Increasing the Accuracy for Computer Vision Systems by Removing the Noise

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***Abstract*—Robots rely on the computer vision systems to obtain the environmental information. As a result, the accuracy of the computer vision systems is essential for the control of the robots. Many computer vision systems make use of markers of the well-designed patterns to calculate the system parameters. Undesirably, the noise exists universally, which decreases the calibration accuracy and consequently decreases the accuracy of the computer vision systems. In this paper, we propose a pattern modeling method to remove the noise by decreasing the degree of freedom of the total calibration markers to one. The theorem is proposed and proved. The proposed method can be readily adopted by different computer vision systems, e.g. structured light based computer vision systems and stereo vision based systems.**

Keywords-degree of freedom; noise; pattern modeling; computer vision

I. INTRODUCTION

Computer vision systems are becoming more and more popular in robotics. It is believed that the next generation robots should mainly rely on the computer vision systems to control their behaviors just as human beings do. Many computer vision systems [1]-[9] utilize some well-designed pattern for calibration. Structured light based computer vison systems project the designed patterns onto the surface of the object to be measured. From the distorted pattern, the surface's profile could be calculated based on the system's parameters calculated from a set of calibrated markers. Thus, the calibration accuracy is critical for the measurement accuracy of the structured light based computer vision systems. Traditionally, these computer vision systems use as many calibration markers as they can until the calibration accuracy improvement reached zero growth. The camera calibration [10] makes use of multiple views of the well-designed pattern to calculate intrinsic and extrinsic parameters. Similarly, it also uses as many views of the designed pattern as it can until the calibration accuracy could not be improved any more. Unfortunately, none of them could avoid the annoying noise in both calibration stage and measurement stage even if they might reduce the noise to a low level by averaging more markers or views of the designed pattern. The noise induced error during the calibration stage may affect the measurement accuracy of the computer vision systems greatly for some techniques [6] and limits their applications undesirably.

During camera calibration or the structured light based 3D scanning computer vision system calibration, a set of known markers on the designed pattern are used to calculate the system parameters. Before they can be used for calibration, the two-dimensional coordinates of these points in the camera view need to be computed, where the noise is introduced when the coordinates of the points are computed as the Gaussian mean of all the corner or bright pixels. Consequently, calibration error is caused by the noise. To remove the noise caused error, we propose a pattern modeling method in this paper to reduce or eliminate the noise by reducing the degree of freedom of all the calibration markers to one. Experimental results show that the proposed method is effective in removing the noise in the developed structured light computer vision systems [1-4], [8], [9]. The accuracy improvement is significant in the sense of mean squared errors. We use the proposed method to remove the noise for camera calibration [10] and its effectiveness is also verified by the experimental results. Since camera calibration is fundamental to most computer vision applications, the proposed method has the potential to benefit them greatly.

II. THE PROPOSED PATTERN MODELING METHOD

The pattern modeling method is implemented based on the distances between the center point and the other points and contains the following steps:

Step 1: Model the rays with points in the designed pattern and the projection center $C(x_c, y_c, z_c)$. The unit of the modeled points can be chosen as convenient as pixel or as mm depending on the convenience of the application. The modeled rays are formulated by Eq. 1.

$$\frac{x^m - x_c}{x_i - x_c} = \frac{y^m - y_c}{y_i - y_c} = \frac{z^m - z_c}{z_i - z_c} = t_i^{\mathrm{m}} \qquad (1)$$

where (x_i, y_i, z_i) is the i th point in the designed pattern.

Step 2: Use the plane $ax + by + cz = 1$ to intercept the modeled rays. Then compute the distances between the center points and a set of points around it.

$$d_i^m = \sqrt{\left(x_i^m - x_0^m\right)^2 + \left(y_i^m - y_0^m\right)^2 + \left(z_i^m - z_0^m\right)^2} \qquad (2)$$

Step 3: For the captured pattern, compute the distances between the center point and the same set of points as those used in Step 2 by the following equation.

$$d_i^p = \sqrt{\left(x_i^p - x_0^p\right)^2 + \left(y_i^p - y_0^p\right)^2 + \left(z_i^p - z_0^p\right)^2} \qquad (3)$$

Step 4: Compute the total difference of all the distances by the following equation.

$$\triangle d = \sum \triangle d_i = \sum \left| d_i^m - d_i^p \right| \tag{4}$$

Step 5: Find the optimal interception plane $P(a,b,c)$ that makes $\triangle d$ minimum.

$$\overline{P} = \arg\min_{P} \triangle d \tag{5}$$

The modeled points are computed in a virtual coordinate system instead of the world coordinate system. A registration is thus needed between the modeled points and the practically intercepted points to convert the coordinates correctly. We register the two set of points based on the least square errors by finding the transformation matrix A that makes the sum of square errors, d_r minimum.

$$\begin{bmatrix} \overline{x}_i^p \\ \overline{y}_i^p \\ \overline{z}_i^p \\ 1 \end{bmatrix} = \omega \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} x_i^m \\ y_i^m \\ z_i^m \\ 1 \end{bmatrix} \tag{6}$$

$$d_r = \sum_{i=1}^{N} \sqrt{\left(\overline{x}_i^p - x_i^p\right)^2 + \left(\overline{y}_i^p - y_i^p\right)^2 + \left(\overline{z}_i^p - z_i^p\right)^2} \tag{7}$$

$$\overline{A} = \arg\min_{A} d_r \tag{8}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \tag{9}$$

where ω is a constant and N denotes the totoal number of points in the registered pattern. After pattern modeling, all the computed points in the captured pattern are replaced with the modeled points in the ideal pattern. Then they are used for system calibration.

III. Implementation of the Proposed Method

For the practical implementation, the searching range to find the optimal parameters (a,b,c) is limited since it will be intractable to search all the possible values thoroughly. In our conducted experiments, we choose the searching ranges as $a \in [-50,50]$, $b \in [-50,50]$ and $c \in [-50,50]$ respectively. The complexity of the searching is 1000000 and it takes less than one minute in MATLAB.

Since the searching range is fixed, the center used to model the rays will affect the equations of the modeled rays, which might in turn affect the final pattern modeling accuracy significantly. Thus, an additional search around the arbitrarily assigned center is performed to find a center that could yield more accurate registration results by minimizing the total mean squared error between the modeled points and the original points.

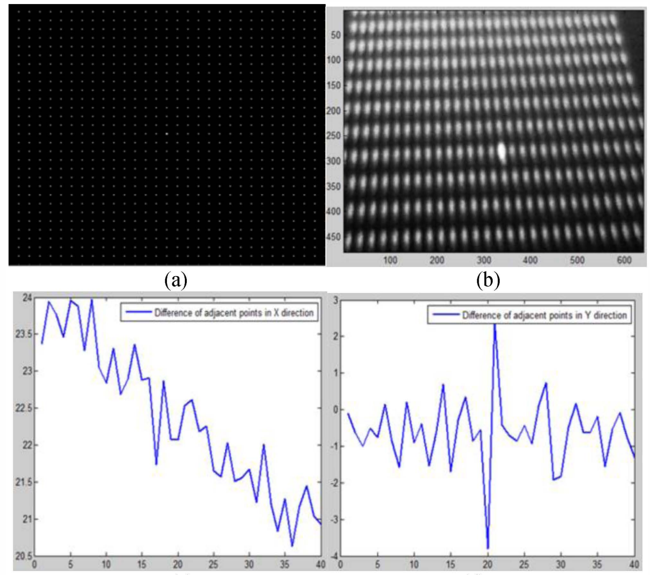


Figure 1. Illustration of noise; (a) Designed pattern; (b) Captured pattern; (c) plot of the x coordinate differences in pixels; (d) plot of the y coordinate differences in pixels. (The y axis label is mm and x axis label is index number for (c) and (d))

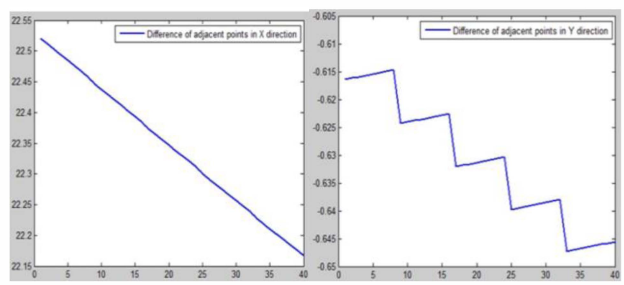


Figure 2. Differences after modeling: (a) x coordinate differences; (b) y coordinate differences.

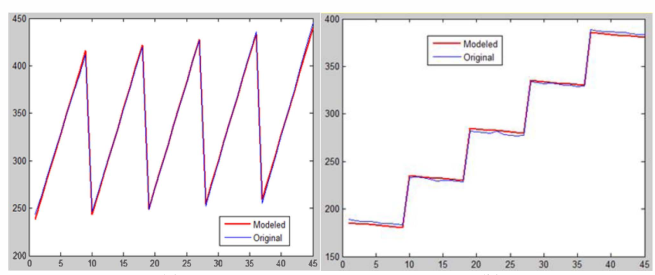


Figure 3. Results of modeling the pattern in the camera view (Fig. 1 (b)) with the searched projection center (a) Modeled and original x coordinates; (b) Modeled and original y coordinates.

We use the projected laser dot pattern to demonstrate the process of removing the noise by the proposed method. Fig. 1 (a) shows the designed pattern and it is projected by a Pico Laser Projector onto a horizontal diffusive plane. The brightest point in the center denotes the center marker. The camera captures the projected pattern as shown in Fig. 1 (b). These laser dots are segmented by the method proposed in [11-12]. The coordinates of the bright laser dots are calculated based on the Gaussian mean of the bright pixels. To demonstrate the noise, we select 44 points around the center laser dot and plot the differences of the x coordinates and y coordinates between adjacent laser dots respectively. Fig. 1 (c) and (d) show the calculated x coordinate differences and y coordinate differences respectively. Based on the designed pattern, the differences should be a constant without noise while noise adds the random variations. These random variations are the introduced noise. We plot the differences of the x and y coordinate for these 45 points before modeling and after modeling in Fig. 2 (a) and (b) respectively. As can be seen, the noise (random variation) is eliminated successfully. For the modeled results shown in Fig. 2, the computed mean squared errors (MSE) are 2.8061 and 2.0916 for the x and y coordinate respectively. We search a new projection center in a small range [-5, 5] in three dimensions and find the center that yields the minimum MSE. The MSEs are reduced to 2.2204 and 1.6357 respectively. Fig. 3 shows the modeled coordinates after pattern modeling (in red) versus the original original coordinates (in blue). The modeled y coordinates with the new center match better than the modeled y coordinates with the original center, which indicates that searching the optimal parameters is a challenging engineering problem that needs great effort. With the proposed pattern modeling method, the accuracy of the computer vision system proposed in [9] could be improved from millimeter to femtometre [13].

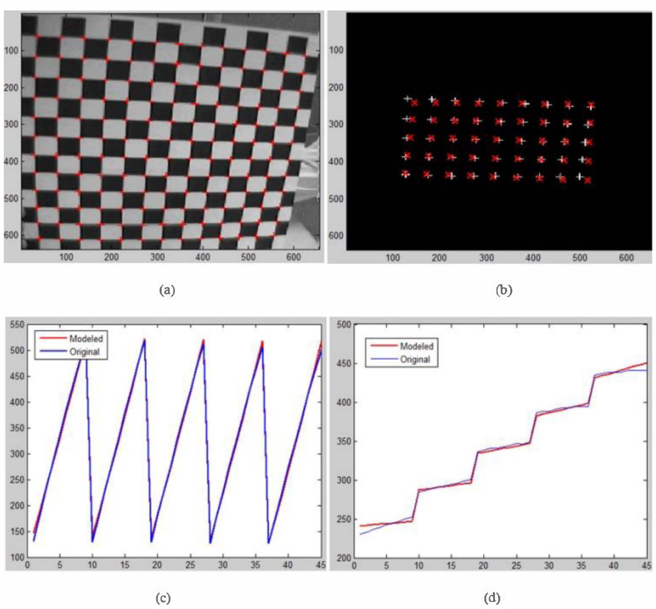


Figure 4. Illustration of camera calibration pattern modeling: (a) Captured calibration pattern; (b) Modeled points against the original points; (c) Modeled and original x coordinates; (d) Modeled and original y coordinates.

IV. Experimental Results

Firstly, we model a camera calibration pattern [10] in Fig. 4. We see obvious mismatches between the modeled y coordinates and the original y coordinates. The mean squared errors are 1.8155 and 2.8142 respectively. We then search around the projection center within the range [-5, 5] in three dimensions. We found the new center that could yield the minimum MSEs, which are reduced to 1.074 and 1.6262 respectively. The new modeling results are shown in Figure 5. It is seen that the modeled points and original ones match significantly better than those in Fig. 4.

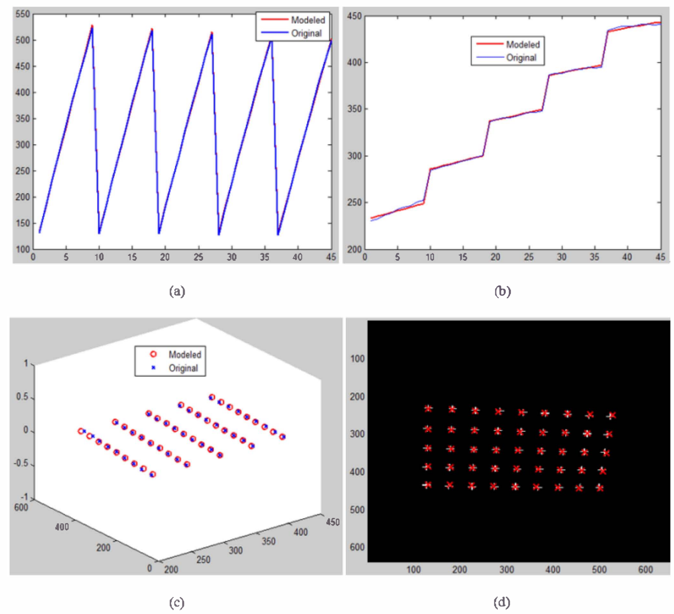
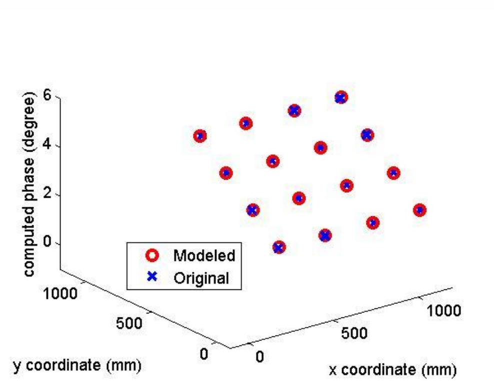


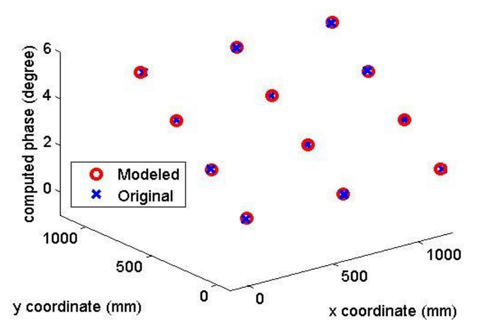
Figure 6. Illustration of camera calibration pattern modeling with another found center: (a) Modeled and original x coordinates; (b) Modeled and original y coordinates; (c)-(d) Modeled points against the original points.

Secondly, we model the calibration grid for the computer vision system in [1]-[4]. We model the points on the two planes (the blue points on the back plane and the red points on the front plane as shown in Fig. 6) independently. The modeled points versus the two sets of computed points on the two planes (Fig. 6 (b)) are shown in Fig. 7 (a) and (b) respectively. As can be seen, they match well, which indicates that it is correct to apply the proposed pattern modeling method in phase shift profilometry 3D imaging system [1]-[4]. The measurement accuracy with and without pattern modeling are 0.65 mm and 0.95 mm respectively for measuring the object with the length about 1000 mm. The measurement accuracy percentages are thus 0.00065 and 0.00095 respectively.

Please note that the proposed pattern modeling method has the upper limit in improving the accuracy of some computer vision systems. In other words, the system noise always exist for some computer vision systems, e.g. the phase shift profilometry [1-4]. Only when the system is based on analytical solutions, its accuracy could be improved to be as close as zero [12].

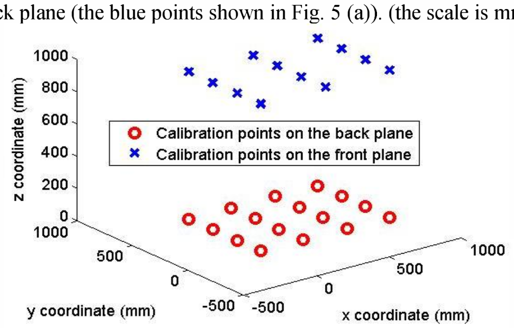


(a)

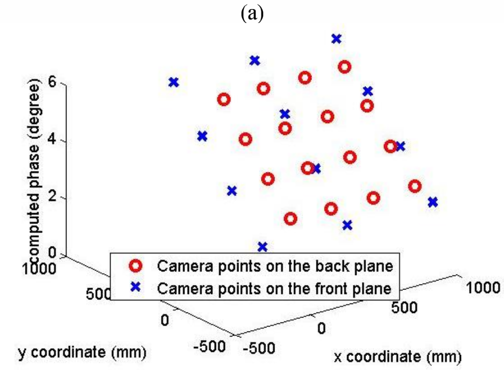


(b)

Figure 7. Registered points versus computed points: (a) For the points on the front plane (the red points shown in Fig. 5 (a)); (b) For the points on the back plane (the blue points shown in Fig. 5 (a)). (the scale is mm).



(a)



(b)

Figure 5. Two sets of points used for calibration: (a) Designed points in the virtual space (X_i^W, Y_i^W, Z_i^W) $i = 1,...,28$; (b) Computed points (x_i^c, y_i^c, y_i^p) $i = 1,...,28$ in the world coordinate sytem by the phase shift profilometry 3D imaging system.

V. CONCLUSION

In this paper, a pattern modeling method is proposed to remove the noise by reducing the degree of the freedom of the all the calibration markers (points) to one. As a result, the calibration error caused by the noise can be removed effectively. Both the camera and the projector can be modeled by the proposed method based on the requirements of the practical computer vision systems. Experimental results validated the effectiveness of the proposed method.

In the future, we will apply the proposed method to more computer vision systems.

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