Simultaneous Geometric and Colorimetric Camera Calibration

Daniel Kapusi[1], Philipp Prinke[1], Rainer Jahn[1], Darko Vehar[2], Rico Nestler[12] and K.-H. Franke[2]

[1]Zentrum für Bild- und Signalverarbeitung (ZBS) e.V. Ilmenau

[2]University of Technology Ilmenau, Computer Graphics Group

Abstract A mixed adjustment of monocular or stereo cameras is used to observe an areal of interest autonomously from different points of view and to extract location and movement parameters of interesting objects. To obtain a geometric relationship between the different imaging sensors, they have to be calibrated in a preferably simple calibration procedure. A plane chessboard target with integrated color markers acts as the calibration reference for gathering the radial and tangential distortion values as well as the intrinsic and extrinsic parameters from multiple cameras by means of subpixel accurate edge detection and the color transformation parameters at one go. The statistical uncertainty of the determined parameters decreases by extracting and collecting the features of interest from the chessboard at multiple target poses for each camera. Furthermore the resulting calibration parameters enable the correction of lens distortions, the rectification of stereo images and the color correction.

1 Introduction

In modern computer vision the sophisticated task of camera based autonomous areal observation has a great application field, which is often subjected to very high safety requirements. So the data acquisition and interpretation at such security systems has to be failsafe. Therefore multiple points of view are used to increase redundancy, to handle occlusions and to obtain additional 3D informations which leads added together to a robust and extensive scene modeling.

To fuse the image data from different points of view to a global representation of the scene it is assumed, that the geometrical relationship between the sensors is known. Additionally it is essential for tasks like object-classification and -tracking that the manner of perception

is aligned between the sensors. That means that lens distortions and differences in color exposition have to be corrected.
The radial and tangential distortion values as well as the intrinsic and extrinsic camera parameters and the parameters for color balancing are gathered by means of a common calibration procedure.
The geometrical calibration methods are classifiable into the 2d/3d reference object-based calibration, where the camera calibration is performed by observing a calibration target whose geometry is exactly known [1][2], and into the Auto-calibration techniques, where the calibration parameters are estimated directly from uncalibrated images from different views [3][4], which is a flexible but also very complex attempt that can not obtain reliable results in any case. Bouguet [5] introduces a formalism based on a so called dual space which allows to decouple the intrinsic from the extrinsic camera parameters. Furthermore he picked up and continued the calibration approach of Zhang[6], who has proposed a flexible technique to easily calibrate a camera by using planar pattern at a few different orientations, and a similar method of Sturm and Maybank[7]. Bouguet publishes a Camera Calibration Toolbox for Matlab [8] on his webpage, which uses a plane chessboard target at multiple poses as the calibration reference. The algorithms from the Bouguet Camera Calibration Toolbox for Matlab have been taken over and adapted to the open source library OpenCV[9][10], which have been used to implement the geometrical part of the multi camera calibration described in this article.
Furthermore algorithms from the ZBS e. V. CCal-library [11] have been utilized for a contemporary color calibration to the end that also a unified color representation between the imaging sensors can be achieved.
The geometric and the colorimetric reference features are located at the same calibration target; so that the entire calibration procedure can be performed simultaneously.

2 Features of the Calibration Target

The calibration target includes two types of calibration features. On the one hand there are striking points in a regular grid needed for geometrical referencing, from which the chessboard position in relation to the camera position and the intrinsic camera parameters as well as the distortion values are calculable. The edges from the squares of a chessboard act as these points, how it is employed by Bouguet[8].
The number of the edges in the horizontal and the vertical direction have a different parity. So there exists only one symmetry axis, which allows determining the orientation of the chessboard clearly. The edges are detected with sub pixel accuracy by means of a two-step iterative gradient based corner detection algorithm implemented in the OpenCV library [9]. The real corner position, which should be estimated with sub pixel accuracy, is hereafter referred as q. An amount of reference positions p is determined within a windowed neighborhood around the corner q.
In a first step the corner positions q are detected roughly with pixel precision by a contour extraction around the black squares, which have been binarized with an adaptive threshold before. For the second step the mathematical fact of resulting zero by dot product between a vector and an orthogonal vector is used. This relation is usable at corners, where a vector from the corner position q to a second position p along the edge of the chessboard square is always orthogonal to the gradient at p (Figure 1). Other positions within a uniform

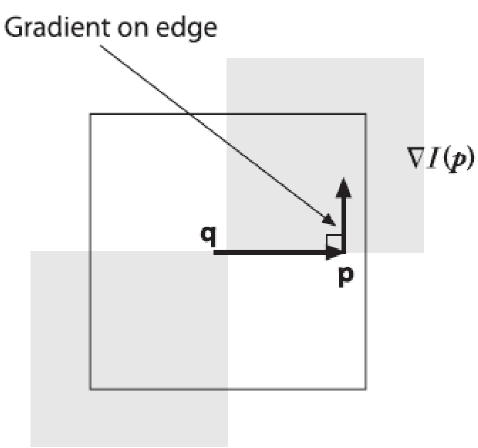

Figure 1: gradient on p is orthogonal to vector $q - p$ [9]

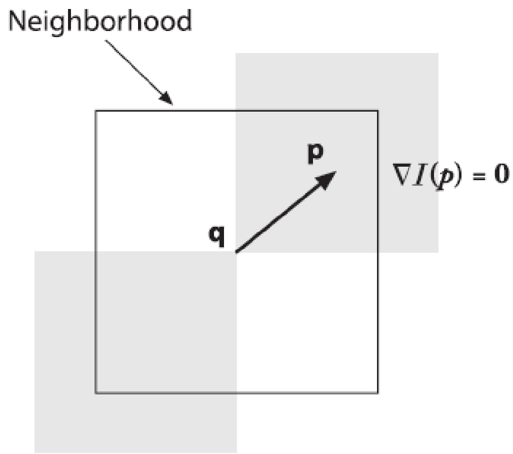

Figure 2: gradient on p within a homogenous region is zero [9]

region are not taken into account, because the gradients at these locations are zero (Figure 2).
Then the result of the dot product of the vectors from q to p and the gradients at the p positions is minimized iteratively to become zero and to obtain an accurate estimate for the corner position q. On the other hand there is a set of circular color markers in each case placed at the center of a chessboard-square on the calibration target (Figure 3). They act as color references. The reference valence of a color marker on the target usually differs from the nominal valence, if the calibration target was simply printed on a paper. In that case the color at the markers should be measured onetime [12], so that the assumed nominal valences can be updated, as far as gathering the real color is important for the application. Normally it is sufficient for many application cases, e. g. object-matching and classification, to have the same color impression of an object from different point of views. So the color measuring and the update of the nominal color valences can be neglected.

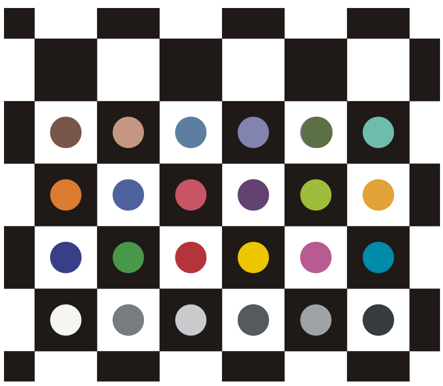

Figure 3: chessboard calibration target with integrated color markers

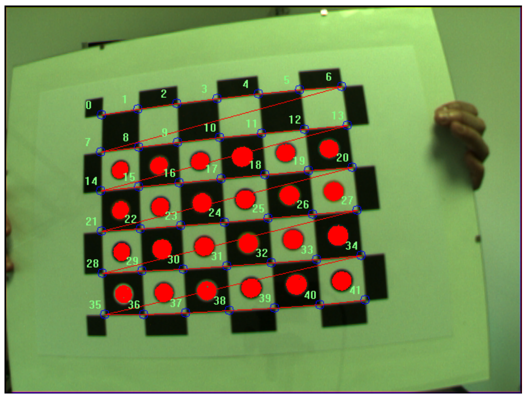

Figure 4: extracted edges and colors from the target

The circular color markers do not impair the edge detection algorithm described above while they are small enough that they are not protruded into the window around a corner for calculating its sub pixel accurate position. The center position of such a color marker is easily calculable from the four corner positions of the surrounded chessboard-square. Starting from the center of the color marker the whole colored circle (Figure 4) is gathered by a simple segmentation algorithm, like region growing [13] with a single seed point. It is recommended to apply a 3-by-3 median filter at the segmentations starting point to be more unaffected by single pixel deviations.

Ideally the dark colors should be placed on the white squares and the bright colors on the black squares to facilitate the segmentation of the color markers. The selection of the target colors depends on the expected colors in the scene and has to be increased with the number of parameters, which are used by the color calibration method. The quality of the color calibration depends on the number of target colors and their distribution. To obtain a high qualitative calibration the color target should be distributed uniformly and densely in the color space. Sparsely occupied regions cannot constrain the transformation rule, which leads to high transformation errors especially if the calibration method uses many degrees of freedom.

In Figure 3 a chessboard target with the colors from the "Macbeth"-ColorChecker-Chart proposed by McCamy [14][15] is shown. The colors from this frequently used chart ensure a good distribution in the color space and are suitable for the most common scenes. The chart provides good results for calibration methods which have sparse degrees of freedom.

3 Geometric Calibration

The geometric calibration procedure determines four intrinsic parameters, the focal length f_x, f_y and the principal point c_x, c_y. In addition there are five distortion parameters - three radial (k_1, k_2, k_3) and two tangential (p_1, p_2) - based on the distortion model of Brown and Conrady [16][17]. The intrinsic parameters are directly related to the 3D geometry and hence the extrinsic parameters of where the calibration target is in space. The distortion parameters are tied to the 2D geometry of how the pattern of points gets distorted, so the constraints on these two classes of parameters are treated separately.

The five distortion parameters can be estimated in principle already from three corner points in a known pattern, but much more are used to increase the robustness. Thus, one view of a chessboard is basically enough to calculate the distortion values. The same view can be used for the computation of the four intrinsic parameters.

The extrinsic parameters describe the location of the calibration target. Therefore three rotation (R_x, R_y, R_z) and three translation (T_x, T_y, T_z) parameters have to be calculated. All in all at least two different views of a 3-by-3 chessboard are needed for the computation of the four intrinsic and six extrinsic parameters. Because of the consideration of noise and the numerical stability the acquirement of further images of a larger chessboard is required for each camera. In practice at least ten images of a 7-by-8 or larger chessboard are recommended by Bradski and Kaehler [9] to calibrate in high quality.

The geometrical transformation between two cameras is calculated by analyzing a set of synchronously captured joint views from the calibration target. The rotation matrix R and the translation vector T between the two cameras which cause the smallest reprojection error is computed by a Levenberg-Marquardt iterative algorithm over the whole set of image pairs from the calibration target in different poses.

The geometric calibration process takes effect to be finished successfully if for each camera a valid transformation rule to its adjacent cameras could be computed. In this case

outgoing from an arbitrary camera a transformation rule to any other camera can be established by following and summarizing the transformation rules from camera to camera along the path with the lowest sum of re-projection errors from the departure to the destination camera. One camera is set to be the reference camera to determine a unified coordinate system.
For stereo camera systems the ascertained calibration parameters are also used for stereo rectification, i. e. the subsequent virtual bringing into line of both cameras to achieve images, which seems to be captured by a standard stereo adjustment, where the principal rays intersect at infinity and where the epipolar lines are horizontally aligned.

4 Colorimetric Calibration

A frequent goal of the colorimetric calibration consists of the image data transformation of the device-specific color space of the camera into a device-independent color space with minimized errors, which permits a reproducible color rendering and color evaluation. Abnormalities from the ideal form and exemplary deviations of filter and sensor characteristics should be compensated and unknown illumination spectra have to be balanced.
As correction procedures transformation rules between the color spaces (general feature spaces) have been proved successfully, which are determined with corresponding supporting points from the set of color markers on the chessboard calibration target in the two color spaces.
Concerning the targets the transformation rule which realizes the smallest middle aberration in the description space is selected. At the same time the required stability has to be ensured. This description space is generally the destination or target space respectively a description, which comes out from a not linear transformation of the target space.
With the selection of a transformation rule appropriate for the respective application and a suitable target set for the entire used description space a minimization of the middle aberration is reached. This leads in the majority of the applications to a clear reduction of color deviations.
The used CCal-library [11] includes a summary of methods for the determination and optimization of target related transformation rules. The main application field of those methods is the mapping of color values in a device-specific three-dimensional color space (actual color space) into an essential nominal color description (nominal color space).
The target related color calibration methods can be systematized on the basis of different criteria. On the one hand a partitioning can take place after the mathematical character of the selected model beginning into linear and non linear as well as into approximating or interpolating procedures; on the other hand an arrangement by the color spaces, which are used for the evaluation of the resulting aberration, is possible.
Depending upon area of application of the respective transformation rule it can be differentiated further into global and local procedures. With local procedures the color space is divided into several subspaces, which are treated separately with differently parameterized transformation rules. Further classification possibilities exist: the mathematical procedure to the determination (optimization) of the transformation rule; the space in that the evaluation of the aberration is effected or the priority of the color targets.
Practically relevant for the global color calibration are all approaches above, which represent a good compromise between correction accuracy, robustness and complexity of the procedure. The complexity of the procedure expresses itself usually in the number of

parameters, which has in particular effects on the necessary computing performance and the necessary target count. The quality of the global color calibration is determined considerably by the number and particularly by the distribution of the test colors in the color space.

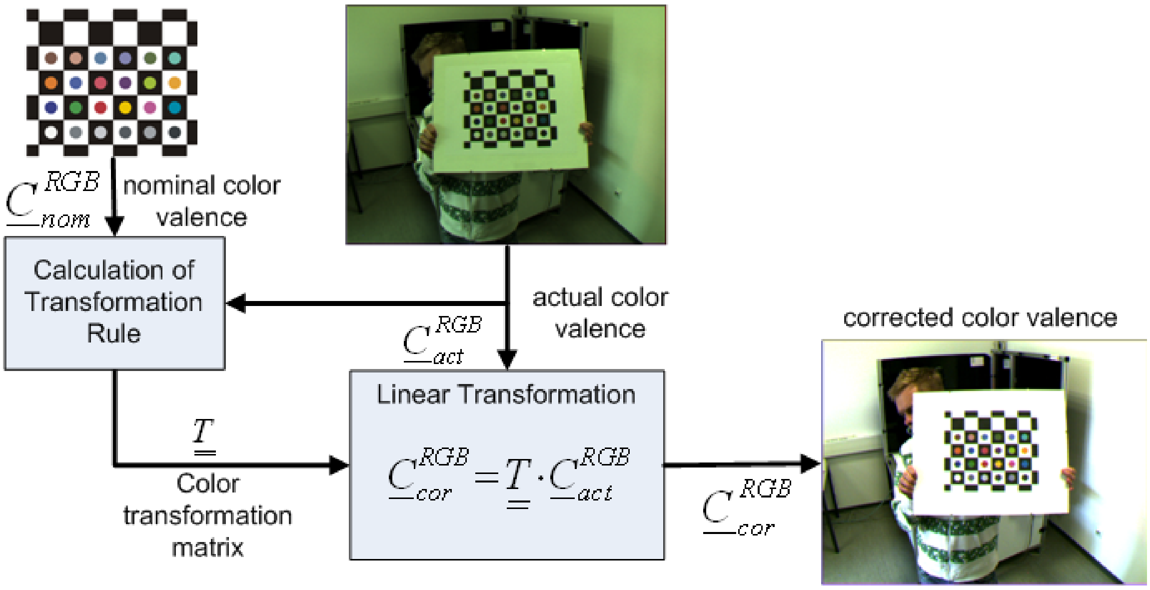

Figure 5: exemplary RGB color calibration and correction using a 3-by-3 linear transformation approach

The use of a global transformation rule leads to a systematic residual error, which is justified by the deviation between the real conditions and the selected model in the respective color space section. This even concerns the color targets which are used for the calibration and thus are well-known. Non linear methods exhibit an improved reproduction in the environment of the supporting points formed by targets. But they tend however contrary to the linear procedures with increasing complexity to a previously not assignable, unstable behavior during the mapping of unknown color valences.
Generally the desired "eye-exact" approximation quality is obtainable by the employment of a global correction approach, if it is applied only in one by color targets occupied limited color space section and thus clearly defined case of application.
In Figure 5 the color calibration and correction is schematically shown. A linear transformation matrix T is calculated between the measured color valences C_{act} and the corresponding nominal color valences C_{nom}, which are located at the color markers positions, by minimizing the middle aberration. Ideally the color valences C_{cor} should correspond best possible with the nominal color valences C_{nom} after the correction.

5 Conclusion

The article proposes a workflow how to calibrate a multi view camera adjustment. The calibration contains a geometrical part, which determines the distortions, the intrinsic and the extrinsic parameters, and a colorimetric part, where a transformation rule is calculated to map an actual device-specific color space into a nominal device-independent color space.

Therefore a calibration target with combined features is used. This is a chessboard target with integrated color markers. The corners of the chessboard target are detected with sub pixel accuracy and are used as geometrical reference points. The color markers act as the nominal color valences.
This calibration procedure is applied for an adjustment of multiple stereo camera systems, which observes a working space, where humans and robots are located. The main task for this observing system is the avoidance of collisions between humans and robots. Therefore objects have to be extracted from the background and merged with the extracted objects from different views, so that they can be classified all into humans and robots and that they are definitely locatable in a three dimensional space. This merging process requires a unified color representation and an exactly known geometrical relation between all used cameras.

References

[1] Roger Y. Tsai. An efficient and accurate camera calibration technique for 3d machine vision. *IEEE Journal of Robotics and Automation*, 3(4):323–344, August 1987.

[2] Janne Heikkila and Olli Silven. A four-step camera calibration procedure with implicit image correction. In *Conference on Computer Vision and Pattern Recognition (CVPR '97)*, page 1106, San Juan, Puerto Rico, 1997.

[3] Richard Hartley and Andrew Zisserman. Multiple view geometry in computer vision. In *2nd ed. Cambridge, UK: Cambridge University Press*, 2003.

[4] Yasutaka Furukawa and Jean Ponce. Accurate camera calibration from multi-view stereo and bundle adjustment. *International Journal of Computer Vision*, 84(3):257–268, September 2009.

[5] Jean-Yves Bouguet and Pietro Perona. Camera calibration from points and lines in dual-space geometry. Technical report, California Institute of Technology, Pasadena, USA/CA, 1998.

[6] Zhengyou Zhang. A flexible new technique for camera calibration. In *IEEE Transactions on Pattern Analysis and Machine Intelligence*, volume 22(11), pages 1330–1334, November 2000.

[7] Peter F. Sturm and Stephen J. Maybank. On plane-based camera calibration: A general algorithm, singularities, applications. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pages 432–437, Fort Collins, Colorado, USA, 1999.

[8] Jean-Yves Bouguet. Camera calibration toolbox for matlab. Website, [2010, July]. `http://www.vision.caltech.edu/bouguetj/calib_doc/index.html`.

[9] Gary Bradski and Adrian Kaehler. *Learning OpenCV*. O´Reilly Media, Sebastopol, USA/CA, 2008.

[10] Gary Bradski and Adrian Kaehler. OpenCVWiki. Website, [2010, June]. `http://opencv.willowgarage.com/wiki`.

[11] ZBS e.V. CCal-Bibliothek Benutzerdokumentation. ZBS internal paper, April 2007.

[12] Rico Nestler, Rainer Jahn, Erik Sparrer, and Karl-Heinz Franke. Praktischer Einsatz von Mehrbereichsfarbmesssystemen zur spektralen Charakterisierung von selbstleuchtenden und nicht selbstleuchtenden Objekten. In *14. Workshop Farbbildverarbeitung*, pages 63–76, Aachen, 2008.

[13] Klaus Tönnies. Grundlagen der Bildverarbeitung. In *1st ed. Magdeburg*, 2005. Deutschland: Pearson Studium.

[14] C.S. McCamy, H. Marcus, and J.G. Davidson. A color-rendition chart. *Journal of Applied Photographic Engineering*, 2(3):95–99, Summer 1976.

[15] Danny Pascale. *RGB coordinates of the Macbeth ColorChecker*. The BabelColor Company, Montreal, Quebec, Canada, Comparison 2006.

[16] Alexander Eugen Conrady. Decentering lens systems. In *Monthly notices of the Royal Astronomical Society*, volume 79, pages 384–390, April 1919.

[17] Duane C. Brown. Decentering distortion of lenses. In *Photometric Engineering*, volume 32(3), pages 444–462, 1966.