Research on Error Correction Algorithms of Oblique Optical Axis in Visual Measurement Based on BP Neural Network

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ABSTRACT

Visual measurement technology is widely used in the field of non-contact measurement. However, in practical measurement, the measurement accuracy is reduced, because of the vertical error between the optical axis of the camera and the plane of the camera. Finally, the corresponding error angle can be obtained directly by acquiring the information of the image punctuation, and the three-dimensional coordinates of the corrected points also can be calculated. To verify the feasibility of the algorithm, a visual measurement platform is built for image acquisition. By collecting the scale relation of rectangular edges and the data set that causes the error angle, the function relation model between proportion and angle is obtained by training the afferent neural network. The BP neural network fitting value is compared with the actual measured value and the calculated value. The result shows that by using BP neural network approximating function, the minimum mean square error can reach 0.5075mm which is close to the expected error of 0.50mm, and the oblique optical axis correction error of single camera in visual measurement can be achieved. In this paper, the visual measurement errors caused by oblique optical axis are theoretically analyzed and an oblique optical axis error correction algorithm based on BP neural network algorithm are proposed.

KEYWORDS
Single Camera, Visual Measurement, BP neural Network, Oblique Optical Axis, Correcting.
INTRODUCTION

Visual measurement technology has the advantages of fast speed, high accuracy, non-contact and so on, and it has been widely used in the field of non-contact measurement, in recent years. This technology mainly includes: structured light vision measurement, monocular vision measurement, stereo vision measurement, etc. Structured light measurement is limited by light source, and its application situation is relatively fixed. Monocular vision measurement is often used in two-dimensional measurement. Stereo vision measurement takes the same scene through two fixed cameras and restores three-dimensional information in two images by using the parallax of space points\(^1\). It is still a technique to restore the three-dimensional scene world by using two-dimensional projection images.

Compared with stereo vision measurement, monocular vision measurement is more widely used because of its simplicity, low cost and ability to meet most of the measurement requirements\(^2\). In practical measurement applications, the verticality of camera optical axis and object is the key to ensure the accuracy and stability of measurement. Because the deviation between optical axis and normal line of measured object surface always exists and causes larger measurement errors, it is necessary to study the error correction of oblique optical axis measurement. Moreover, due to the lack of relative information between lens optical axis and the measured target plane, which limits the application of monocular vision measurement in stereo measurement.

At present, many domestic and foreign scholars have studied oblique optical axis error correction technology, Chen Daqin\(^3\) proposed the reference measurement technology that can overcome the influence of oblique optical axis imaging position change; Gong Hao\(^4\) studied the non-perpendicularity adjustment between optical axis and the digital image processing based on digital image processing. Murata N\(^5\) studied the multi-objective adaptive optical axis adjustment system with genetic algorithm; Jung Rae Ryoo\(^6\) proposed an automatic adjustment of object lens position in optical disk driver; Zhao Jingjing\(^7\) used area method to judge the verticality of optical axis and object surface, and used which to guide the adjustment of lens or the position of the object to be measured; Tang Zhengzong\(^8\) research the oblique optical axis digital image correlation method based on photogrammetric correction, and two-dimensional DIC technology is applied to three-dimensional measurement, which verifies the feasibility of using single camera to measure three-dimensional information. However, all these of deviation angle correction methods between the optical axis of the camera and the measured plane have to under the case that the optical axis of the camera is absolutely perpendicular to the measured plane, which is very difficult to be met in the two-dimensional measurement.
In this paper, an oblique optical axis error correction algorithm based on BP neural network algorithm is proposed. No matter what the measured plane axis is parallel to the longitudinal and transverse axis of the camera or not, the measured plane rotates around the axis uniformly. With the camera image capture, the proportional relationship between the rectangular edges and the error angle data set are calculated, and the proportion and the angle are obtained by training the neural network. The function relation of the. Finally, the corresponding error angle can be obtained directly by acquiring the image punctuation information, and the actual world coordinates can be corrected, and the oblique optical axis error correction method with single camera is realized.

ERROR ANALYSIS CAUSED BY OBLIQUE OPTICAL AXIS IN VISUAL MEASUREMENT

CONVERSION FROM COMPUTER IMAGE COORDINATE SYSTEM TO WORLD COORDINATE SYSTEM

The classical geometric model of single camera measurement is based on perspective principle\footnote{9}, which requires three basic transformations\footnote{10}. Its geometric structure model is shown in Figure 1. \((O_WX_WY_WZ_W)\) is world coordinate system, \((O_CX_CY_CZ_C)\) is the camera coordinate system, \((x_s, y_s)\) is the pixel coordinate (unit pixels), and \(f\) is effective focal length of camera. The coordinates of space object point \(P\) in the world coordinate system and the camera coordinate system are \((X_{WP}, Y_{WP}, Z_{WP})\) and \((x_{cp}, y_{cp}, z_{cp})\) respectively. The relationship between the world coordinate system and the camera coordinate system, that is the relationship between \((O_WX_WY_WZ_W)\) and \((O_CX_CY_CZ_C)\), as shown in Formula (1).

\[
\begin{bmatrix}
x_{cp} \\
y_{cp} \\
z_{cp} \\
1
\end{bmatrix} = \begin{bmatrix} R & T \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X_{WP} \\
Y_{WP} \\
Z_{WP} \\
1 \end{bmatrix}
\] (1)

In the formula, \(R\) is \(3 \times 3\) order rotation matrix and \(T\) is \(3 \times 1\) order translation matrix.
Without considering the distortion of ideal perspective, the relationship between camera coordinate system and image coordinate system is shown in equation (2)

\[
\begin{align*}
\begin{aligned}
     \begin{cases}
         x_i = \frac{X_{cp}}{Z_{cp}} \\
         y_i = \frac{Y_{cp}}{Z_{cp}} \\
     \end{cases}
\end{aligned}
\end{align*}
\]

\((x_i, y_i)\) is the physical coordinates of the object point P in space; \((x_{cp}, y_{cp}, z_{cp})\) is the three-dimensional coordinates of the object point P in the camera coordinate system.

The relationship between image coordinate system and world coordinate system is shown in equation (3).

\[
\begin{align*}
\rho \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{f}{d_x} & 0 & c_x \\ 0 & \frac{f}{d_y} & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}
\end{align*}
\]

In the formula, \((x_s, y_s)\) is the coordinates of the pixels, \(c_x, c_y\) are the coordinates of the origin of the camera plane coordinate system in the computer graphics (unit pixels), the size of the pixels is \(d_x, d_y\), \(f\) is the focal length of the camera and \(\rho\) is the constant coefficient. Simultaneous of formula (1), (2) and (3) is

\[
\begin{align*}
\rho \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{f}{d_x} & 0 & c_x \\ 0 & \frac{f}{d_y} & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_{WP} \\ Y_{WP} \\ Z_{WP} \\ 1 \end{bmatrix}
\end{align*}
\]

Abbreviated as
\[ \rho \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} = M_1 M_2 \begin{bmatrix} X_{WP} \\ Y_{WP} \\ Z_{WP} \\ 1 \end{bmatrix} \] (5)

M1 is an internal parameter matrix determined by the camera's internal parameters \(d_y, c_x, c_y\), M2 is an external parameter matrix determined by the camera's external parameters relative to the world coordinate system. Therefore, the main factors affecting the accuracy of point P measurement are two of them.

Figure 1. Schematic diagram of coordinate transformation.

THEORETICAL ANALYSIS OF ERRORS

In visual measurement, the optical axis of the camera is required to be parallel to the normal line of the object plane in theory, but it is difficult to be achieved in the real. Because the optical axis of the camera is not parallel to the normal line of the
measured plane, but it is always assumed that the two are parallel to each other in theoretical calculation, and the measurement error caused by the change of the actual imaging position of the observation point on the camera image sensor is neglected\cite{13-17}. As shown in Figure 2, $O_C$ is the image center of the camera, $Z_C$ is the optical axis of the camera, the imaging plane of the camera is $(O_i x_i y_i)$, $L_1$ is the object plane whose normal is parallel to the optical axis, and $L_2$ is the object plane whose normal deviates from the optical axis at an angle of theta is $\theta$.

Ideally, the projection of point A on the surface $O_i x_i y_i$ is point B. When the target plane shifts from $L_1$ to $L_2$ (deflection angle is $\theta$) and point P moves to point $P'$, the projection position of point A on the camera imaging plane moves to point B, and the pixel error caused by deflection is AB. If calculation according to the premise of no deflection, the result would be ignored such error and the measurement accuracy also would be affected.

![Figure 2. The reason of error creation.](image)

In order to correct the calculation errors of the camera imaging plane, under the condition that the inside and outside camera parameters are the same (including focal length, aperture, principal point position, relative position between the camera and the measured plane). The two methods can be found by formula(4), One is to correct the measured pixel coordinates to obtain the final correct world coordinates; the other is to correct the calculated world coordinates, and corrected it by introducing the deviation angle.
In this paper, the first method is used to correct the error caused by the non-perpendicularity of the optical axis of the camera to the measured plane. Introduce the \((x'_i, y'_i)\) as the computer image coordinates after error correction. The parametric matrix is \(M'_1\)

\[
\rho \begin{bmatrix} x'_i \\ y'_i \\ 1 \end{bmatrix} = M'_1 \cdot M_2 \begin{bmatrix} X_{WP} \\ Y_{WP} \\ Z_{WP} \\ 1 \end{bmatrix}
\]

\[
M'_1 = \begin{bmatrix} f_x & f_s & c_x & 0 \\ 0 & f_y & c_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}
\]

And

\[
\begin{aligned}
X_w &= -\frac{T_y c_y f_s + T_x c_y f_x - T_y c_x f_y}{\sin \theta (c_x x_s + c_y y_s) + \cos \theta c_y f_x} \\
Y_w &= -\frac{T_z c_y f_y - T_y y_s}{\cos \theta f_y + \sin \theta (c_y - y_s)} \\
Z_w &= T_z
\end{aligned}
\]

\[
f_x = \frac{f}{dx}(x'_s, y'_s) \quad f_y = \frac{f}{dy \sin \theta} \quad f_s = -\frac{\cot \theta \cdot f}{dx} \quad c_x = -\frac{1}{dx}(\hat{c}_x - \hat{c}_y \cot \theta) \quad c_y = -\frac{\hat{c}_y}{\sin \theta dy}
\]

\((x'_s, y'_s)\) are the corrected coordinates of the pixel points, \(dx\) and \(dy\) are the size of the pixel, \(f_x\) and \(f_y\) are the values of the focal length in the direction of \(x\) and \(y\), and \(\hat{c}_x\) and \(\hat{c}_y\) are the camera plane coordinate system’s origin estimation value in the computer graphics. However, in practice, the angle \(\theta\) is difficult to be measured, so it is difficult to obtain accurate three-dimensional coordinates by theoretical calculation.
P CORRECTION METHOD OF OBLIQUE OPTICAL AXIS BASED ON BP NEURAL NETWORK

PRINCIPLE OF BP NEURAL NETWORK

BP neural network has powerful non-linear approximation ability. Its topological structure includes input layer, hidden layer and output layer. It can store and learn complex mapping relationship without knowing the mathematical expression of input and output, then use back propagation strategy to get the parameter combination of minimum error with the sub-velocity gradient information. And it has been proved that as long as the number of hidden layer neurons is enough, BP neural network can ensure the accuracy of the calculation of complex continuous mapping relations. So BP network has excellent function fitting function. In theory, it can arbitrarily approximate the non-linear rational function\(^{[18]}\).

Figure 3. Structure of BP NN.
AN OBLIQUE OPTICAL AXIS CORRECTION ALGORITHM BASED ON BP NEURAL NETWORK

THEORETICAL BASIS

The model construction principle of oblique optical axis correction algorithm based on BP neural network is shown in Figure 4, according to its geometric relationship.

\[ h_1 = \left( \frac{D'C'}{DC} - 1 \right) f \]  \( \theta \)  \( \text{(9)} \)

\[ h_2 = \left( \frac{AB}{A'B'} - 1 \right) f \]  \( \text{(10)} \)

In the formula, the length of \( f \), \( D'C' \) and \( DC \) can be calculated by measurement and it can be seen from the graph.

\[ h_2 - h_1 = AD \cdot \cos \theta \]  \( \text{(11)} \)

Finally, it can be got

\[ \cos \theta = \frac{\left( \frac{D'C'}{DC} - 1 \right)f - \left( \frac{AB}{A'B'} - 1 \right)f}{AD} \]  \( \text{(12)} \)

In summary, in two-dimensional vision measurement, the relationship between the deviation angle and \( \theta \) can be obtained only by knowing the \( D'C' \) and \( A'B' \).
As can be seen from the above figure, DC, AB and F are already known, so the relationship between them and the offset angle can be deduced based on the coordinate information of the acquired image, but the deduction and calculation process is complex and error prone. So we can derive the function model by utilizing the function fitting of BP neural network, calculating the offset angle and correcting it to get the correct point coordinates in the world coordinate system.

CONSTRUCTION OF NEURAL NETWORK

In traditional two-dimensional vision measurement process, the optical axis of the camera must be strictly perpendicular to the plane of the object to be measured, but this condition cannot be satisfied in the actual measurement, so it will inevitably lead to measurement error\[19\]. The modification by theoretical calculation is cumbersome and complicated, especially in the case of tracking and recording dynamic points, as long as the relative position between the camera and the measured plane changes slightly, the external parameter matrix in the coordinate transformation relationship will be changed. In this paper, a vision measurement method based on BP neural network is proposed. Sigmoid function is used as the activation function of BP neural network model. Pixel coordinates of continuous movement of marking points are collected by camera, and three-dimensional coordinates of marking points in world coordinates are collected by total station as data sets. Then the training neural network is introduced to obtain world coordinates and fitting function model of their corresponding angular relations. Finally, the error angle is obtained from the incoming image and which is used to correct the subsequent world coordinate calculation.
Data set preparation:

1. Fixed the high-speed camera and the measured plane, and the Z axis of the high-speed camera and the rotation axis of the measured plane are perpendicular to the ground.

2. The camera is calibrated by standard checkerboard calibration paper with 7*4 specification of 4*4 cm. The checkerboard calibration paper is placed in 20 positions at random, and the corner pixel coordinates of the checkerboard calibration paper are obtained by importing OpenCV operation after high-speed camera recording.

3. To ensure that the measured plane rotates uniformly around the rotation axis, a high-speed camera is used to record in every 0.01 degree interval, when the camera and the measured plane in the range of -45 ~ 45 degree, and the corresponding deviation angle is also recorded at the same time.

4. Repeat the experiment three times, and get a lot of image data of the measured plane rotation state and corresponding deviation angle data.

5. Complete the data set preparation, the amount of data up to 20,000.

Model training:

1) The data are preprocessed by the mathematical model construction method described in Section 2.2.1. Firstly, the pixels distance of |p1p2| and |p2p3| are calculated by python.

2) The input value is pixel distance and the output value is angle. Therefore, the number of neurons in the input layer is set to 2, the number of neurons in the output layer is set to 1, and the number of hidden neurons is set to 10.

3) Construct BP neural network by tensor flow.

4) Input the angle distance value to the network, and input the corresponding angle as the label.

5) Model training, when loss is stable and unchanged, network training is completed. The parameters of the model are obtained: the training network model is derived and the data of the model is checked.
EXPERIMENTS AND ANALYSIS

1) Sample Collection Experiment of BP Network

a) Construction of Measurement Platform

The traditional measurement method is to fix the measured plane and rotate the camera to change the angle between the optical axis and the measured plane. While, in this paper, it is on the opposite as it is difficult to measure the deflection angle of the camera in actual operation by the traditional method. In order to verify the feasibility of the experimental scheme and ensure the accuracy of the data, a visual measurement platform is built. The principle of the platform is shown in Figure 6 (a). The three-axis test turntable shown in Figure 6 (b) on the experimental site is SGT320E multifunctional turntable which is produced by China Aviation Industry Group
Corporation. And it has the functions of position, speed and low-frequency rocking motion, and the angular position accuracy can reach to second level. The Phantom M310 high-speed camera \cite{20}, made by Vision Research Corporation of the United States, has a resolution of 1280*800, a maximum sampling frequency of 3260 frames/second and a time precision of 1 microsecond. The KTS-462R4L model total station of KOLIDA manufacture is adopted, and its’ laser alignment, laser pointing, waterproof and dust-proof grade all reach to IP55 level.

The Other test materials include PC, cable and light source and so on. In this paper, only explores the perpendicularity between the camera and the measured plane. In order to facilitate the test, standard checkerboard calibration paper is pasted on the inner frame of the three-axis multi-functional turntable to control the change angle between its’ outer and middle frame.

![Diagram of Vision Measurement Platform](image)

(a) The principle of the platform

![Experimental Site](image)

(b) Experimental site

Figure 6. Vision measurement Platform.
b) The internal parameter calibration of Camera

Researches show that lens distortion is an important factor affecting the accuracy of vision measurement, and camera distortion correction is needed[22]. High-speed camera is used to collect 20 sets of data placed at different angles. As shown in Figure 7, during the calibration process, the calibration board should be as close as possible to the camera view frame to ensure the accuracy of camera distortion correction. The method of BP neural network is used to process the image captured by the camera. So the camera distortion correction and internal parameters can be achieved. The calibration results are as follows.

The internal parameter matrix is:

\[
M_1 = \begin{bmatrix}
-3.5923 \times 10^3 & 0 & 6.2783 \\
0 & 3.6533 \times 10^3 & 4.0806 \\
0 & 0 & 1
\end{bmatrix}
\]

\[k_1 = -2.08511382; k_2 = 4.15180977 \times 10^2; k_3 = -4.14400935 \times 10^{-3}; p_1 = -3.21212318 \times 10^{-3}; p_2 = 1.74884918 \times 10^4.\]

![Calibration image](image)

Figure 7. Image calibration.

c) Image Acquisition Method

The high-speed camera and the measured plane are fixed, the z-axis of the high-speed camera and the rotation axis of the measured plane are perpendicular to the
ground. Zeroing the inner frame, the middle frame and the outer frame of the three-axis multi-functional turntable respectively (returning to the mechanical zero position). Then, in the position mode, every change of 0.01 degree in the range of -45 ~ 45 degree is recorded, and the corner points of the calibration paper are measured by the coordinates in the world coordinate system with an angle between the optical axis of the camera and the measured plane ranging from - 45 to 45 degree with an interval of 5 degree, and the subsequent comparison with the fitting values of the neural network can be obtained. The above steps are repeated three times each, and the images and videos are saved.

![Sample graph of data set.](image)

Figure 8. Sample graph of data set.

2) BP Neural Network Model Training

Network initialization: BP neural network is constructed by tensor flow. The number of nodes in the input layer is set to \( n = 2 \), the number of nodes in the hidden layer is set to 1, and the number of nodes in the output layer is set to \( m = 1 \). The excitation function is \( g(x) \), and \( g(x) = \frac{1}{1+e^{-x}} \), the pixel distance in the data set is used as the input of BP neural network model and the angle value is used as the output of data in the output layer. The process of model training is shown in Figure 7. The process is as follows:

Based on the above description of the key parts of oblique optical axis correction algorithm based on BP neural network, the specific steps of the correction algorithm are shown in algorithm 1 and the algorithm flow is shown in Figure 5.

Algorithm 1 oblique optical axis correction algorithm based on BP neural network
Input: Angular distance value

Output: Angle corresponding to angular distance value

Expected error and the maximum iteration number are set to 0.5 and 14,000 respectively, and finally, the optimal function model is obtained to meet the system accuracy training is 20036, the loss value tends to be stable, the minimum mean square error is 0.5075mm, which is close to the expected error, and the function model has reached the best fitting effect.

3) Analysis of test results

The training model of BP neural network is derived, and the training data of the model are tested. The actual angle measured by the instrument is compared with the fitting angle calculated by BP neural network. The results are shown in Figure 10, which is the angle comparison curves of 19 states in the range of -45 to 45 degree, and the angle fitted with BP neural network. $E_j = 0.2644mm$, $E_x = 0.00074mm$.

Figure 9. Training process for the BP neural network.

Figure 10. Contrast between Real Angle and Fitting Angle.
In order to see the error of point coordinate measurement calculation caused by deviation angle $\theta$, and the verification of the feasibility and practicability of BP neural network algorithm more directly, pixel coordinates of point $P$ obtained by OpenCV, rotation vectors and translation vectors of corresponding angles processing are imported into BP neural network to fit the world coordinates.

Step 1: Collect pictures and preprocess them to build data sets.

Step 2: Construct and initialize the neural network.

Step 3

1) Set the training times and select a batch data from the data set to train the structural parameters of the neural network.

2) Test the error of test data set and modify the network structure when the training times reach the upper limit.

3) Repeat 1 when the error does not meet the requirement.

4) When the error satisfies the requirement, when loss is stable and unchanged, the training of the model is completed.

In the actual training process, the sample data collected by 3.1 is trained by BP neural network algorithm. The needs. The training process is shown in Figure 9. When the number of corresponding to the pixels (using the actual measuring instrument as the origin for conversion, so as to ensure that the same world coordinate system is shared with the instrument measurement). When dealing with the three-dimensional rotation problem, the rotation matrix is usually used to describe it. Therefore, it is necessary to transform the rotation vector into the rotation matrix. Rodrigues transformation is used to transform the rotation vector. The translation vector can be directly transformed into the translation matrix, so no conversion is needed.

Set $r$ as the rotation vector, $r = [r_x, r_y, r_z]$. The rotation is expressed by the length of $r$, and the rotation in the form of coordinate axis-scalar is transformed into a rotation matrix $R$.

Then:

$$R = \cos(\theta) I + (1 - \cos(\theta))rr^T + \sin(\theta) \quad (13)$$
By substituting the obtained pixel coordinates, the rotation matrix and translation matrix corresponding to each angle and the internal parameter matrix obtained by Table 1 into the formulas (4) and (7), the world coordinates of point P can be calculated theoretically before and after correction.

APPENDIXES

| Deviation angle θ | Point P Pixel coordinates /pixs | Angle θ corresponding rotation vector | Angle θ corresponding Translation vector |
|--------------------|----------------------------------|--------------------------------------|----------------------------------------|
| -45°               | (521.53503, 420.5019)           | [-1.41539735, 0.04100232, -2.79251075] | [0.10677352, 33622439, 73.18030942]   |
| -40°               | (521.85425, 420.68027)          | [-1.2901316, 0.04117936, -2.85271715] | [0.39952646, 1.3352927, 87.309822674] |
| -35°               | (523.23193, 420.8689)           | [1.16311153, 0.04042546, -2.90699447] | [0.6912427, 1.3337393, 372.99124561]  |
| -30°               | (525.4871, 421.2069)            | [-1.03275634, 0.04042546, -2.95637785] | [0.98032574, 1.3317164, 772.97731204] |
| -25°               | (528.6055, 421.37042)           | [-0.90040845, 0.03987681, -2.99961014] | [1.26217302, 1.3291092, 472.94854892] |
| -20°               | (532.68353, 421.50665)          | [-0.76722927, 0.03918845, -3.03666057] | [1.53586907, 1.3261496, 2.97242952]   |
| -15°               | (537.67365, 421.67743)          | [-0.63034909, 0.03807932, -3.06837918] | [1.80017308, 1.3230689, 87.305264233] |
| -10°               | (543.51636, 421.84042)          | [-0.49509913, 0.03816908, -3.09367257] | [2.05064787, 1.3195835, 35.314464251] |
| -5°                | (550.201, 422.02786)            | [-0.35576924, 0.03614321, -3.11304394] | [2.28854041, 1.3158935, 47.7329472146] |
y comparing the point P’ theoretical calculated world coordinates before and after correction in Figure. 11 and Table 2 (see appendices), the fitting coordinates of BP neural network with the actual world coordinates measured by the instrument, it can be seen that the theoretical calculation error is large without considering the deviation angle error $\theta$. The average absolute error $E_J$ is 75mm, the average relative error $E_X$ is 64.9mm; after substituting error angle $\theta$, the average absolute error of theoretical calculation value $E_J$ is 11.5, the average relative error $E_X$ is 10.2mm; and the average absolute error of fitting world coordinates with BP neural. Network correction $E_J$ is $1.3395 \times 10^{-2} mm$, and the average relative error $E_X$ is $1.75 \times 10^{-2} mm$; In summary, after substituting deviation angle $\theta$, the values of theoretical calculation and BP neural network correction are all meet the accuracy requirements of three-dimensional

| Angle | World Coordinates | BP Neural Network Corrected World Coordinates |
|-------|-------------------|-----------------------------------------------|
| 0°    | (557.64075, 422.15482) | [0.21402764, 0.03495487, -3.12658518] |
|       |                    | [2.51058325, 1.31105585, 73.48548711] |
| 5°    | (565.7804, 422.248)  | [-0.04761698, 0.05532634, -3.13366875] |
|       |                    | [2.7159498, 1.3066006, 73.7770237] |
| 10°   | (574.671, 422.32544) | [0.09742134, 0.07014036, -3.13217616] |
|       |                    | [2.89373669, 1.2997937, 1.73.91043038] |
| 15°   | (584.09283, 422.3211) | [0.22247407, 0.04887071, -3.12690151] |
|       |                    | [3.05493809, 1.2938757, 6.74.12022337] |
| 20°   | (594.0078, 422.2691) | [0.35571522, 0.04455983, -3.11513466] |
|       |                    | [3.19472215, 1.2870540, 9.74.39188346] |
| 25°   | (604.3961, 422.13348) | [0.49056688, 0.03985817, -3.09750515] |
|       |                    | [3.31319265, 1.2791912, 5.74.70162742] |
| 30°   | (615.31866, 421.6589) | [0.62588457, 0.03625953, -3.07377117] |
|       |                    | [3.41109729, 1.2668162, 3.75.55008551] |
| 35°   | (626.52606, 422.8843) | [0.76087644, 0.03452624, -3.0451803] |
|       |                    | [3.49063487, 1.2852837, 4.75.46942995] |
| 40°   | (637.5413, 422.86584) | [0.8942018, 0.03346078, -3.00762477] |
|       |                    | [3.53739975, 1.2799669, 1.75.84901194] |
| 45°   | (648.56976, 423.21744) | [1.02582041, 0.03338643, -2.9656778] |
|       |                    | [3.55829777, 1.2801860, 6.76.23276337] |
coordinate measurement of the point. However, BP neural network can avoid the errors caused by multi-angle substitution of external parameters into the calculation of tedious procedures or the errors caused by cameras’ movement in operation, and can select the best solution which is closest to the real value within the internal learning and feedback of the network.

Figure 11. 3D coordinate of point P.

**TABLE II. COMPARISON OF CORRECTION RESULTS.**

| Deviation angle $\theta$ | Point P Real World Coordinates /m | Before Correction Point P Theoretically calculated World coordinates | After Correction Point P Theoretically calculated World coordinates | Neural network fitting to get World coordinates of Point P |
|--------------------------|----------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| -45°                     | (-0.211,1.784,1.176)             | (-0.215,2.1854,1.176)                                        | (-0.2142,1.7290,1.176)                                       | (-0.2110,1.7836,1.176)                                         |
| -40°                     | (-0.214,1.775,1.176)             | (-0.2160,1.784,1.176)                                        | (-0.2160,1.7240,1.176)                                       | (-0.2140,1.7749,1.176)                                         |
| -35°                     | (-0.217,1.758,1.177)             | (-0.2292,2.2352,1.177)                                        | (-0.2170,1.7190,1.177)                                       | (-0.2170,1.7585,1.177)                                         |
| -30°                     | (-0.218,1.746,1.177)             | (-0.2290,2.2394,1.177)                                        | (-0.2180,1.7140,1.177)                                       | (-0.2179,1.7458,1.177)                                         |
| -25°                     | (-0.218,1.732,1.177)             | (-0.2283,2.2268,1.177)                                        | (-0.2161,1.7090,1.177)                                       | (-0.2180,1.7315,1.177)                                         |
| -20°                     | (-0.217,1.719,1.177)             | (-0.2267,2.0596,1.177)                                        | (-0.2143,1.7040,1.177)                                       | (-0.2170,1.7195,1.177)                                         |
| -15°                     | (-0.216,1.712,1.176)             | (-0.2170,1.7190,1.176)                                        | (-0.2125,1.6990,1.176)                                       | (-0.2160,1.7198,1.176)                                         |
| -10°                     | (-0.213,1.703,1.177)             | (-0.2256,2.0408,1.177)                                        | (-0.2107,1.6940,1.177)                                       | (-0.2130,1.7026,1.177)                                         |
| -5°                      | (-0.209,1.689,1.177)             | (-0.2238,2.0092,1.177)                                        | (-0.2088,1.6890,1.177)                                       | (-0.2090,1.6896,1.177)                                         |
| 0°                       | (-0.207,1.684,1.176)             | (-0.2204,1.9604,1.176)                                        | (-0.2070,1.6840,1.176)                                       | (-0.2070,1.6843,1.176)                                         |
| 5°                       | (-0.200,1.671,1.176)             | (-0.2189,1.9336,1.176)                                        | (-0.2000,1.6710,1.176)                                       | (-0.2003,1.6708,1.176)                                         |
| 10°                      | (-0.194,1.689,1.176)             | (-0.2013,1.7940,1.176)                                        | (-0.1930,1.6580,1.176)                                       | (-0.1940,1.6884,1.176)                                         |
In addition, it is found that if the data sample set was too small or offset is too big, it is easy to make the approximation failure. In order to prevent the occurrence of such problems, we should try our best to obtain a large amount of data and improve the accuracy of coordinate measurement, in order to ensure the feasibility and accuracy of the method.

| Angle | Before Correction | After Correction | Theoretical | Actual |
|-------|-------------------|------------------|-------------|--------|
| 15°   | (-0.185,1.650,1.177) | (-0.192,1.708,1.177) | (-0.186,1.645,1.177) | (-0.185,1.650,1.177) |
| 20°   | (-0.178,1.644,1.176) | (-0.188,1.637,1.176) | (-0.179,1.632,1.176) | (-0.178,1.643,1.176) |
| 25°   | (-0.170,1.637,1.176) | (-0.170,1.558,1.176) | (-0.172,1.619,1.176) | (-0.170,1.637,1.176) |
| 30°   | (-0.160,1.632,1.176) | (-0.165,1.463,1.176) | (-0.165,1.606,1.176) | (-0.160,1.632,1.176) |
| 35°   | (-0.150,1.622,1.176) | (-0.150,1.367,1.176) | (-0.158,1.593,1.176) | (-0.150,1.621,1.176) |
| 40°   | (-0.138,1.619,1.176) | (-1.151,1.256,1.176) | (-0.139,1.580,1.176) | (-0.138,1.619,1.176) |
| 45°   | (-0.129,1.614,1.176) | (-0.144,1.171,1.176) | (-0.133,1.567,1.176) | (-0.129,1.614,1.176) |

In addition, it is found that if the data sample set was too small or offset is too big, it is easy to make the approximation failure. In order to prevent the occurrence of such problems, we should try our best to obtain a large amount of data and improve the accuracy of coordinate measurement, in order to ensure the feasibility and accuracy of the method.

CONCLUSIONS

A method of oblique optical axis correction based on BP neural network is proposed in this paper.

1) After theoretical analysis of measurement error caused by oblique optical axis of camera in two-dimensional vision measurement, it is concluded that internal and external parameters of camera are the main factors affecting measurement accuracy. And based on this the feasibility of oblique optical axis correction using BP neural network is analyzed.

2) A visual measurement platform is built. After collecting pictures, data sets are pre-processed, Sigmoid function is used as activation function, and BP neural network model is constructed. Data and labels are imported for training. The results show that the theoretical value of the neural network training model deviates less from the actual value, and the actual deviation angle can be calculated effectively by deducing the acquired pixels. By calculating loss deviation value verified that the fitting effect is well, and the deviation is small.

3) A validation test is designed based on the built visual measurement platform. The three-axis test turntable is used as the test platform. Theoretical calculation data before and after correction and the fitting of neural network are compared with
the real data. The experimental results show that the measurement accuracy of this method \( E_j = 1.3395 \times 10^{-2} \text{mm} \) and \( E_x = 1.75 \times 10^{-2} \text{mm} \), which can meet the calibration requirements of oblique optical axis measurement, and this method has good application prospects.

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REFERENCES

1. Zhang Xiaolong, Yin Shibin, Ren Yongjie, et al. Research on high precision flexible vision measurement system based on global spatial control [J]. Infrared and laser engineering. 2015, 44 (09): 2805-2812.

2. Pan B, Qian K, Xie H, et al. Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review[J]. Measurement Science and Technology. 2009, 20(6): 62001.

3. Chen Daqing, Gu Jihua, Jiang Jinhu. Digital speckle correlation method for in-plane displacement measurement of oblique optical axis [J]. Journal of Optics. 2005 (07): 907-912.

4. Gong Hao, Lu Naiguang, Lou Xiaoping, et al. Adjustment method of optical axis and carrier platform verticality in two-dimensional vision measurement [J]. Journal of Beijing Machinery Industry Institute. 2006 (03): 35-38.

5. Murata N, Nosato H, Furuya T, et al. An automatic multi-objective adjustment system for optical axes using genetic algorithms[C]. 2005.

6. Ryoo J R, Doh T. Auto-adjustment of the Objective Lens Neutral Position in Optical Disc Drives[J]. IEEE Transactions on Consumer Electronics. 2007, 53(4): 1463-1468.
7. Zhao Jingjing, Bai Ruilin, Li Du, et al. New method for adjusting the verticality of optical axis and object surface in embedded machine vision [J]. Photoelectric Engineering. 2010 (05): 63-69.

8. Tang Zhengzong, Liang Jin, Guo Cheng. Digital image correlation method of oblique optical axis based on photogrammetric correction [J]. Journal of Optics. 2011 (11): 157-165.

9. Wang Xiangjun, Yu Tong, Zhang Jiali, et al. DEM and single camera collision coordinate measurement method [J]. Infrared and laser engineering. 2018 (09): 264-269.

10. Jin H, Bruck H A. Theoretical development for pointwise digital image correlation[J]. Optical Engineering. 2005, 44(6): 67003.

11. Xiao Wenjian, Ma Dongxi, Chen Zhibin, et al. Evaluation of optical axis pointing uncertainty for large-scale space angle measurement system [J]. Infrared and Laser Engineering. 2016 (11): 237-243.

12. Zhang Lei, Qiu Wei, Zhang Kai. Parallelism Detection Method of Large Spacing Optical Axis Based on Bipentaprism Module [J]. Infrared and Laser Engineering. 2018 (07): 176-180.

13. Wang Yang, Huang Yu, Li Zhanfeng, et al. Calibration of optical axis parallelism of astronomical observation system using stars [J]. Infrared and laser engineering. 2017 (05): 124-129.

14. Xiao Yingjie, Wang Wei, Deng Shijie, et al. Vibration measurement of two-sided array CCD with vertical optical axis model [J]. Photoelectric Engineering. 2015 (03): 51-59.

15. Liu Changchun, Cao Tingfen, Ye Haixian, et al. Collimation error analysis method of large precision optical system and its application [J]. Journal of Optics. 2015 (09): 236-244.

16. Zhang Tianshu, Jinguang, Liu Chunyu. Optical system design of multi-angle coupled framing camera [J]. China Optics. 2018 (04): 615-622.

17. Han Yanxiang, Zhang Zhisheng, Dai Min. Monocular vision measurement method for target ranging [J]. Optical Precision Engineering. 2011 (05): 1110-1117.

18. Shi Zelin, Kangjiao, Sun Rui. Large field of view imaging distortion correction method based on BP neural network [J]. Optical Precision Engineering. 2005 (03): 348-353.

19. Zhang Xiaoling, Zhang Baofeng, Lin Yuchi, et al. [J]. Optoelectronics. Laser. 2010 (11): 1693-1697.

20. Waluś M, Bernacki K, Konopacki J. Impact of NIR wavelength lighting in image acquisition on finger vein biometric system effectiveness[J]. Opto-Electronics Review. 2017, 25(4): 263-268.