is symmetrical in traditional SLM measurement. Based on this assumption, magnification, baseline distance and central axis angle are calibrated to reconstruct the shape of object. Kim et al. assumed that the left and right optical

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paths are linear and established a vision model with orthographic projection and epipolar constraint conditions [7]. Taking into consideration of the nonlinearity in imaging, Danuser et al. established a weak perspective projection model by adding distortion terms [8]. Wang *et al*. proposed the concept of weak disparity (WD) and used the cross-correlation function of the left and right paths as the metric of WD [9]. However, the abovementioned models require the imaging paths in SLM to be symmetric, which cannot be guaranteed in low-cost microscopes. It is noticed that, in macro camera calibration, each path is calibrated independently based on pinhole imaging model [10], which does not require the two paths to be symmetric. The pinhole-model based calibration methods requires the image used in calibration to have extended depth of field. However, as the field depth of SLM is limited, the pinhole-model based calibration methods cannot be directly applied on SLM [11].

The objective of stereo measurement is to estimate the 3-D coordinates of objects based on the relationship between left and right images. In general, the relationship between left and right images is described using a certain imaging model whose parameters are calibrated prior to stereo measurement [11], which will increase the complexity of the problem. As a result, a direct and simple method is expected. In this paper, a depth estimation method of micro objects based on geometric transformation is proposed where geometric transformation distance (GTD) of 3-D points is used to estimate the depth. To reduce the complexity of the method, direct relation between left and right image is used.

The following content of this paper is organized as follows. Section 2 derives the depth estimation method based on geometric transformation and introduces the framework of stereo measurement. Section 3 reports the experimental results, and Section 4 draws the conclusion.

2. The proposed depth estimation method

The proposed depth estimation method, as illustrated in Figure 1, consists of two main steps, i.e., parameter calibration and depth estimation. In the first step, standard image pairs with known 3-D coordinates are captured, and reference matching point pairs are obtained through image feature extraction. Then the left image and the geometric transformation of right image are used to estimate the object depth, where geometric transformation parameters are calibrated using pairs with different depths. The details are explained as follows.

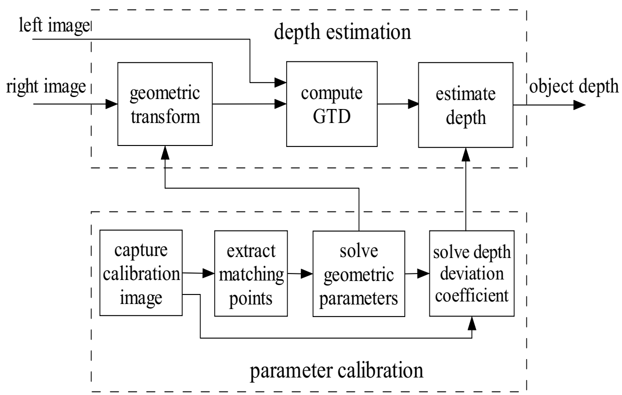


Fig. 1. Flowchart of the depth estimation method.

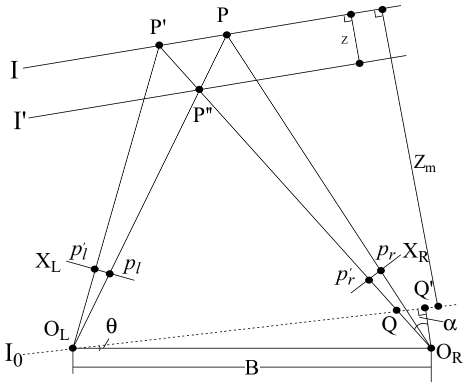


Fig. 2. Imaging geometry for SLM.

2.1. GTD based depth estimation

Figure 2 shows the imaging geometry of SLM, where X_L and X_R represent the left and right image planes, respectively. O_L and O_R represent the optical centers of the left and right cameras, respectively. The straight line with notation *I* represents a plane in 3-D space, the one with notation *I'* represents a plane parallel to plane I, and the dotted-line with notation I_o represents a plane passing through point O_L and also parallel to plane I. The distance between plane I and plane I' is z, and that between I and I_0 is z_m. Point P is on plane I, and $p_l(x_l, y_l)$ and $p_r(x_r, y_r)$ are the left and right image points of P, respectively.

Point P'' is the cross-point of line O_L-P and plane I'. As known from the imaging model, the left image point of P'' is $p_l(x_l, y_l)$, and its right image point will be $p_r^{'}(x_r^{'}, y_r^{'})$ (as shown in Figure 2). The straight line crossing points O_R and P'' intersects plane I at point P', and the left and right image points of P' are $p_l^{'}(x_l^{'}, y_l^{'})$ and $p_r^{'}(x_r^{'}, y_r^{'})$, respectively. Q is the point of intersection between plane I_o and line O_R-P', and line O_R-Q' is perpendicular to line O_L-Q. B is the baseline distance of SLM. θ is the angle between line O_L-Q and O_L-O_R, and α is the angle between line O_R-Q and O_R-Q''.

In a pinhole imaging model, according to the projective geometry of SLM, the relationship between the left and right image can be expressed by perspective transformation. Neglecting the effect of deformation, affine transformation can be used instead, which gives

$$[x_l \quad y_l \quad 1] = [x_r \quad y_r \quad 1]T \tag{1}$$

where *T* is the affine matrix. G*eometric transformation distance* (GTD) *l* of Point P is defined as:

$$\begin{cases} (x_l^t, y_l^t) = T\{(x_r, y_r)\} \\ l = \sqrt{(x_l^t - x_l)^2 + (y_l^t - y_l)^2} \end{cases} \tag{2}$$

As illustrated in Figure 2, GTD of point P'' is the distance between image points pl and pl'. Since the triangle PP'P'' is proportional to the triangle OLQP'', the following relationship can be derived:

$$\frac{z}{z_m - z} = \frac{l_{P-P'}}{l_{O_L-Q}} \tag{3}$$

where l_{O_L-Q} is the distance between O_L and Q and $l_{P-P'}$ is the distance between P and P'.

Also based on the geometrical relationship shown Figure 2, the following equation can be derived:

$$\frac{z}{z_m - z} = \frac{l}{\beta_l \cdot B(\cos\theta - \sin\theta\tan\alpha)} \tag{4}$$

Provided z_m is much greater than z, Eq. (4) can be approximated by

$$z = \frac{z_m}{\beta_l \cdot B(\cos\theta - \sin\theta\tan\alpha)} \cdot l = k \cdot l \tag{5}$$

where the proportionality coefficient k is called the depth distance coefficient.

2.2. Parameter calibration

In macro calibrations, grid corners of calibration board are used as candidates for matching point pairs. However, the corner detection algorithms are often very sensitive to blur and noise, resulting in low accuracy in point matching. To overcome such problems, this paper proposes to use the geometrical centers of grids on the images of the calibration board as the candidates for matching points. Image segmentation algorithms such as Watershed [12] algorithm are used to recognize the grid regions, and the geometrical center of a gird region is estimated.

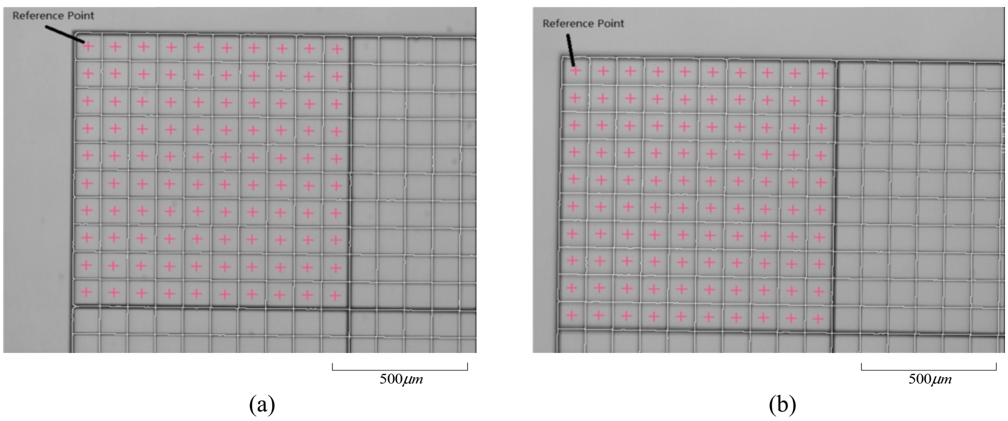


Fig. 3. Matching point pairs finding: (a) left image; (b) right image.

The next step is to find out the matching point pairs from numbers of candidate points. To simplify calculations, corner regions of the calibration board is selected, as shown in Figure 3. Reference points are selected by calculating the minimum distance from the origin and the reference matching pair obtained. The other pairs are obtained by the relative position relation with the reference points.

By substituting the corresponding matching point pairs in Eq. (1), a series of equations about the relationship of the matrix T can be established. Although only a certain amount of equations are required to solve matrix T, yet more equations are obtained. As a result, Least squares method is used to improve the accuracy and stability of matrix T. The value of k could be obtained using a known depth and its corresponding GTD. Actually, in order to improve the stability of the calculated results, average values of the same depth points are used.

3. Experimental results

As shown in Figure 4, stereo measurement system is composed of a SLM, a precision motorized stage and a computer. Two cameras (Watec WAT-902B, 720*576 pixels) are mounted on a NOVEL OPTICS NSZ-800 SLM. A calibration board of plane glass plate etched with orthogonal grid is placed on a one-dimensional motorized stage (CHUO SEIKI XA07A-R2H, 2 um/step). The spatial frequency of the calibration board is 10 lines/mm in two directions and the pitch is 100 um.

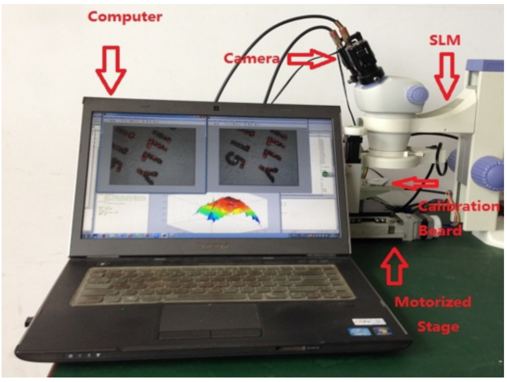


Fig. 4. Measurement system of SLM.

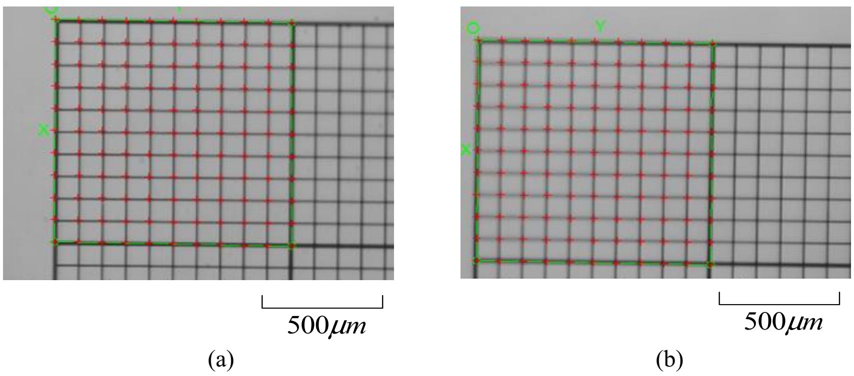
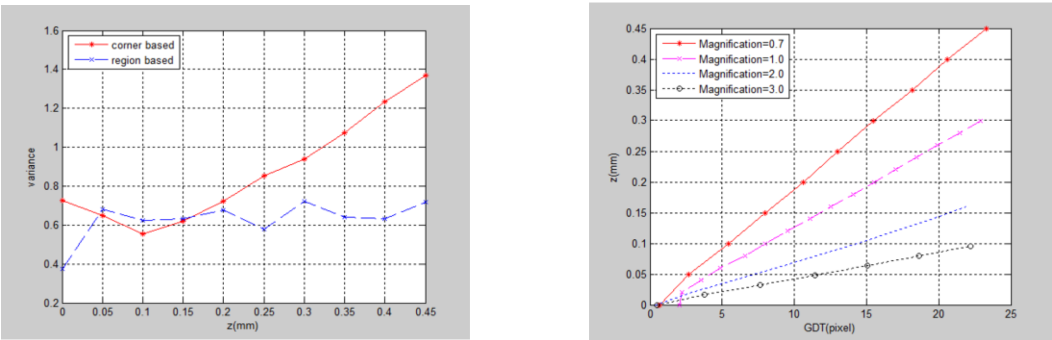


Fig. 5. Matching point pairs finding by corner based method: (a) left image; (b) right image.



(a) (b)

Fig. 6. Statistical results: (a) Relationship between the standard deviations of GTD and depth; (b) Relationship between depth and GTD.

Matching point pairs of each image pair are obtained by region based method mentioned in Section 2.2, and geometric transformation parameters are calibrated. To compare the method proposed in this paper with the traditional ones, matching point pairs found out by corner based method are illustrated in Figure 5.

As mentioned in Section 2.1, GTD is proportional to the depth. Thus the standard deviation of GTD of same depth points is taken as the metric of geometric transformation accuracy, given by

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(l_i - \mu)^2} \quad (6)$$

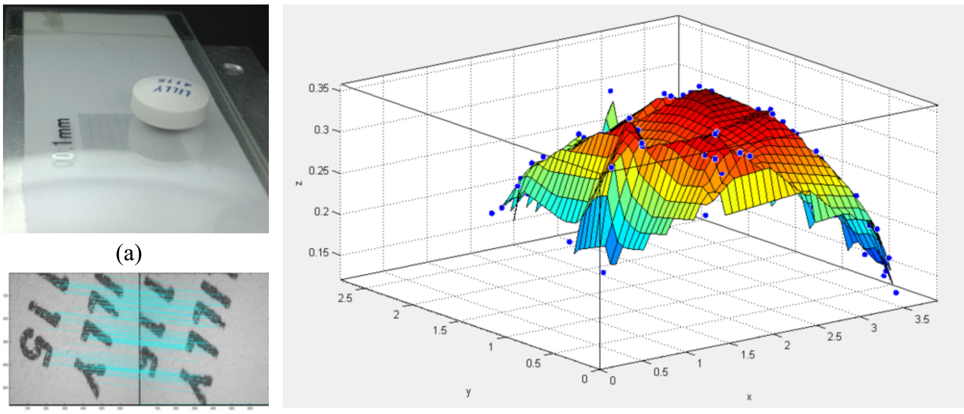
where N is the number of point pairs, l_i is the GTD of a certain point and μ is the averaged GTD of all points. The standard deviations of GTD are shown in Figure 6(a). Ten image pairs of different depth are used as test samples and the standard deviations of corner based and region based method are demonstrated. Most standard deviations of region based method are lower than that of corner based method, especially in large depth.

Figure 6(b) demonstrates the relationship between depth and GTD, which confirms the validity of Eq. (5). Figure 6(b) also shows that as the SLM magnification increases, the proportion coefficient decreases.

As shown in Figure 7(a), an olanzapine tablet is taken as the sample to reconstruct the surface depth map. First SIFT feature matching algorithm is used to search a number of matching point pairs, as shown in Figure 7(b). Then geometric transformation is applied to the right image matching points to achieve GTD. By multiplying the depth distance coefficient, the depth of 3-D point is obtained. The 3-D image of the tablet surface is shown in Figure 7(c), with the unit of the coordinates in millimeter. Please be noted that the scale of z-axis (depth) is ten times larger than that of x-axis and y-axis.

4. Conclusion

A depth estimation method based on geometric transformation is proposed in this paper. Parameters consist of geometric transformation matrix and depth distance coefficient are calibrated in aid of a



(c)

Fig. 7. Reconstruction of olanzapine tablet surface: (a) physical image; (b) matching point pairs; (c) 3-D image.

precision motorized stage. The depth map of 3-D micro object is estimated with low complexity and high speed. The method could be used to reconstruct 3D information of biomedical objects with low-cost SLM in an automatic inspection system. In order to improve the measurement accuracy, other complicated transformation considering imaging distortion can be used to replace the geometric transformation.

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