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Analysis of different camera calibration methods on a camera-projector measuring system

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Abstract

The accuracy of metrology equipment formed by a camera-projector pair depends directly on the calibration procedure used. This kind of equipment allows to perform the calibration by two different approaches: as a whole system or separately. The most common approach is the second one: conventional calibration. Studies show that the uncertainty of the camera parameters from its calibration propagates to the projector parameters. The objective of this study is to have a clear comprehension of the relationships between the camera and projector parameters and of how uncertainty is propagated. This will be done by using a camera previously calibrated by Tsai, Zhang or Direct Linear Calibration (DLC) methods, followed by the calibration of the projector using DLC.

Keywords: Projector-camera calibration; Error propagation

1. Introduction

Nowadays, 3D measurement systems are extensively applied in industrial metrology, medicine, cultural heritage and other areas [1-5] and many of those applications require considerable measurement accuracy. This is why it is important to study and improve this kind of systems. The accuracy of 3D measurement systems formed by a camera-

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projector pair depends to some extent on the accuracy of the calibration of the whole measurement system. Single camera calibration has been extensively studied and numerous calibration methods have been proposed [6-8]. Several authors conclude that the three most widespread are: Tsai, Zhang and Direct Linear Calibration. Several authors conclude that the three most widespread are: Tsai, Zhang and Direct Linear Calibration. Tsai is based on the model of the pin-hole camera, this model transforms points in the world reference frame (*Xw, Yw, Zw*) to points in the frame of image reference (*u, v*) and considers radial distortion. Zhang also uses traditional calibration techniques (known calibration points) and self-calibration techniques (correspondence between calibration points when they are in different positions). Moreover, this method considers and compensates three distortion types: radial distortion, decentering distortion and thin prism distortion. Direct Linear Calibration ignores the lens distortion and it is based on the co-linearity between a point expressed in the world reference system (*x, y, z*), its directly equivalent in the image reference coordinates (*u, v*) and the central projection point of the camera [9]. On the one hand, the comparison of these methods shows their advantages and disadvantages in different situations [10-11]. On the other hand, there are studies that are focused on how distortions affect the results [12-13]. When a projector is included in the system, it is usually modelled as an inverse camera because it works fundamentally like a pin-hole reverse camera, projecting an image instead of capturing it [14]. Therefore, it is possible to calibrate it with any conventional camera calibration method. This presents the option to calibrate the system by two different approaches: as a whole system or separately. The most common approach is the use of a camera previously calibrated, followed by the calibration of the projector, using the Direct Linear Calibration method, with this camera. Nevertheless, studies show that with this method the uncertainty derived from the camera calibration procedure propagates to the projector [15], and consequently the importance of the camera calibration increases. Authors have analyzed the system sensitivity to each factor in a rigid configuration, using only the Direct Linear Calibration method in both calibrations (camera and projector), and have verified the effect of the errors on the lens distortion parameters, extrinsic parameters, concluding that the first ones have the greatest impact [16]. In this study, a camera previously calibrated by Tsai, Zhang and Direct Linear Calibration methods was used, followed by the calibration of the projector using Direct Linear Calibration. The objective of this study is to provide two contributions: from a general point of view, to obtain a better understanding of the relationship among the camera and projector parameters, and how uncertainty propagates from the camera to the projector. Specifically, the comparison of the three configurations (camera calibration by DLC, Tsai and Zhang, and projector calibration by DLC) as well as the advantages and disadvantages of each of them and how to compensate them.

Nomenclature

DLC	Direct Linear Calibration method
dx	Image pixel size in X
dy	Imagen pixel size in Y
Cu	Coordinates u of principal point (center of camera coordinates)
Cv	Coordinates v of principal point (center of camera coordinates)
Ncx	Number of sensor elements in x direction of the camera
Nfx	Number of pixels in x direction of the frame grabber
k1	First order radial lens distortion coefficient
f	Focal length
Tx	Part of translational vector referring to translation in X axis
Ty	Part of translational vector referring to translation in Y axis
Tz	Part of translational vector referring to translation in Z axis

2. Methodology

The three calibration configurations of the complete system were simulated in MATLAB. The camera was calibrated by three different methods: Direct Linear Calibration, Tsai and Zhang. Once the camera was calibrated, the projector calibration was executed by the Direct Linear Calibration method. In each of these configurations, some of the factors that could influence the generation of uncertainty on the results were analyzed by using synthetic experiments based on the Monte Carlo method (1000 simulations for each configuration).

The factor selection was determined by a preliminary mathematical analysis of the three calibration methods. We could appreciate that the camera data corresponding to the size of the pixel (*dx* and *dy*) and the center of the camera coordinates (*Cu* and *Cv*) directly affect the calculation of the camera calibration intrinsic and extrinsic parameters in the Direct Linear Calibration and Tsai methods. On the other hand, those camera data (*dx* and *dy*) only affect the focal length calculation (*f*) in calibration Zhang method. The robustness of this method prevents directly affecting most of the camera calibration intrinsic and extrinsic parameters calculation. In this case, the measurement error is affected mostly by extrinsic parameters and distortion calculation. For that reason, it was decided that an error was introduced in the parameters that interfere in the calculation of the camera calibration extrinsic parameters and a radial lens distortion of calibration Zhang method. An error was introduced in the parameters *dx, dy, Cu* and *Cv* for Direct Linear Calibration and Tsai methods. It was decided that the errors mentioned before follow a normal Gaussian distribution.

3. Results

The synthetic experiment based on the Monte Carlo method simulated the calibration of a measurement system formed by a camera-projector pair separately. The projector resolution was 1024x768, the camera radial lends distortion coefficient was $k1$=0.0015 and the camera data are shown in Table 1.

Table 1: Camera data

PIXELINK					
dx (mm)	dy (mm)	Cu	Cv	Ncx	Nfx
0.0067	0.0067	1280/2	1024/2	1280	1280

The first part of this section shows the behavior of the different parameters of the camera and the projector, obtained by a Monte Carlo synthetic experiment in MATLAB. For this simulation, a ±5% error was introduced in the camera data: *dx*, *dy*, *Cu* and *Cv*. As an example, Fig 1 shows the results of camera focal length calculation by the three different methods in function of camera *dy*.

The projector focal length calculation, in DLC-DLC configuration and Zhang-DLC configuration, was no significant affected by the introduction of error in camera data. It was only in Tsai-DLC configuration that projector focal length calculation was affected. Fig 2 shows the results of that.

For the rest of parameters calculation and measurement error in Zhang-DLC configuration, a ±0.5% error was introduced in the parameters that interfere in the calculation of the camera calibration extrinsic parameters and a radial lens distortion of calibration Zhang method.

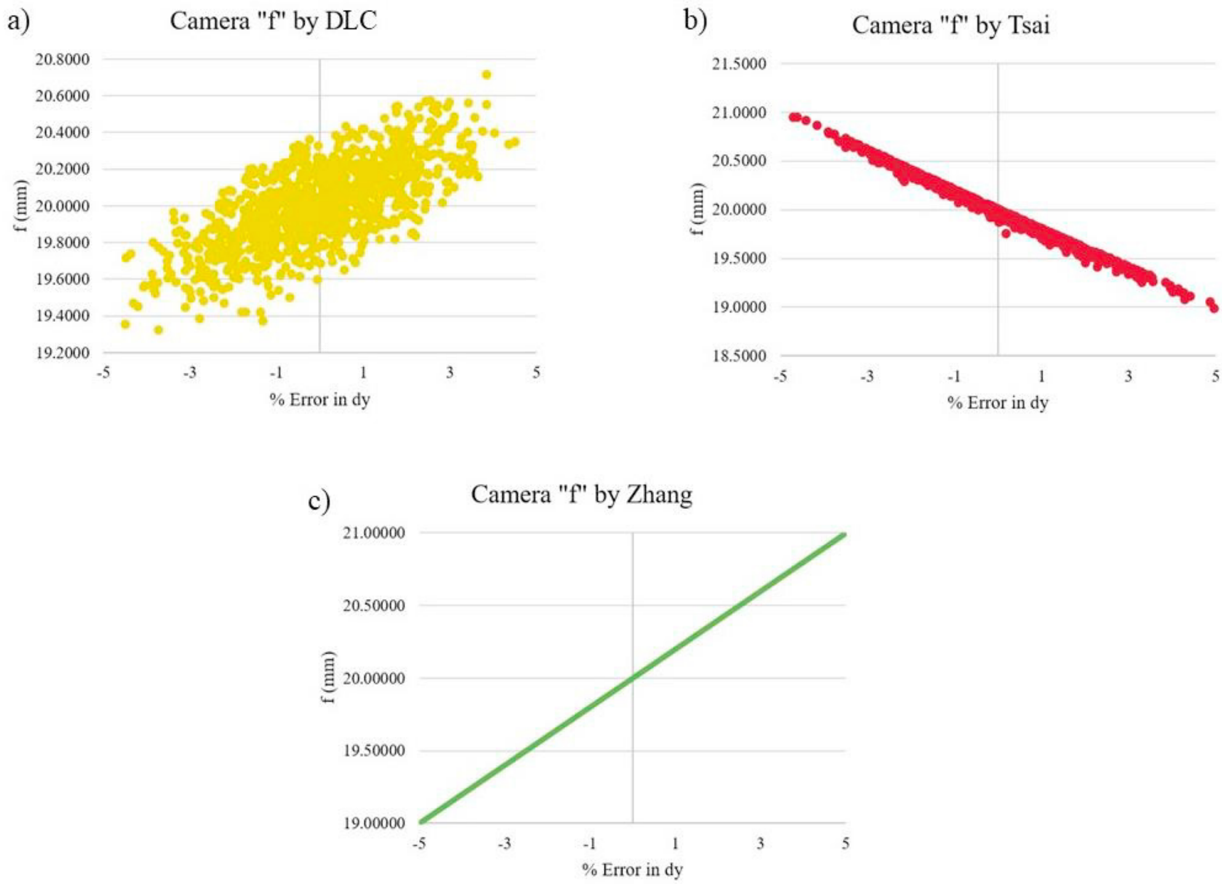

Fig. 1. (a) Camera f by DLC; (b) Camera f by Tsai; (c) Camera f by Zhang.

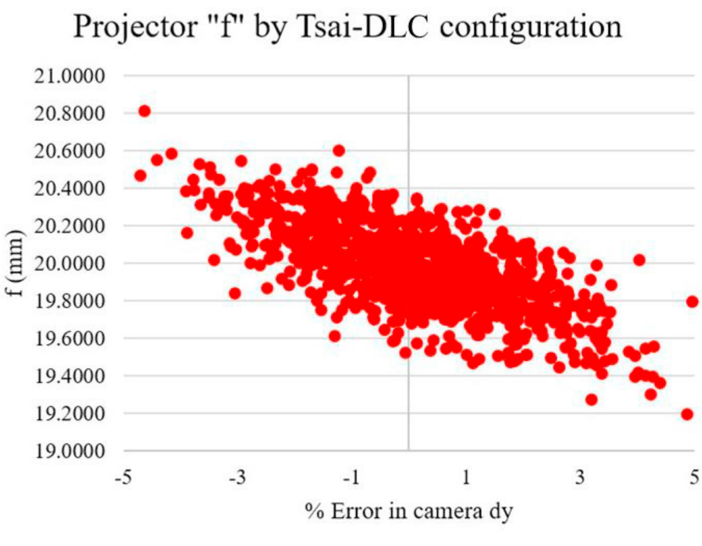

Fig. 2. Projector f in Tsai-DLC configuration.

It was observed that the camera calibration extrinsic parameters substantially affected the projector calibration extrinsic parameters, even when it was simulated a projector without errors. As an example of this, it is shown the results obtained in the translational vector calculation when nominal distances were 90 mm in X axis, 90 mm in Y axis and 900 mm in Z axis. Table 2 displays the average error values and standard deviation that were obtained in the camera translational vector.

Table 2. Camera translational vector error

	DLC			TSAI			ZHANG		
	Tx (mm)	Ty (mm)	Tz (mm)	Tx (mm)	Ty (mm)	Tz (mm)	Tx (mm)	Ty (mm)	Tz (mm)
AVG.	3.2110	2.9510	2.7000	6.4965	4.0900	0.2100	2.8102	2.0547	1.1397
STD. DESV.	2.0304	2.4937	0.5080	3.8572	2.6271	1.4626	1.5522	2.0781	0.8005

Table 3 displays the average error values and standard deviation that were obtained in the projector translational vector.

Table 3. Projector translational vector error

	DLC-DTC			TSAI-DLC			ZHANG-DLC		
	Tx (mm)	Ty (mm)	Tz (mm)	Tx (mm)	Ty (mm)	Tz (mm)	Tx (mm)	Ty (mm)	Tz (mm)
AVG.	2.3010	1.6765	0.8100	4.482	3.2720	0.2700	1.8734	1.6819	0.9497
STD. DESV.	2.1684	1.7746	0.2834	4.0529	2.6225	1.4701	1.5969	1.3224	0.5774

The second part of this section shows the results corresponding to the mean measurement errors and their standard deviation, obtained by a Monte Carlo synthetic experiment in MATLAB. As in the case of calibration extrinsic parameters, it was observed that the camera measurement error affected both the projector measurement error and camera-projector measurement error. Table 4 displays the measurement error in the camera after introducing the previous mentioned error.

Table 4. Camera measurement error after calibration

	DLC		TSAI		ZHANG	
	Error X (mm)	Error Y (mm)	Error X (mm)	Error Y (mm)	Error X (mm)	Error Y (mm)
AVG.	0.0047	-0.0018	-0.1398	-0.0301	0.0011	0.0010
STD. DESV.	0.0117	0.0281	1.9279	0.8193	0.0003	0.0002

Table 5 displays the measurement error in the projector, originally without errors, after introducing the previous mentioned error.

Table 5. Projector measurement error after calibration

	DLC-DLC		TSAI-DLC		ZHANG-DLC	
	Error X (mm)	Error Y (mm)	Error X (mm)	Error Y (mm)	Error X (mm)	Error Y (mm)
AVG.	0.0006	-0.0008	-0.1419	-0.0497	0.0003	0.0002
STD. DESV.	0.0117	0.0093	3.8593	2.6798	0.0002	0.0003

In Table 6, it is possible to observe the measurement error in the camera-projector pair system for the three combinations of calibration methods (DLC-DLC, Tsai-DLC and Zhang-DLC).

Table 6. Camera-Projector measurement error after calibration

	DLC-DLC		**TSAI-DLC**		**ZHANG-DLC**	
	Error X (mm)	Error Y (mm)	Error X (mm)	Error Y (mm)	Error X (mm)	Error Y (mm)
AVG.	0.0054	-0.0025	-0.1463	-0.0499	0.0014	0.0011
STD. DESV.	0.0225	0.0365	3.8565	2.6798	0.0002	0.0002

As may be observed, the Zhang-DLC configuration provided the smallest measurement error values because its base error, camera measurement error, was the smallest too. The camera-projector measurement error result is the combined effect of both sets of extrinsic parameters (camera and projector), therefore, some errors can be balanced with the others. It is important to mention that the DLT method does not take into account the lens distortion; therefore, it is necessary, after the calibration, to make some type of subsequent optimization, for example the bundle method [16].

It is also possible to observe that the statistical error distribution was maintained until the latest measurement error results [17]. In Fig 3, the measurement error distribution of Zhang-DLC combination after applying the Monte Carlo method is shown. It can be noted that the distribution may be considered a Gaussian distribution in both histograms.

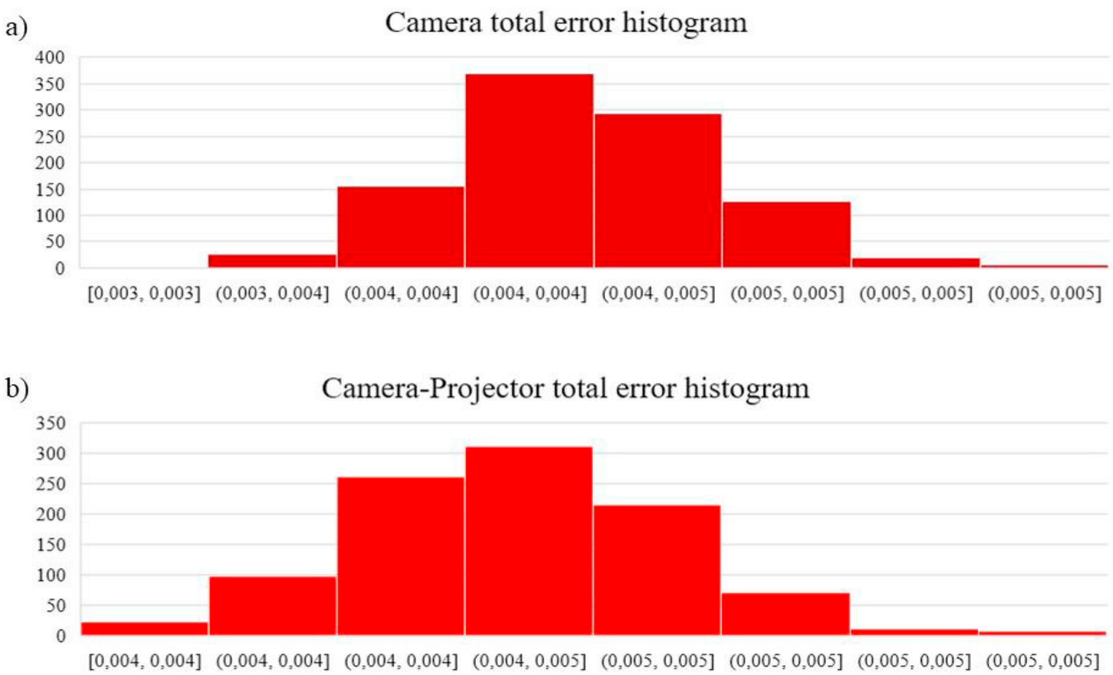

Fig. 3. (a) Camera total error histogram of Zhang-DLC configuration; (b) Camera-Projector total error histogram of Zhang-DLC configuration.

4. Conclusion

Numerous simulations were performed in MATLAB by the Monte Carlo method to characterize the behavior of measurement errors in a camera-projector pair, when they are calibrated separately. To understand the relationships between the camera and projector parameters better, and how uncertainty propagates from the camera to the projector, two error types were introduced. For DLC-DLC configuration and Tsai-DLC configuration, a ±5% error was introduced in the camera data: *dx*, *dy*, *Cu* and *Cv* and a camera radial lens distortion coefficient $k1$=0.0015. For Zhang-DLC configuration, a ±0.5% error was introduced in the parameters interfering in the calculation of the camera calibration extrinsic parameters and a camera radial lens distortion coefficient $k1$=0.0015.

The Table 3 showed a base error (camera measurement error) on X axis and Y axis. With these measurement errors in the camera, the projector was calibrated by Direct Linear Calibration. And it was observed that projector calibration extrinsic parameters were affected and consequently the measurement errors of the camera-projector system. As we mentioned before, the camera-projector measurement error result is the combined effect of both sets of extrinsic parameters (camera and projector) that, therefore, some errors can be balanced with the others.

As was expected, the evidence seems to indicate that the Zhang-DLC configuration provides the smallest measurement error values, 0.0014 mm on the X axis and 0.0011 mm on the Y axis. From the beginning, the camera calibration by Zhang method gave smaller errors in the extrinsic parameters and measurement results than the other methods. It is also possible to conclude that the Tsai method is extremely sensitive to the variables dx, dy, Cu and Cv, while Zhang method is the least sensitive to them. As we mentioned before, DLC method does not take into account the lens distortion and it is necessary, after the calibration, to make some type of subsequent optimization. It is recommended to use a bundle adjustment algorithm to improve Direct Linear Calibration when there is no time limit to calculate the optimal solution, due to its high computational cost.

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