

A COMPREHENSIVE SIMULATION SOFTWARE FOR TEACHING CAMERA CALIBRATION

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Abstract – This paper describes the Metrovisionlab computer application implemented as a toolbox for the Matlab program. It is designed for learning the key aspects of camera calibration techniques in dimensional metrology applications such as laser triangulation sensors and photogrammetry or stereovision systems. The software is used in several industrial vision courses for senior undergraduate mechanical engineering students. The application: 1) simulates a virtual camera, providing a simple and visual understanding of how the various characteristics of a camera influence the image that it captures; 2) generates the coordinates of synthetic calibration points, both in the world reference system and the image reference system, commonly used in camera calibration; and 3) can calibrate with the most important and widely-used methods in the area of vision cameras, using coplanar (2D) or non-coplanar (3D) calibration points. Thus, the main goal is to have a simulation tool that allows characterizing the accuracy, repeatability, error mechanisms and influences for different measurement conditions and camera calibration algorithms.

Keywords: Camera calibration, software engineering education, vision camera simulation.

1. INTRODUCTION

Camera calibration is essential for most vision systems used in dimensional inspection and control during various manufacturing processes. For this reason, we developed the Metrovisionlab application for students studying the End of Degree Project and the subjects Measurement Techniques in Production and Maintenance and Further Industrial Process in the College of Industrial Engineering in Zaragoza (Spain), to help them learn about questions relating to camera calibration. Fig. 1 shows a flow diagram of the main functions of the application.

We created the application as a toolbox for the commercially available Matlab program, thus simplifying the programming of complex mathematical algorithms and making it readily available to the teaching and research communities, given the widespread use of Matlab in these areas. The basis of Metrovisionlab is the simulation of a virtual camera defined by the student by setting various parameters that determine the outcome of the image taken by the simulated camera. The image will change depending

on the parameters of the application. This means that the student can understand the effect of the various parameters of the camera on the obtained image intuitively.

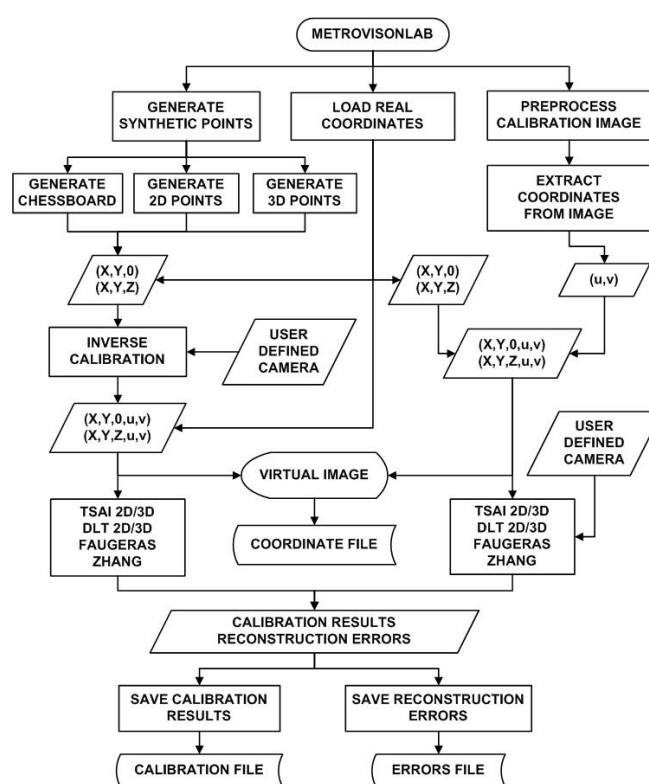


Fig. 1. Flow diagram of the main functions of Metrovisionlab.

The other indispensable element for obtaining the virtual image generated by the application is the object captured by the camera. For the sake of simplicity, we decided to use groups of calibration points distributed in matrix form. The synthetic point generator included in the application creates these points, which the student can use to define the spatial layout and the size of the dot matrix. As well as the coordinates obtained with the point generator, the user can also load real calibration point coordinates from a file.

One of the most important functions of the application is to calibrate cameras with one of the calibration methods with which it is equipped. These include the most important and widely-used methods in the field of camera calibration: 1) DLT (Direct Linear Transformation) [1], 2) Tsai [2], 3)

Faugeras [3] and 4) Zhang [4]. Depending on the method selected, the user can calibrate with different aspects in mind, such as 1) the use of coplanar or non-coplanar calibration points, or 2) the possibility of making or not making corrections to radial distortion caused by the camera lenses. Given that the focus of the application is instructional, we have tried to make the results of the calibrations provided as detailed and comprehensive as possible. This means that Metrovisonlab is also a very useful tool for research purposes.

2. DEVELOPED TOOL

2.1. Virtual camera

The interface of the application (Fig. 2) has a wide area showing the virtual image taken by the simulated camera from calibration points defined by their world coordinates. These coordinates can be synthetically generated, loaded from a file or extracted from a calibration image. If the world coordinates of the calibration points are synthetically generated or loaded from a file, the points appearing in the virtual image are defined by the coordinates in the reference image system associated to the coordinates in the world reference system of the defined points.

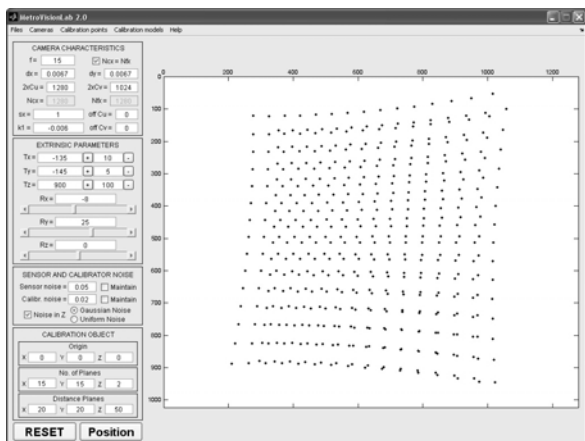


Fig. 2. Application's interface.

An inverse calibration algorithm based on the Tsai method finds these image coordinates. The algorithm generates these coordinates from the coordinates in the world reference system of the points and the intrinsic and extrinsic parameters of the camera. We based our algorithm on the Tsai method because of its low computational cost: it is important that any change the student makes to the camera parameters should be reflected in the virtual image as quickly as possible.

If the image coordinates of the calibration points are extracted from an image, it is necessary to load the world coordinates associated to the points from a file; with the world and image coordinates the program calculates the extrinsic and intrinsic parameters of the camera.

In the main window, the student can configure the intrinsic parameters that define the characteristics of the camera, and the extrinsic parameters that define the relative position of the camera and the calibration points. Also, there

are other parameters to simulate the virtual camera more realistically such as difference between the number of sensor elements and pixels captured in the image in both directions, the scale uncertainty factor, distortion factors, optical center deviations or Gaussian and uniform noises in calibration points nominal position or in the final captured points. Any change in one of those parameters will update, according to the new calibration situation, the camera view helping to understand the influence of each parameter. Because it is sometimes difficult for students to understand the relative position of the camera and the calibration points, the application can also represent this graphically (Fig. 3).

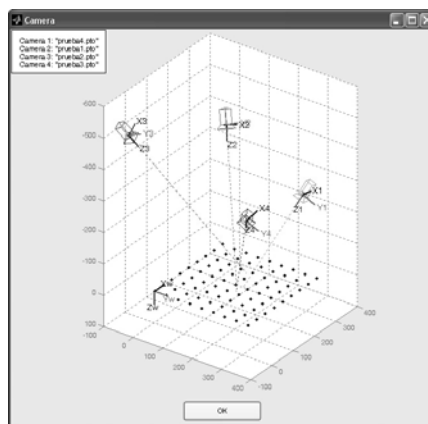


Fig. 3. Representation of the relative position of several cameras and the calibration points.

2.2. Synthetic points generator

Once the camera to be simulated has been characterized, the other essential element for creating a virtual image is the coordinates of the world reference system for the calibration points. The application has a synthetic points generator that can create dot matrices, which it uses in order to generate these coordinates. The generator has options to create a matrix defining 1) the number of rows and columns in the dot matrix; 2) the number of matrices to be generated in planes parallel to the length of the axis Z; 3) the separations between the matrix rows, columns and planes; and 4) the position with respect to the origin of the world coordinates of the matrix.

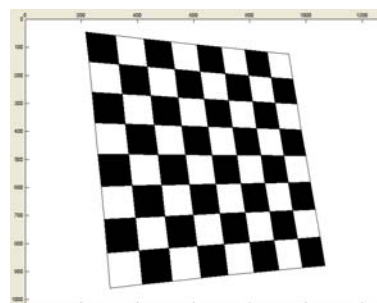


Fig. 4. Synthetic chessboard calibrator.

The user can also load the world coordinates of the points from a file in 8-bit ASCII format. When one of the calibration methods using coplanar points is to be used in

calibration trials of real cameras, it is usual to use chessboard-type calibrators. In these cases, the coordinates of the calibration points correspond to the corners of each one of the chess boards. For this reason, we included an option in the application to use a synthetic chessboard as a calibrator (Fig. 4).

2.3. Points extraction from an image

In addition to the synthetic points generator, the application permits the extraction of image coordinates from images of real calibrators; two pattern types can be used in the extraction process: 1) matrices of circles and 2) chessboard patterns (Fig. 5). The program is capable of find the coordinates associated to the circles centres by several methods: 1) centre of gravity based on grey levels, 2) shape centroid and 3) ellipse approximation. For chessboard patterns, the user can use Canny and Sobel filters for the searching of the line intersections coordinates on the image. Besides of the extraction methods, a threshold filter can be applied to remove noise from images and to facilitate the searching of the image coordinates. In order to be able to use the obtained image coordinates to calibrate a camera, it is necessary to load the associated world coordinates from a file.

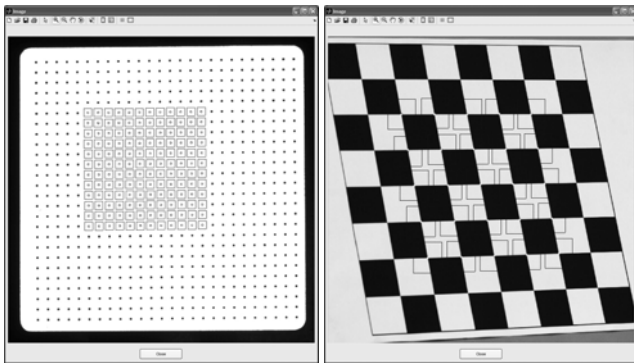


Fig. 5. Image coordinates extraction from an image.

2.4. Camera calibration

The results of the application depend on the calibration method used, but there is a series of results common to all methods, as follows:

- 1) Image coordinates reconstruction error, offering for both coordinates a) the average, b) the maximum value and c) the standard deviation.
- 2) Reconstruction error of the world coordinates, offering for each coordinates a) the average, b) the maximum value and c) the standard deviation.
- 3) NCE factor (Normalized Calibration Error) [5]. This is very useful for comparing different trials and different calibration methods, given that this error is independent of the trial conditions and the method characteristics.
- 4) Computation time. It is very useful to analyze whether the computational cost of certain

calibration methods is acceptable depending on the trial conditions and the camera characteristics.

As well as providing results in numerical form (Fig. 6), the application can show in graphical form (Fig. 7) the results of the reconstruction errors of the calibration points, both in world coordinates and in image coordinates. This greatly facilitates understanding. The application also has all the usual options for storing results obtained in different files.

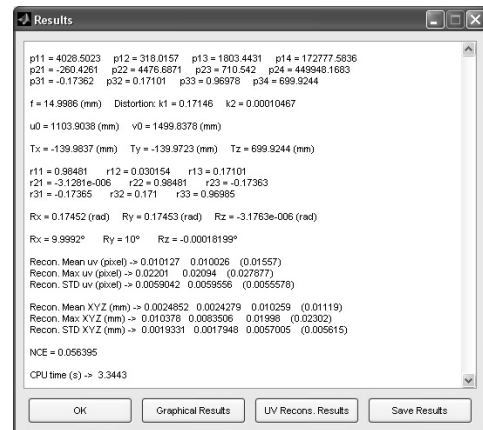


Fig. 6. Calibration results in numerical form.

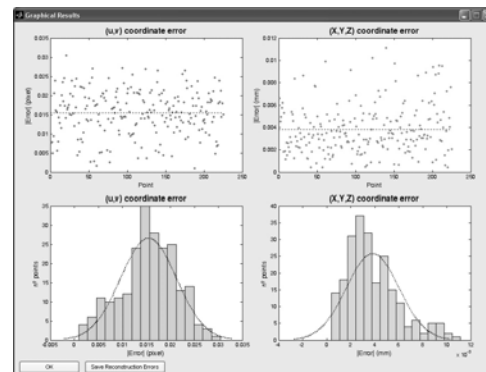


Fig. 7. Calibration results in graphical form.

The application allows making calibrations with the following methods: 1) DLT, 2) Tsai, 3) Faugeras and 4) Zhang.

The Tsai calibration method finds the intrinsic and extrinsic parameters of the camera from the coordinates of the calibration points in the world and image reference systems. We improved Tsai's algorithm in our implementation by incorporating a series of improvements suggested by other authors [6, 7]. The Tsai method included in the application can calibrate with both coplanar and non-coplanar points. In this case there is no possibility of not correcting the radial distortion of the lenses, as this is included in the method itself.

In contrast to the Tsai method, the DLT calibration method calculates what is called the projection matrix; this matrix enables the change from the calibration point coordinates of the world system to the coordinates of the image system. From the elements making up the projection

matrix, the application can calculate both the intrinsic and extrinsic parameters of the camera. In the implementation of the DLT method coplanar and non-coplanar calibration points are allowed. Furthermore, in the case of non-coplanar points, the user can calibrate the camera while correcting the radial distortion of the lenses and the optic center of the camera.

The Faugeras method is similar to DLT method, where the main difference is the way in which the radial distortion is corrected. The DLT method calculates the distortion parameters together with the other parameters, while the Faugeras method separately calculates an initial approximation of the camera parameters and of the distortion factors. Doing these initial approximations separately achieves a high degree of optimization of all the parameters a posteriori, implying that the Faugeras method has a much lower computational cost than that of the same calibration with the DLT method. As with the DLT method, the application provides as a solution of the Faugeras method the intrinsic and extrinsic parameters of the camera together with the elements constituting the projection matrix of the method itself. The user can also perform the Faugeras method calibration without taking into account the corrections necessary for eliminating the distortion effects of the lenses.

The last calibration method is the proposed one by Zhang; this method differs slightly from the other calibration methods. In Zhang calibration at least three different images from a coplanar calibrator are needed, the application has been designed to work with a minimum of three images and a maximum of five. These images can be obtained moving the calibrator or changing the camera position. The method provides the intrinsic parameters of the camera and the extrinsic parameters associated to each image. Like in the Faugeras calibration, the user can perform the calibration without taking into account the correction of the lens distortion; in this case two factors are used for correcting this distortion.

3. SIMULATOR VALIDATION

In order to verify that the synthetic points generated by the program are trustworthy, several tests have been realized. In these tests images of real calibrators have been used for obtaining the calibration parameters of the camera used for capture the images, then with these parameters the synthetic calibrator have been calculated. Comparing the image coordinates of the real calibrator with the calibrator generated synthetically we obtain the difference between both calibrators. It is necessary to consider that within this difference there are several factors that influence in it: 1) errors in the measurement of the calibration marks, 2) errors in the extraction of the image coordinates from an image, 3) errors in the estimation of the lens distortion and 4) others related with the camera.

Three different calibrators have been used in the tests (Fig. 8):

- 1) A 26x26 dot-grid pattern target on soda lime glass, with 1 mm diameter dots separated 4 mm

horizontally and vertically. The distances have been determined with an uncertainty of 0.0009 mm at $k=2$.

- 2) A 7x7 circle-grid pattern target printed with a conventional printer, with circles separated 19 mm.
- 3) A chessboard pattern target printed with a conventional printer, with squares of 35 mm.

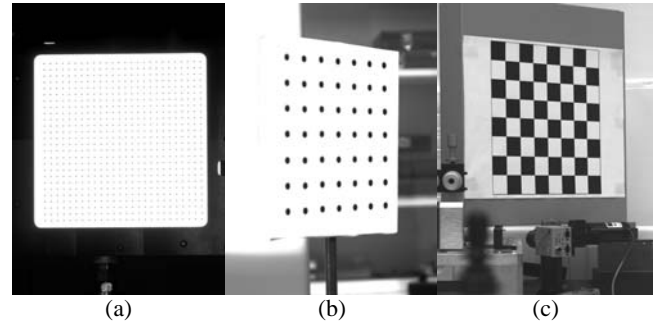


Fig. 8. Calibrators used in the tests. (a) 26x26 dot-grid, (b) 7x7 dot-grid and (c) chessboard pattern.

The first test was made with the 26x26 dot-grid, a Pixelink PL-A781 camera with a 50 mm focal length lens and in the most optimum conditions possible to try to diminish the error factors that affect the calibration of cameras. For the illumination a leds ring of red light was used and the diaphragm of the camera was closed to the maximum. The other two tests served to verify the robustness of the simulator against more work adverse conditions. In this cases the calibrator were made with a conventional printer, a camera with 24 mm lens and ambient illumination was used.

In each one of the tests, several images were taken from the calibrators in different positions. The image coordinates of these images were extracted and were used to calibrate the cameras, and then with the calibration parameters the synthetic calibrators were simulated. Finally the image coordinates of the real calibrators were compared with the image coordinates of the calibrators generated synthetically.

Table 1. Differences between real calibrators and synthetic calibrators, in pixels.

Calibrator (focal length)	26x26 (f=50 mm)	7x7 (f=24 mm)	Chessboard (f=24 mm)
mean u	0.1595	0.4276	0.3550
mean v	0.1387	0.4340	0.3372
max. u	0.6193	1.2465	1.1469
max. v	0.5509	1.4512	1.1257
std. u	0.1623	0.2828	0.2661
std. v	0.1119	0.3873	0.2065

The comparison errors between calibrators can be seen in Table 1, the mean of these errors for all the tests are at subpixel level and the test with the best calibration conditions presents the smallest errors. In the tests with more unfavorable conditions the maximum error is over one pixel; this must, mainly, to the points located on the corners of the calibrators, these points are the more distorted by the camera lens and therefore the most difficult to simulate.

4. SURVEY QUESTIONNAIRE

The Metrovisionlab application was used with Further Industrial Process students and with students working on the End of Degree Project with the goal of extending their knowledge of the most important aspects relating to the use and calibration of vision cameras. The subject was taught to a total of 83 students divided into three different teaching groups of 28, 26 and 29. The objectives that the students were expected to achieve in the part of the course relating to vision cameras were 1) to understand the meaning of the various parameters relating to vision cameras; 2) to learn to calibrate cameras with different procedures; 3) to know how to select the most appropriate calibration method depending on the working conditions; 4) to know how to calculate the degree of accuracy that can be obtained with specific equipment in given conditions; 5) to learn to do measurements using vision cameras; 6) to be able to select the appropriate equipment depending on the measuring conditions; and 7) to know whether or not a specific measurement can be done using vision cameras.

Table 2. Survey questionnaire.

A1	The use and calibration of vision cameras is useful for my training as an engineer.
A2	Metrovisionlab is an easy to use application.
A3	Metrovisionlab has helped me to better understand how the characteristics of a camera and its optics influence the generated image.
A4	Metrovisionlab has helped me to learn more about the characteristics of calibration methods.
A5	Metrovisionlab has helped me learn more about the use of cameras in measurement and verification processes.
A6	The complementary material provided with the application has been useful for improving my learning (website).

We taught the subject actively and collaboratively so that the students could achieve the objectives and develop associated capacities. Through project-based learning, the students had to do tasks relating to the calibration of vision cameras and their use as tools for measuring and verification. They were provided with the Metrovisionlab application in order to do these projects. Once the exercises were finished, we asked the students to fill out an anonymous survey (Table 2) in order to evaluate the usefulness of Metrovisionlab as a teaching tool. A total of 83 students took part in the survey, in which they had to assess a series of statements on a scale from 1 to 5 where 1) 1 represented total disagreement, 2) 2 was disagreement, 3) 3 was neutral, 4) 4 was agreement and 5) 5 was complete agreement.

Of the total of 83 students who took part in the survey, fewer than 10% thought that learning about the use of vision cameras was not useful for their engineering training, while almost 50% thought the opposite. Looking at the results of question A2, it is significant that 78% of the students who used the application thought it easy to work with, while barely 4% did not agree that it was an easy tool to use. With respect to the usefulness of Metrovisionlab for learning

about the use of vision cameras, the replies to statements A3, A4 and A5 showed that about 56% of the students were in agreement or complete agreement that Metrovisionlab had helped them, while only 5% thought that it had not helped their learning. Finally, 25% found the additional material accompanying the application in the form of a website useful, while 10% did not find it useful (Fig. 9).

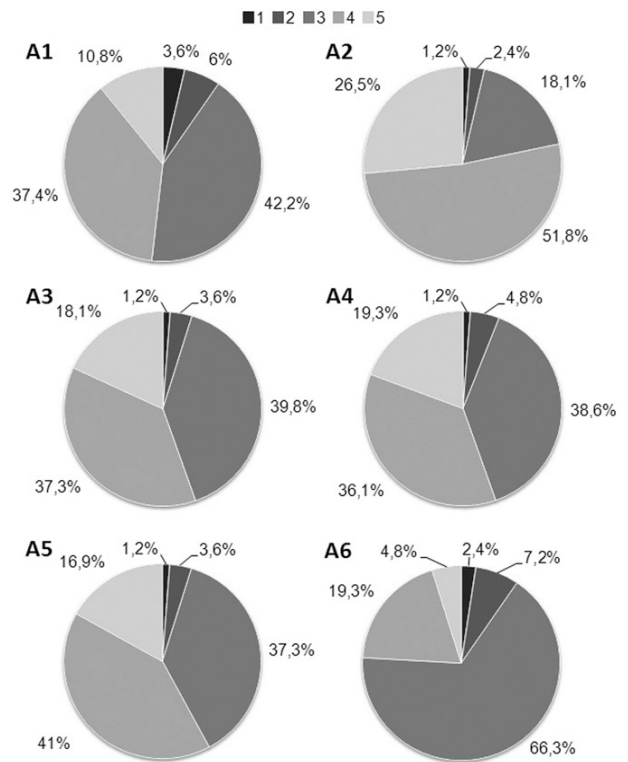


Fig. 9. Survey Results.

5. CONCLUSIONS

The Metrovisionlab application provides a simple way to understand how various parameters determining the characteristics of a camera can affect the image taken with that camera. It also provides knowledge of what factors influence the calibration of a camera and to what extent. The application is also useful for comparing the various calibration methods to see what advantages and disadvantages they have in specific situations. For these reasons, Metrovisionlab is a very useful teaching tool in the area of vision camera calibration, a fact that has been corroborated by students who have used the application so far.

Another aspect worth emphasizing is the possibility of using Metrovisionlab as a research tool. The application has already been successfully used in an exhaustive study on the effects on the final calibration results of several factors involved in a calibration trial when the Tsai method is used to calibrate a camera.

Future work will concentrate on the potential for broadening the scope of the application, for example 1) implementing new calibration methods; 2) increasing the complexity of the modeling of the lens distortion, taking

into account the effects of tangential and prismatic distortions; 3) increasing the functions of the synthetic points generator; and 4) providing the application with more complex tools for the extraction of points coordinates from real images. We will focus on all of these questions, making the application a more powerful teaching tool in the area of vision cameras.

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