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A New Method for Calibrating Multi-linear CCD in Spatial Objects Exterior Attitude Measurement System

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Abstract. *A new calibration method for the multi-linear CCD exterior attitude measurement system of spatial objects based on back propagation (BP) neural network is proposed in this paper. Linear CCD camera calibration is an fundamental procedure in the exterior attitude measurement system of spatial objects. Traditional methods is direct linear transformation(DLT)method that involve complicated mathematical models, which typically estimate the perspective projection transformation matrix between 3D coordinates in world coordinate system and pixels of matched point in image coordinate system. However, the estimation of the transformation matrix is not accurate and stable. The linear CCD calibration based on BP neural network is proposed by using the ability of neural network which has eRectively dealt with complicated nonlinear mapping. Then the mapping relationship between spatial cooperation target in 3D coordinate system and pixels in image coordinate system is described in the exterior attitude measurement system. The proposed method circumvents reconstructing complicated mathematic model explicitly and utilizes the multi-layer feed forward neural network to compensate the nonlinear error of exterior attitude measurement system introduced by lens distortion as well as other factors of distortion. The experiment results show that the proposed method consistently exhibits higher precision than some traditional methods.*
Keywords: linear CCD calibration; direct linear transformation; back propagation neural network

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1. **Introduction.** The exterior attitude measurement of spatial object has very important effect in the fields of robot research, flexible manufacture, aviation, spaceflight and so on. Compared with the exterior attitude measurement based on the other vision mea-

surements, the measurement system based on multi-linear CCD combination has high precision and rapid speed characteristic, and it is the research hotspot in recent years. Linear CCD camera calibration is a key technology in the exterior attitude measurement system of spatial object [1, 2]. At present, when the exterior attitude measurement system based on linear CCD calculates 3D coordinates, traditional calibration method is often linear, and the common method is direct linear transformation(DLT) method which calculates L coecients of camera DLT equation through some identification points that their spatial 3D coordinates and image point coordinates are known to reconstruct spatial 3D coordinates of identification points. This method need not calculate directly intrinsic and extrinsic parameters of linear CCD camera [3, 4, 5, 6], but it need establish precise mathematical model and has great calculated quantity. At the same time, it is a complicated process that analyzing the system errors brought faulty mathematic model.

Considering the reasons listed above, a linear CCD calibration based on BP neural network is proposed in the foundation of analyzing multi-linear CCD the exterior attitude measurement system of spatial object using neural network' self-learning nonlinear imaging ability that can deal with hardly descriptive system by mathematic model. Multi-layer feed forward neural network can approach continuous function and their every order derivative. BP neural network learns nonlinear mapping relation between 3D spatial object identification point and image point that dispenses with establishing precise mathematic model of measurement system to reconstruct the 3D information of spatial cooperation target and obtain the tri-dimensional attitude [7, 8, 9]. The experiment results show that the measurement accuracy of the method we proposed is higher than it of traditional DLT method.

2. **The Calibration Method of Measurement System.** In the exterior attitude measurement of spatial object based on multi-linear CCD, the linear CCD camera calibration is the premise to obtain precise 3D information of spatial cooperation target.Because linear CCD is one dimension, the reconstruction of 3D coordinates of objects needs three linear CCDs at least. The sketch map of system is shown in Fig 1.

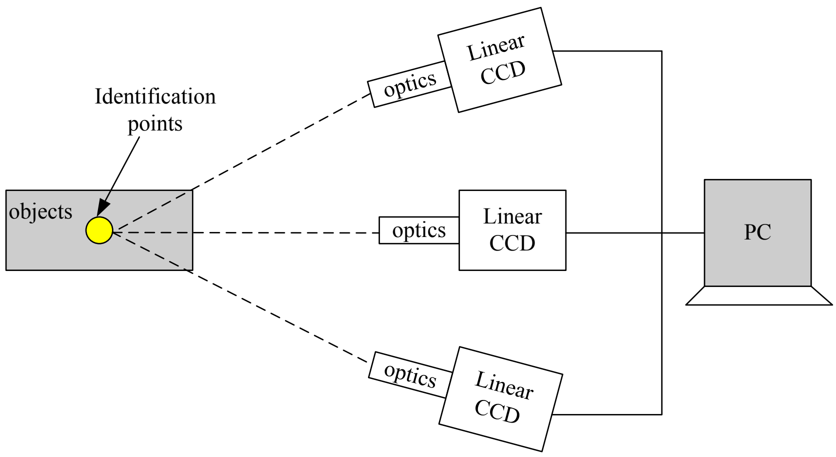

FIGURE 1. The sketch map of system

2.1. **The DLT method.** DLT method calibrates linear CCD camera through some identification points that their spatial 3D coordinates and image point coordinates are known to calculate L coecients of camera DLT equation. It has need seven comparatively absolute L coefficients that to obtain spatial 3D coordinates and image point coordinates of identifcation points. DLT that it is based on the principle of collinearity establishes the direct linear relationship between three dimension world coordinate system and corresponding linear dimension image point coordinate system. The basic equation of DLT is given by

$$u = \frac{L_1X + L_2Y + L_3Z + L_4}{L_5X + L_6Y + L_7Z + 1} \tag{1}$$

where u is the image point coordinates, x, y and z are the world coordinates. The spatial 3D coordinates of identification points can be measured by theodolite and the corresponding image point coordinates in linear CCD camera can be measured by measurement system. According to equation of (1), the seven L coecients can be obtained. The every L coecient is the function of intrinsic and extrinsic parameters that can be inversely calculated by L coefficients.

Equation (1) can be expressed as :

$$L_1X + L_2Y + L_3Z + L4 - uL_5X - uL_6Y - uL_7Z = u \tag{2}$$

Equation (2) has seven unknown L coecients, so it has seven identification points at least that their spatial 3D coordinates and image point coordinates are known to calculate L coefficients. In general, more than seven identification points are selected to calculate the optimum solution of L coefficients by least-squares method. The matrix form for equation (2) is described as follows: Equation (1) can be expressed as :

$$NL = B \tag{3}$$

where

$$\mathbf{N} = \begin{pmatrix} X^{(1)} & Y^{(1)} & Z^{(1)} & 1 & -u^{(1)}X^{(1)} & -u^{(1)}Y^{(1)} & -u^{(1)}Z^{(1)} \\ X^{(2)} & Y^{(2)} & Z^{(2)} & 1 & -u^{(2)}X^{(2)} & -u^{(2)}Y^{(2)} & -u^{(2)}Z^{(2)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X^{(m)} & Y^{(m)} & Z^{(m)} & 1 & -u^{(m)}X^{(m)} & -u^{(m)}Y^{(m)} & -u^{(m)}Z^{(m)} \end{pmatrix}$$

$$\mathbf{B} = \begin{pmatrix} u^{(1)} \\ u^{(2)} \\ \vdots \\ u^{(m)} \end{pmatrix}$$

L coecients can be obtained by generalized inverse matrix.

$$L = N^{+}B \tag{4}$$

After L coecients obtained, equation (2) can be expressed that is rearranged as follows:

$$(uL_5 - L_1)\,X + (uL_6 - L_2)\,Y + (uL_7 - L_3)\,Z = L_4 - u \tag{5}$$

The coordinates(X, Y, Z)can be requested by three equations (5). Usually more than three equations are chosen in order to gain optimal solutions of coordinates using least square method. Then the 3D coordinates of identication points can be obtained.

2.2. **Calibration of linear CCD camera based on BP neural network.** BP network is a multi-layers feed forward neural network. It is composed of input layer, hidden layer and output layer that can implement random nonlinear mapping from input to output. The guide idea of BP neural network is that modifies every layer's network weights and thresholds from output layer along the fastest function descent orientation that is negative gradient orientation according to square error between sample's expected output value and actual output value [10, 11, 12]. The BP neural network model is shown in Fig 2. The network has 3 layers, whose input layer has m neurons, output layer has n neurons, hidden layer has l neurons, number of sample is N, input vector is N, input vector is $x_1, x_2, ..., x_m$, where w^{ji} is connect weight between the j^{th} hidden layer neurons and the i^{th} input layer neurons. The neuron inputs and outputs in hidden layer are respectively:

$$net_j = \sum_{i=1}^{N} w_{ji} x_i \tag{6}$$

$$o_j = f_1\left(net_j\right) \tag{7}$$

where the activation function f_1 of hidden layer neuron usually select S model transforming function, and w_{kj} is connect weight between the kth output layer neurons and the $j^t h$ hidden layer neurons. The activation function f_1 of hidden layer neuron usually select linear transforming function. Thus the k^{th} neuron's outputs in output layer are shown as follows:

$$y_k = f_2\left(\sum_{j=1}^{l}\left(w_{kj} o_j\right)\right) \tag{8}$$

While the expected value of output neuron is t_k, the error of the output neuron is shown as follows:

$$\begin{aligned} E &= \frac{1}{2}\sum_{k=1}^{N}\left(t_k - y_k\right)^2 = \frac{1}{2}\sum_{k=1}^{N}\left(t_k - f_2\left(\sum_{j=1}^{l}\left(w_{kj} o_k\right)\right)\right) \\ &= \frac{1}{2}\sum_{k=1}^{N}\left(t_k - f_2\left(\sum_{j=1}^{l}\left(w_{kj} f_1\left(\sum_{i=1}^{N} w_{ji} x_i\right)\right)\right)\right) \end{aligned} \tag{9}$$

In the process of calibration using BP neural network, some points which are dispersive and nonlinear are chosen as the training set. The coordinates (X, Y, Z) of these points are measured accurately by 3D coordinate measurement machine , then the projection of points on the CCD are used as inputs to train the network.The parameters of network are calculated by several iteratives. In the measurement, the inputs are the project coordinates of identification points, and the outputs are the actual 3D coordinates [13].

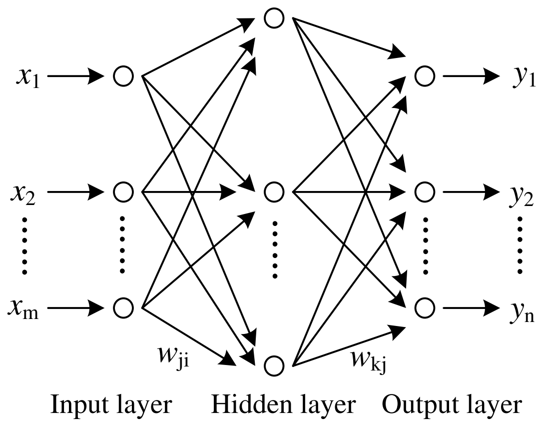

FIGURE 2. Three-layer BP neural network model

3. Experiments.

3.1. **The obtainment of sample data.** In the experiment, the measured point that is the point cooperation target of spatial object uses the point light-emitting diode(LED). Because the precision of identification point position in the drone inXuences directly the calibration precision of linear CCD camera, experiments use a 3D coordinate measuring machine to construct virtual stereo-drone. The point LED is put on the column of 3D coordinate measuring machine and removes on the plane and depth orientation along with the column removing. As can be seen from Fig 3.

Twenty identification points are selected randomly as the linear CCD calibration point whose spatial coordinates are obtained by 3D coordinate measuring machine. Combining the image point coordinate from linear CCD, the sample data can be obtained.

During the neural network training, the transfer function of hidden layer and it of the output layer all use the pureline function. In the experiment, the single hidden layer number is 4 and every layer has twenty neurons. Except for twenty identification points as training set, seven point is selected randomly as test point set.

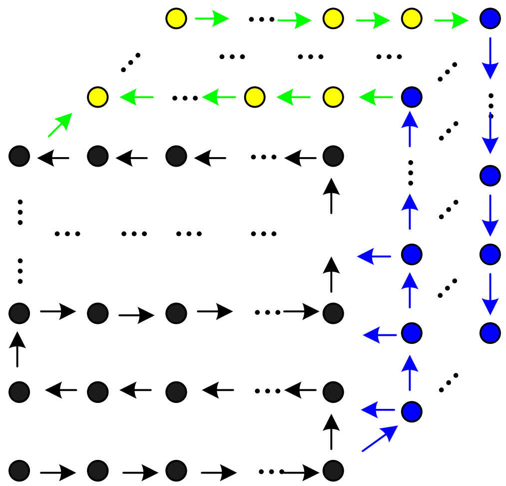

FIGURE 3. 3D target

3.2. **Experiment results.** The calibration method based on BP neural network we proposed compares with common DLT method in the experiment. Using these two methods recover 3D coordinates of the measured points. And the root-mean-square error(RMS) between seven points coordinates that are obtained by two methods and real world coordinates is regarded as the calibration precision index, which is shown as follows:

$$e_p = \sqrt{\frac{(x - x_w)^2 + (y - y_w)^2 + (z - z_w)^2}{3}} \tag{10}$$

$$e_m = \sqrt{\frac{(e_1)^2 + (e_2)^2 + ... + (e_i)^2}{N}} \, (i = 1, 2, ..., N) \tag{11}$$

where e_p is the RMS of random point, e_m is the RMS of all the test point set, x, y and z are the coordinate value calculated by BP neural network, x_w, y_w and z_w are the real coordinate value of the test points, e_i is the RMS of the j^{th} point, N is the number of the test point.

The effect graph of space coordinate reconstruction for the test point set is shown in Fig 4. The RMS between seven points coordinates and real world coordinates are obtained by two methods, which is shown in Table 1. According to the data from table, the method based on BP neural network can calibrate linear CCD camera of the exterior attitude measurement system primely, whose precision is 47.4% higher than that of DLT method.

4. **Conclusions.** A linear CCD camera calibration based on BP neural network is proposed. Using the powerful approach ability of BP neural network for complicated nonlinear mapping relationship, it establishes the relationship between 3D spatial cooperation target coordinates and corresponding image point coordinates of linear CCD in the exte-

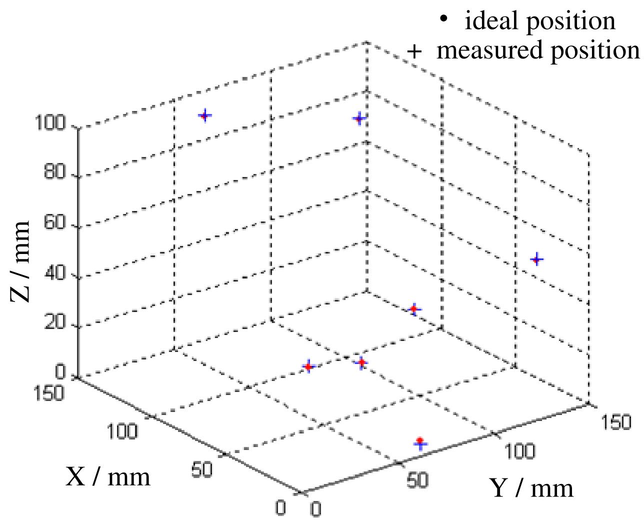

Figure 4. Effect graph of space coordinate reconstruction by the proposed method

Table 1. Root mean square error of spatial point coordinate reconstruction.

	1	2	3	4	5	6	7	$e_m(mm)$
DLT	1.25	0.52	0.61	1.18	0.59	0.32	0.26	0.76
BP	0.40	0.32	0.47	0.53	0.28	0.34	0.38	0.40

rior attitude measurement system to calculate the attitude of spatial object. This method need not consider the influence brought by lens distortion , environment factor and so on. It can reduce the system errors due to the mathematic model faultiness, advance the measurement accuracy and is a effective method of exterior attitude measurement system of spatial object. The results show that this method can obtain higher precision.

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