Projector Calibration by "Inverse Camera Calibration"

Ivan Martynov, Joni-Kristian Kamarainen, and Lasse Lensu

Machine Vision and Pattern Recognition Laboratory (Kouvola Unit)
Lappeenranta University of Technology, Finland
http://www2.it.lut.fi/mvpr

Abstract. The accuracy of 3-D reconstructions depends substantially on the accuracy of active vision system calibration. In this work, the problem of video projector calibration is solved by inverting the standard camera calibration work flow. The calibration procedure requires a single camera, which does not need to be calibrated and which is used as the sensor whether projected dots and calibration pattern landmarks, such as the checkerboard corners, coincide. The method iteratively adjusts the projected dots to coincide with the landmarks and the final coordinates are used as inputs to a camera calibration method. The otherwise slow iterative adjustment is accelerated by estimating a plane homography between the detected landmarks and the projected dots, which makes the calibration method fast.

1 Introduction

In the recent years, video projectors have become the devices of choice for computer vision systems of active scene exploration and reconstruction. A camera-projector pair alleviates the difficult task of establishing correspondences between the views, and therefore, systems like Structured Light [10] can provide accurate 3-D reconstructions. Lately, projector-camera pairs have also become increasingly popular in modern game controllers such as Kinect (XBox). However, even if active systems alleviate the matching problem, calibrated video projectors are still required.

The camera calibration problem, i.e., the estimation of camera intrinsic and extrinsic parameters, has been studied for a particularly long time and the existing state-of-the-art techniques including [14,15,6,4] can be used for accurate calibration [12]. The basic working flow is the following: i) a set of images of a known calibration pattern are captured from various camera poses, ii) pixel coordinates of the calibration pattern "landmarks", such as the corners of a printed checkerboard pattern, are located, and iii) the camera parameters are non-linearly estimated based on correspondence of the located 2-D image coordinates and the known 3-D landmark coordinates under the selected camera model. The video projector projection is usually modelled as the inverse projection of a pin-hole camera, and therefore, it is treated as a perspective projection similar to the camera models. Therefore, if correspondences between the projector pixels and the calibration landmarks can be established, the standard camera calibration methods can be adopted for the video projector calibration as well.

This work is based on the popular camera calibration technique implemented in Bouguet's Camera Calibration Toolbox for Matlab [2]. The technique is extended for fast video projector calibration by adopting the inverted camera calibration procedure based on an iterative search of 2-D projector coordinates coinciding with the calibration pattern landmarks. The calibration results are reported for several real settings.

1.1 Related Work

During the last few years, the interest to use inexpensive off-the-shelf cameras and video projectors for active and computer vision has increased considerably. Camera and projector calibration are the necessary steps, and therefore, various approaches and methods have been proposed to calibrate video projectors. The idea of "inverting" the camera calibration is not new, and it has been exemplified by several authors [9,7]. However, their formulations are different to the ones presented here: they project a calibration pattern onto a plane, "the wall", capture it by a camera, and then utilise the standard calibration work flow. The main disadvantage of this approach is that it requires a calibrated camera and, moreover, errors from the camera calibration are transferred to the projector.

One class of the calibration methods utilise known relations of the camera, and the wall or the projector [11,13]. This makes the methods accurate and the problem easier to formulate, but also less flexible than those requiring a calibrated camera. These methods can be used for fixed industrial camera-projector systems, but not in the general case where configurations and poses are unknown.

Another important class of the methods includes those referred to as auto-calibration methods. These methods do not require a physical calibration target. Most auto-calibration methods work only for the extrinsic parameters [8] or require a calibrated camera [7], but lately even more automatic methods have been proposed. For example, the method by Draneni et al. [3] assumes a plane projection geometry, "the wall", and that one of the projector poses is "roughly frontal". These methods are attractive choices due to their automatic processing, but there always exists the need for very accurate calibration in the structured light and active vision systems. The extrinsic parameters can be solved by the auto-calibration methods, but the intrinsic parameters should be solved by the inverted camera approach utilising a physical calibration target, since this is accurate and needs to be done only once.

2 Projector Calibration

2.1 Camera Calibration

The main objective of camera calibration is to solve camera's intrinsic parameters (focal length, lens aberration model parameters, etc.). Similarly, also the extrinsic parameters (location and pose) are accurately found by the same optimisation process. Typically, the intrinsic parameters do not change when the camera is moved and camera's optics is not touched, and therefore, solving the extrinsics with known intrinsics is considered as its own problem, e.g. [1]. The standard camera calibration methods aim to solve the parameters as accurately as possible, and therefore, they typically use a physical calibration pattern, such as a printed planar checkerboard pattern. Images from the pattern are captured from different camera poses, and the camera model parameters are optimised to match the 2-D image coordinates and the known 3-D coordinates of the pattern. The most popular methods with their implementations available are Tsai's [14], Zhang's [15] and Heikkilä's [6] methods. The methods mainly differ by the camera model parameters and how they utilise the calibration pattern landmarks.

For our study, the Matlab toolbox implementation by Bouguet [2] was chosen. The toolbox makes use of Zhang's method and a planar checkerboard as the calibration pattern. The method requires the user to capture a sufficient number of images with the same camera in different locations. Then the toolbox provides functions to detect the pattern cross points which is done separately for all the images. The detection is semi-automatic as the first four corners need to be annotated manually (see the left image in Fig. 1) and then the algorithm computes the remaining corners automatically (see the right image in Fig. 1). The four corners help to initiate the locations of the other cross points, and then the algorithm searches for the accurate corner coordinates within some predefined window whose default size is 11x11 pixels. To achieve sub-pixel accuracy, the Harris corner detection is applied.

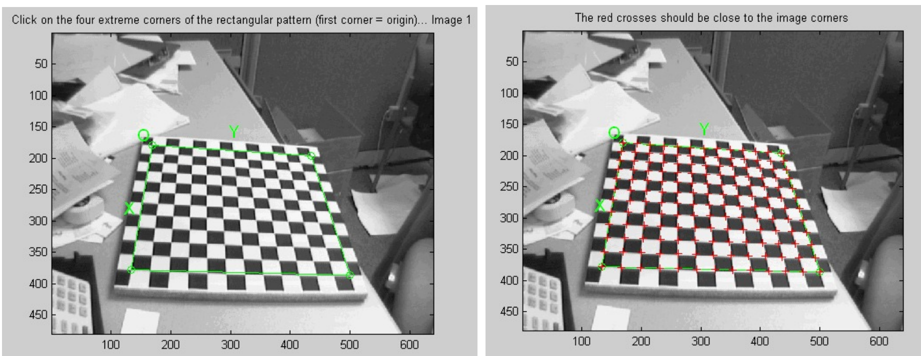


Fig. 1: Semi-automatic location of the checkerboard corners in Camera Calibration Toolbox [2].

If the corner detection fails, the toolbox allows to adjust the detection parameters, such as the size and number of the squares in the checkerboard pattern, a visually estimated distortion factor, etc. For the most cameras, the detection works out-of-the-box, and therefore, it is utilised in our projector calibration.

The next step is to calculate the intrinsic parameters of the camera (focal length, principal point, skew, radial and tangential distortions) using the detected corners. This is done by the main calibration function. After the optimisation process, the toolbox outputs the estimated parameters and the pixel errors. Again, these values can be adjusted and the calibration re-run. It is worth to remark that the detection of corners can be done without knowing the intrinsics, apparently.

2.2 Inverting Camera Calibration

For calibrating the projector, the same checkerboard pattern is used as for the camera calibration. The main problem is to define the grid of cross points in the projector plane which project exactly onto the grid of the real pattern. This task is solved with the help of an uncalibrated camera. The camera can be used to capture the pattern and projected points. The points can be projected with a distinguishable colour which is easy to detect. Again, the detection of the cross points can be achieved with the same semi-automatic method of the toolbox. The projector grid points can be projected onto the same view, captured by the camera and detected in the camera view, i.e., in camera pixel coordinates. The both detected sets of points can be compared, and if the distance between any of them is larger than a specified threshold, the points in the projector plane are moved towards the corners points of the pattern in the camera view. Fig. 2 illustrates this procedure to automatically find the correspondence of the calibration pattern corners (the checkerboard cross points) and the projected grid. In this figure, four steps are shown and it can be seen that the difference between the third and fourth steps is very small (the two bottom images).

After the iterative search, the coordinates in the projector "view" are known and it is possible to directly apply the toolbox functions to compute the intrinsics and extrinsics of the projector. Corresponding to the camera calibration, the projector needs to be put in different locations where the corner detection procedure is repeated. When all corner points in the projector plane are computed for all locations, the main toolbox optimisation process can be started.

2.3 Proposed Calibration Method

For the method, it needs to be decided how to detect the corner points of the calibration pattern in the projector plane. First of all, the relation between the camera and projector points is defined as the projective homography. This relation helps to make an accurate initial estimation of the corners in the projector plane and speed up the iterative search in the next stage. For the homography estimation the direct linear transform (DLT) [5] is used.

To compute the projective homography, at least four points are needed, but the DLT is fast for even hundreds of points. In the current implementation, four points are used in a rectangular configuration in the projector plane and

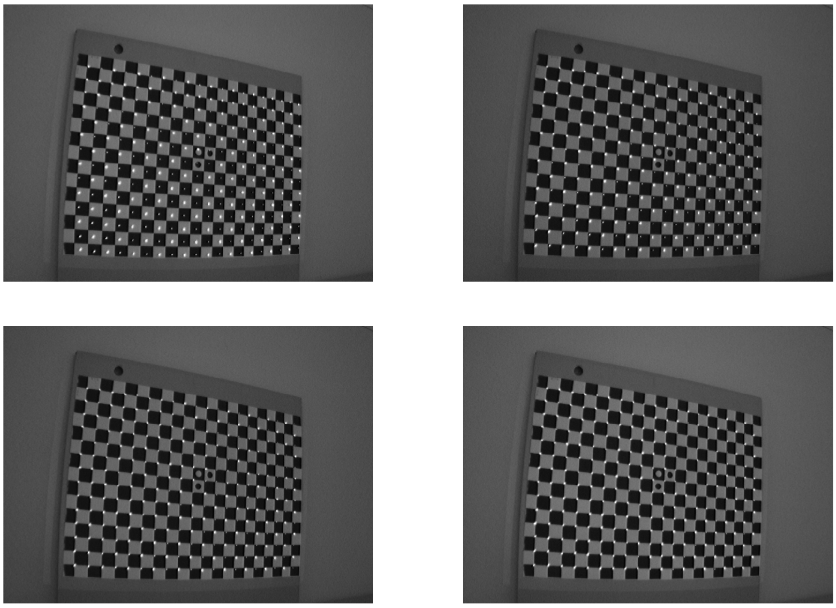


Fig. 2: Example of automatic adjustment of the projected dots to the calibration pattern corners (from the up left to the bottom right).

they are projected on the wall. The wall here denotes any planar background. The points are coloured and, therefore, easy to distinguish and detect. The only consideration is that the points are visible to the camera, i.e., not outside its view. Homography from the camera coordinates to the projector coordinates is computed using the DLT method.

Using the computed homography, all the detected calibration pattern corner points on the camera plane are transformed into the corresponding points on the projector plane. These points can now be projected and their location verified by using the camera. The verification is again achieved by locating the points with the camera and comparing their camera coordinates to the calibration pattern coordinates. The DLT estimated points do not exactly match due to the non-linearity in the projector intrinsics and since the DLT camera model is linear. However, the points are close to the correct locations and can be iteratively adjusted by a re-projection and re-capturing loop.

After the adjusted corner points on the projector plane are computed, the calibration routines of the toolbox are used. The algorithm for the described inverted camera projection method is given in Alg. 1.

Algorithm 1 Inverted camera calibration for video projector calibration.

```
Project four or more points which are visible to the camera.
Capture an image and detect the projected points.
Compute homography H from the camera points to the projector points (DLT).
Capture an image and detect the corners of the checkerboard pattern.
Transform the detected corner points to the projector points using H.
for all corner points do
    Project the projector plane points in the neighbourhood of the transformed
    corner point.
    Capture an image and detect the point's coordinates
    Select the one closest to the detected corner.
end for
```

It should be noted that if the location of the camera does not change while the projector is moved, the corner detection of the calibration pattern needs to be done only once. Generally, there is a need to recompute the corners' locations of the checkerboard pattern in the camera plane only if the location of the camera has changed. Algorithm 1 is executed for each different location of the projector and all coordinate sets are the input to the toolbox calibration function.

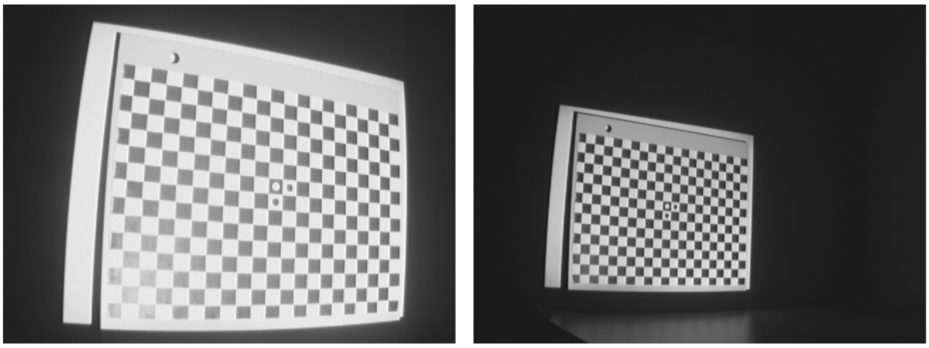
3 Experiments

The proposed algorithm was applied to a camera-projector system. The used camera was Unibrain Fire-i BCL 1.2 with the native resolution of 640×480, and the video projector was ViewSonic DLP projector with the resolution of 800×600. These can be considered as inexpensive commodity hardware.

In the experimental setup, the camera and projector were put in locations where that the angle between the views of the devices was roughly 30 degrees. During the experiments, the location of the projector was changed several times, thus, the angle between the camera and projector varied from 10 to 60 degrees. The configuration is demonstrated in Fig. 3.

Fig. 3: The used camera-projector system.

The main factor affecting the calibration accuracy are the camera properties, mainly the resolution, and the location of the camera from the projection plane. The resolution was kept fixed, but the effect of the camera distance was studied. The two distances used were approximately 60 and 120 cm from the wall. Example images captured from these two distances are shown in Fig. 4. In the both cases, the viewing angle remained approximately the same.



(a) 60 cm (b) 120 cm

Fig. 4: The two camera configurations investigated.

The projector location was changed 8 times, i.e., Algorithm 1 was executed for nine different images. These points were the input to the calibration procedure. The estimated intrinsic parameters are shown in Table 1 and the extrinsic parameters for a roughly similar view in Table 3. For the accuracy evaluation, the reprojection error was used (the last line in the tables). The reprojection error was computed by using the estimated intrinsic and extrinsic values and by projecting the projector plane coordinates on the wall and measuring the standard deviation of the distances to the detected calibration pattern coordinates. From the errors in Table 1 we see that the distance change results to the error increase of 20-30% for the double distance. Note that the error numbers are given in pixel coordinates and are, therefore, affected by the projector resolution.

Table 1: Calibration results for the intrinsics.

Param	*60 cm*	*120 cm*
Focal Length:	fc = [1301.9; 1289.2]	fc = [1317.6; 1314.0]
Principal point:	cc = [360.5; 718.8]	cc = [347.4; 719.3]
Skew:	alpha = -0.00785	alpha = -0.00960
Distortion:	kc = [-0.145; 0.177;	kc = [-0.109; 0.211;
	-0.004; -0.010; 0.000]	0.008; -0.013; 0.000]
Pixel error:	err = [1.051; 1.045]	err = [1.369; 1.240]

In order to see how the distance affects the accuracy, it was necessary to investigate the change of the focal length error because it is less affected by larger errors in a few single pixels than the reprojection error. Several tests were carried out and it was noticed that a degrade of approximately of 25% in the accuracy occurs. In other words, if the distance from the camera to the wall is doubled then the reprojection error becomes roughly one fourth bigger. Table 2 presents the errors in the focal length estimation from the same images.

Table 2: Focal length estimation error from the both distances.

Param	*60 cm*	*120 cm*
Focal length error:	err = [41.79; 40.40]	err = [57.03; 55.11]

The comparison of the extrinsic parameters for the two sets is rather useless since the projector location was different. However, this can be solved by using the same image as an evaluation image. The results for this experiment, the reprojection pixel deviations for the one view, are shown in Table 3. The chosen evaluation view was from the second test where the distance from the camera to the wall was approximately 120 centimetres. Again, the error increased by approximately 17%.

Table 3: Calibration results for the extrinsic parameters of the last location of the projector.

Param	*60 cm*	*120 cm*
Pixel error:	err = [1.539; 1.156]	err = [1.541; 1.160]

The last experiment was the estimation of a sufficient number of images for the calibration of the projector. This means that the algorithm was run with 2 to 9 images. The error is affected by the location of the projector. When the projector is located with a wider angle with respect to the camera, the reprojection error is somewhat larger. However, if the computation of the focal length is considered, the error of the computation of the focal length tends to decrease as the number of planes increases. From Fig. 5 it can be seen that 5 images are sufficient in the sense that the error does not decrease significantly as the number of images further increases. Also, this experiment demonstrates that the computation of the focal length, and the intrinsics in general, are not seriously affected by larger errors in a few single pixels.

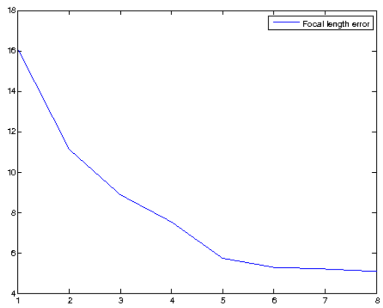


Fig. 5: Focal length error (in pixels) depending on the number of planes.

4 Conclusion

In this work, a method to calibrate a video projector by inverting the work flow of camera calibration is proposed. The method is based on the existing popular camera calibration tool, and by integrating the method to the tool, it can be used to accurately calibrate any camera-projector or single projector system without the need to first calibrate the camera.

At the core of the method is the iterative search of projector plane points which correspond to the points in the calibration pattern. This otherwise slow search is enhanced by introducing good initialisation by plane homography estimation. All code will be made publicly available.

References

1. Ansar, A., Daniilidis, K.: Linear pose estimation from points or lines. IEEE PAMI 25(5) (2003)
2. Bouguet, J.Y.: Camera calibration toolbox for Matlab, http://www.vision.caltech.edu/bouguetj/calib_doc/
3. Drareni, J., Roy, S., Sturm, P.: Geometric video projector auto-calibration. In: CVPR Workshop on Projector-Camera Systems (2009)
4. Furukawa, Y., Ponce, J.: Accurate camera calibration from multi-view stereo and bundle adjustment. Int J Comput Vis 84, 257–268 (2009)
5. Hartley, R., Zisserman, A.: Multiple View Geometry in computer vision. Cambridge press (2003)
6. Heikkilä, J.: Geometric camera calibration using circular control points. IEEE PAMI 22(10) (2000)
7. Kimura, M., Mochimary, M., Kanade, T.: Projector calibration using arbitrary planes and calibrated camera. In: CVPR (2007)
8. Okatani, T., Deguchi, K.: Autocalibration of a projector-camera system. IEEE PAMI 27(12) (2005)
9. Sadlo, F., Weyrich, T., Peikert, R., Gross, M.: A practical structured light acquisition system for point-based geometry and texture. In: Eurographics Symposium of Point-Based Graphics (2005)
10. Salvi, J., Fernandez, S., Pribanic, T., Llado, X.: A state of the art in structured light patterns for surface profilometry. Pattern Recognition 43, 2666–2680 (2010)
11. Shen, T.S., Menq, C.H.: Digital projector calibration for 3-D active vision systems. J. Manuf. Sci. Eng. 124(1) (2002)
12. Sun, W., Cooperstock, J.: An empirical evaluation of factors influencing camera calibration accuracy using three publicly available techniques. Machine Vision and Applications 17(1), 51–67 (2006)
13. Tao, J.: Slide projector calibration based on calibration of digital camera. In: SPIE. vol. 6788 (2007)
14. Tsai, R.: A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses. IEEE J of Robotics and Automation 3(4) (1987)
15. Zhang, Z.: Flexible camera calibration by viewing a plane from unknown orientations. In: ICCV (1999)