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Study on Comparative Analysis of Camera Calibration

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Abstract. Several error factors exist when restoring three-dimensional images from two-dimensional images acquired by cameras. In particular, studies that interpret error factors from camera parameters are critical to stereo convergence and three-dimensional image restoration performance. Several error factors exist when restoring three-dimensional images from two-dimensional images acquired by cameras. In particular, in order to interpret the error factors arising from the camera parameters, the camera inspection was performed by applying the methods of calibration of the Tsai camera and the Direct Linear Transformation (DLT) camera calibration using various images entered by the camera. The camera inspection was carried out by applying the method of calibration of the Tsai camera and the method of calibration of the DLT camera. The performance of each camera calibration method was compared by presenting the results of evaluating stereo convergence and restoration performance using camera parameters obtained through camera tests. Modeling techniques for the camera test process were presented through this study. In the future, it is believed that these findings will be used as basic data for image information correction when obtaining image information from the imaging system.

Keywords: Camera Calibration, Tsai Calibration Method, Three-dimensional Images, Camera Parameter, Direct Linear Transformation, Computer Vision

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INTRODUCTION

Camera calibration is to determine spatial pose and positional relation of camera in the process of determining geometrical relationship between any image point and any point on 3D spatial coordinates, and to calibrate image distortion arising from this process, which is a very important issue in the field of computerized visual recognition. Only when these camera parameters are accurately calibrated, an accurate 3D real position can be obtained from the image coordinates, and conversely, 2D image coordinates can be accurately estimated from 3D real coordinate[1,2].

As a basic research for the development of 3D TV, it is necessary to formulate the correlation between interior and exterior parameters of camera for camera calibration. Interior parameters of camera include characteristics of camera and lens itself, principal point, focal distance and distortion parameters, and exterior parameters of camera include those related to the external environment of camera such as camera rotation and position movement. Information on these parameters can be obtained by a precise optical experiments, or estimated using the geometric relationship between camera and control points.

The normal zoom lens cameras that are currently in use have a lot of merits in acquiring images, but they are geometrically unstable in the course of acquiring real images, and have considerable difficulties in calibrating camera lens due to various zoom movements during the shooting process. Since the camera parameters for calibrating zoom lens are different at each zooming point, the calibration parameters are calculated over various focal distances during the calibration of camera lens, and especially, if the zoom is moved at the time when the lens calibration has already been completed, there are difficulties to recalculate the camera calibration parameters[3,4,5].

Accordingly, this study proposes a comparative analysis on Tsai's camera calibration method and DLT (Direct Linear Transformation) calibration method used to acquire accurate images available for computer vision or photogrammetry that has calibrated zoom lens distortion.

2. Camera Calibration Method

When you know the real-world spatial coordinates for any points, you can use camera parameters associated with camera model to calculate the coordinates projected into images for three-dimensional points in the image coordinate system. However, the zoom lens model is difficult to directly apply a fixed focus lens model such as pinhole camera used in a single lens camera, so the individual fixed focus lens model is erected at each discrete point in time, when the zoom movement occurs, to perform calibration.

Principal point, focal distance, three radial distortion parameters and two tangential distortion parameters can be taken into account as the camera interior parameters, and the camera exterior parameters include rotation matrix and translation vector from the origin of the real-world spatial coordinate to the origin of the camera spatial coordinate.

In order to obtain these cameral parameters, this study conducted a comparative analysis of two camera calibration techniques; Tsai's calibration method and DLT (Direct Linear Transformation) calibration method[6,7].

2.1 Tsai's Calibration Method

Figure 1. shows a Tsai camera model assuming parallelism constraint where a 3D spatial coordinate $P(x_w, y_w, z_w,)$, a coordinate projected on the image by radial distortion $Pd(X_d, Y_d)$, and an image coordinate without radial distortion $Pu(X_u, Y_u)$ meet the parallelism condition at all time like equation (1), regardless of the degree of radial distortion or the distance from the camera.

$$\overline{O_i Pd} // \overline{P_{oz} P} // \overline{O_i Pu} \quad (1)$$

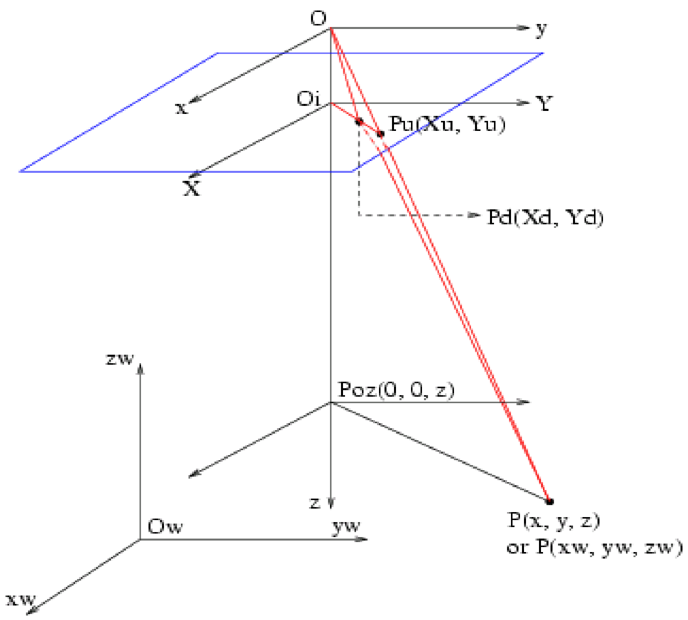

Figure 1 Tsai's Camera Model (Parallelism Constraint)

Tsai's calibration method calculates the camera parameters from a relational equation between control point and the image projection point on the 3D spatial coordinate, based on parallelism constraint in the above equation (1).

2.2 DLT (Direct Linear Transformation) Calibration Method

In order to decide theses interior and exterior parameters of camera, this study conducted camera calibration by means of DLT (Direct Linear Transformation) technique based on the collinearity condition that the lens center of camera, the image point in photograph, and the corresponding target point on the actual 3D space must be placed in a straight line.

When you know the real-world spatial coordinate for any points, you can use camera parameters associated with camera model to calculate the coordinates projected into images for three-dimensional points in the image coordinate system. However, the zoom lens model is difficult to directly apply a fixed focus lens model such as pinhole camera used in a single lens camera, so the individual fixed focus lens model is erected at each discrete point in time, when the zoom movement occurs, to perform calibration. Principal points (X, Y, Z), three radial distortion parameters and two tangential distortion parameters can be taken into account as the camera interior parameters, and the camera exterior parameters include translation vector, x', y' and z' from the origin of the real-world spatial coordinate to the origin of the camera spatial coordinate [8,9,10]. In order to obtain these cameral parameters, this study applied a camera calibration technique under DLT (Direct Linear Transformation).

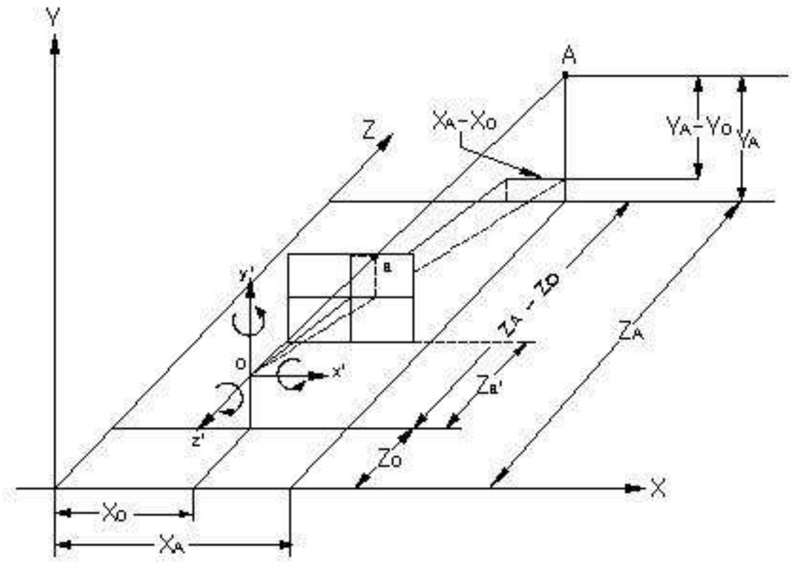

Figure 2 Collinearity condition in the ground photogrammetry

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3. 3D Restoration applying Tsai's Calibration Method

Camera parameters obtained through the calibration process in Chapter 2 allow a stereo camera system to be modeled on 3D space as shown in Figure 3.

In such case, 3D spatial coordinate for P_1 and P_2, the matching points of the right camera (R) with respect to the left camera (L), can be expressed as coordinates of intersection points for $k_1\overrightarrow{R_1}$ and $k_2\overrightarrow{R_2}$, the vectors extended at a certain ratio, $\overrightarrow{R_1}=\overline{O_1P_1}/\left|\overline{O_1P}_1\right|$ and $\overrightarrow{R_2}=\overline{O_2P_2}/\left|\overline{O_2P}_2\right|$, the unit vectors for O_1 and O_2 for the optical axis centers of each camera.

However, in general, the vectors, $k_1\overrightarrow{R_1}$ and $k_2\overrightarrow{R_2}$, cannot intersect exactly at one spatial coordinate due to the matching errors caused by errors in the resolution of images or calibration parameters. Therefore, taking these errors into account, it is possible to approximate the position of the intersection point at the position where the distance between two vectors, $k_1\overrightarrow{R_1}$ and $k_2\overrightarrow{R_2}$, becomes the shortest. In such case, the intersection point, where the distance between two vectors, $k_1\overrightarrow{R_1}$ and $k_2\overrightarrow{R_2}$, becomes the shortest, may be assumed to be mid-positioned on the vector $\vec{D}$ perpendicular to both vectors, and the vector $\vec{D}$ perpendicular to both vectors can be expressed as outer products of $\overrightarrow{R_1}$ and $\overrightarrow{R_2}$ as shown in Equation (2).

$$\vec{D} = \overrightarrow{R_1}\times\overrightarrow{R_2} \qquad (2)$$

Consequently, 3D spatial coordinates for the matching points of the two cameras are expressed like the vector equation (3).

$$k_1\overrightarrow{R_1} - k_2\overrightarrow{R_2} + \mathrm{d}\cdot\vec{D} = \vec{b} \qquad (3)$$

Where, d and $\vec{b}$ represent the length of $\vec{D}$, the vector of intersection point, and the baseline distance vector between the left and right cameras, respectively.

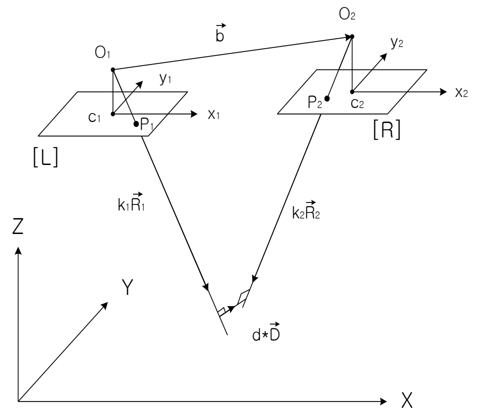


Figure 3 Relationship between parallax and intersection point of stereo model

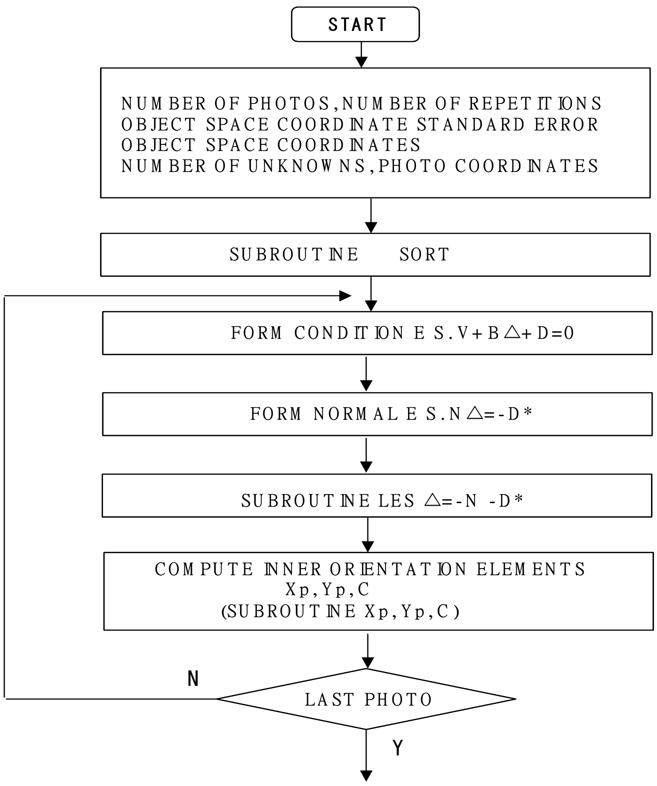
If we conduct vector analysis on equation (3) again, we can interpret the scale factors, k_1, k_2, and d as shown in equation (4).

$$k_1 = \frac{\vec{b}\cdot\vec{D}\times\vec{R_2}}{\vec{R_1}\cdot\vec{D}\times\vec{R_2}}\ ,\ k_2 = \frac{\vec{R_1}\cdot\vec{D}\times\vec{b}}{\vec{R_1}\cdot\vec{D}\times\vec{R_2}}\ ,\ \mathrm{d} = \frac{\vec{R_1}\cdot\vec{b}\times\vec{R_2}}{\vec{R_1}\cdot\vec{D}\times\vec{R_2}} \qquad (4)$$

Therefore, if equation (4) is put into equation (3), 3D spatial coordinate for the intersection point is expressed as shown in equation (5).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{O_1} \\ Y_{O_1} \\ Z_{O_1} \end{bmatrix} + k_1 \begin{bmatrix} R_{1_x} \\ R_{1_y} \\ R_{1_z} \end{bmatrix} + 0.5\mathrm{d} \begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} \qquad (5)$$

The following Figure 4 shows the flow chart of Direct Linear Transformation(DLT).



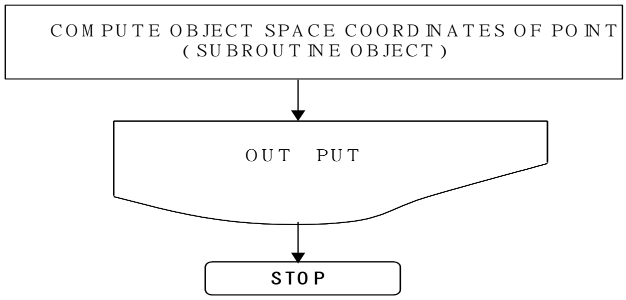


Figure 4 Flow chart of Direct Linear Transformation(DLT)

4. Analysis of experimental results

In order to evaluate the restoration performance according to the distance from camera in 3D space, subjects were installed at various distances from camera in the experimental image, and Tsai's calibration method and DLT calibration method were conducted for the acquired images, and the performance of each method were evaluated. Stereo matching and 3D restoration performance were also evaluated using camera parameters obtained from camera calibration.

4.1 Camera Calibration using Tsai's Coplanar Method

In order to evaluate the performance of camera calibration using Tsai's coplanar method, this study conducted a camera calibration, making one section of the cubic model in size as a control point, and the performance was evaluated in a manner of restoring cubic model based on camera parameters obtained therefrom. Table 1 shows the calculated value of camera parameters (mm). Table 2 represents the results of error analysis on camera calibration using Tsai's coplanar method.

Table 1 Camera Parameters ($\boldsymbol{mm}$)

	f[1]	k1[2]	T_x[3]	T_y	T_z	R_x[4]	R_y	R_z	s_x[5]	C_x[6], C_y
Left	17.52	-4.63e-9	-27.34	113.97	1934.34	61.94	-32.58	-162.14	0.75	1003.40, 550.46
Right	16.48	-2.98e-9	-29.64	121.77	1819.49	102.05	-35.20	-162.26	0.75	960.25, 539.88

Table 2 Results of error analysis on camera calibration using Tsai's coplanar method

Control Point		Average of restoration errors			Standard deviation of restoration errors		
Left	Right	X	Y	Z	X	Y	Z
1.225	1.239	2.945	4.128	2.874	3.417	4.877	3.446

4.2 Camera Calibration using Tsai's Non-coplanar method

In order to the performance of camera calibration using Tsai's non-coplanar method, this study tested two settings. The first is to use cubic model like the coplanar method, and the second is to evaluate the performance of camera calibration using a random control point distributed in the image. Non-coplanar camera calibration was conducted using a cubic model. Like the Coplanar method, camera calibration was

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1 f: focal length

2 k1: Radial distortion parameters

3 T_x T_y T_z: Translation vector

4 R_x R_y R_z: Rotation matrix

5 S_x: Scale vector

6 C_x C_x: Principal coordinate

conducted, making three planes of the cubic model as control points, and the performance was evaluated in a manner of restoring cubic model based on camera parameters obtained therefrom.

Table 3 shows the calculated value of camera parameters (mm). Table 4 represents the results of error analysis on camera calibration using Tsai's non-coplanar method.

Table 3 Camera Parameters ($\boldsymbol{mm}$)

	f	k1	T_x	T_y	T_z	R_x	R_y	R_z	s_x	C_x, C_y
Left	17.92	-5.57e-4	-17.28	137.13	1984.99	62.54	-32.97	-162.38	0.75	978.13, 535.84
Right	18.33	-1.10e-3	-7.21	138.27	2045.35	101.79	-35.96	-162.13	0.76	926.34, 517.62

Table 4 Results of error analysis on camera calibration using Tsai's non-coplanar method

Control Point		Average of restoration errors			Standard deviation of restoration errors		
Left	Right	X	Y	Z	X	Y	Z
1.208	1.183	2.459	3.322	2.190	1.950	2.816	1.861

As shown in the experimental results, both camera calibrations using Tsai's coplanar method and non-coplanar method show similar results, but the performance of non-coplanar method seems to be slightly superior because the non-coplanar method expresses more information about the space through a random control point.

In conclusion, it can be confirmed that Tsai's camera calibration method affects the result of camera calibration according to the method of setting the control point. However, the error of each method is within a negligible error range depending on the purpose of using the stereo image system. Therefore, the appropriate camera calibration method can be used depending on the purpose.

4.3 Camera Calibration using DLT Method

The accuracy of DLT camera calibration was conducted in two aspects as follows. The first was to evaluate accuracy after analyzing the difference between the 3D position estimated from the calculation of model equation and the actually observed 3D position, and the second was to evaluate accuracy in an absolute manner according to the pixel position projected on the image plane in 3D space of the object, that is, the accuracy of the pixel unit.

Table 5 is the result of conducting calibration using the basic DLT coefficients and calculating 3D position, showing that the error from the actual 3D observed value is 1.985cm in the X direction, 12.376cm in the Y direction and 1.283cm in the Z direction.

Table 5 Comparison of 3D positioning results with 11 DLT coefficients and the observed values (unit: cm)

View points	Observation points			Modeling result points			Errors		
	X	Y	Z	X	Y	Z	ΔX	ΔY	ΔZ
1	60.02	610.603	56.497	54.299	630.213	59.496	5.721	-19.61	-2.999
2	89.845	620.181	56.096	88.093	626.135	56.953	1.752	-5.954	-0.857
3	119.626	615.424	56.306	119.622	611.355	55.57	0.004	4.069	0.736
4	164.595	624.99	55.471	164.342	612.328	53.766	0.253	12.662	1.705
5	209.18	615.195	55.532	211.189	634.202	58.834	-2.009	-19.007	-3.302
6	238.38	617.552	55.183	239.287	620.346	55.607	-0.907	-2.794	-0.424
7	269.584	610.227	55.271	275.344	630.731	58.595	-5.76	-20.504	-3.324
8	89.845	620.181	31.105	91.516	608.309	29.809	-1.671	11.872	1.296
9	239.462	620.088	30.459	241.391	629.118	31.479	-1.929	-9.03	-1.02
10	59.953	610.233	6.511	60.839	607.109	6.118	-0.886	3.124	0.393
11	89.899	620.131	6.122	92.423	603.005	5.424	-2.524	17.126	0.698
12	119.685	615.01	6.318	117.198	632.701	6.896	2.487	-17.691	-0.578
13	164.627	624.929	5.687	164.374	663.178	6.916	0.253	-38.249	-1.229

14	209.296	614.998	5.591	211.293	635.249	6.239	-1.997	-20.251	-0.648
15	239.508	619.984	5.478	239.697	622.109	5.518	-0.189	-2.125	-0.04
16	269.585	610.069	5.368	267.26	603.369	5.021	2.325	6.7	0.347
17	59.901	610.311	-43.48	59.839	609.189	-43.563	0.062	1.122	0.083
18	89.965	620.052	-43.889	89.949	617.651	-43.878	0.016	2.401	-0.011
19	119.786	615.054	-43.649	120.328	608.829	-43.342	-0.542	6.225	-0.307
20	164.635	624.96	-44.374	163.8	606.808	-42.764	0.835	18.152	-1.61
21	209.416	614.861	-44.392	210.468	623.921	-45.409	-1.052	-9.06	1.017
22	239.586	620.186	-44.548	242.87	636.551	-46.319	-3.284	-16.365	1.771
23	266.947	604.138	-44.223	272.384	621.475	-45.891	-5.437	-17.337	1.668
24	89.996	620.059	-68.865	88.692	625.129	-69.773	1.304	-5.07	0.908
25	239.708	619.875	-69.544	233.169	590.764	-64.97	6.539	29.111	-4.574
Average							1.985	12.376	1.283

Table 6 shows the calibration results using the basic 11 DLT coefficients for images taken at a distance of 1m from the calibration plate and about 5m from the camera, indicating accuracy errors of 1.1cm in the X direction, 62.4cm in the depth direction (Y) and 0.77cm in the Z direction.

Table 6 Calibration accuracy for images (distance from calibration plate: 1m, 11 DLT coefficients)

Observed Value (cm)			DLT calculation value (cm)			Error (cm)		
X	Y	Z	X	Y	Z	ΔX	ΔY	ΔZ
165.535	467.168	-13.195	164.864	542.351	-13.973	0.671	75.183	0.778
145.799	485.374	-5.59	144.340	572.727	-5.754	1.459	87.353	0.164
165.677	504.569	0.386	164.617	544.880	-0.31	1.06	40.311	0.696
185.367	486.065	-7.188	186.663	569.719	-8.151	1.296	83.654	0.963
144.493	495.063	-31.907	144.425	564.141	-32.142	0.068	69.078	0.235
164.346	476.734	-39.527	164.002	532.851	-39.542	0.344	56.117	0.015
184.183	495.621	-33.523	181.409	520.743	-31.007	2.774	25.122	2.516
Average						1.10	62.40	0.77

5. Conclusion

This study compared stereo image correction techniques using Tsai's camera calibration method and DLT camera calibration method.

Tsai's coplanar/non-coplanar techniques were able to obtain the reliable interior/exterior parameters of camera in the simulations. DLT method was not able to conduct camera calibration based on a control point existing on a plane, but it was confirmed that a stable camera calibration could be performed at high speeds, taking into account the general environment, such as 3D TV or modeling, and the placement of control point.

Both methods seem to be greatly affected by the performance, depending on the distribution of control points in the image. Therefore, the control points should be evenly placed when using in the actual measurement environment.

Analysis results of camera calibration obtained from this study are thought to be used as reference data for camera calibration when obtaining precise 3D image information in the future.

6. Acknowledgment

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