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**Machine Learning for**

**Computer Vision**

Faculty of Computer Science

Institute of Artificial Intelligence

Chair of Machine Learning for Computer Vision

Module CMS-PRO - Research Project

**Camera Calibration with a Bar**

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Born on: 16th June 1997 in Chennai, India

Matriculation number: 4986158

to achieve the academic degree

**Master of Science (M.Sc.)**

Examiner

Prof. Dr. Bjoern Andres

Supervisor

Mr. Holger Heidrich

Submitted on: 02nd May 2023

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**Machine Learning for**

**Computer Vision**

**Faculty of Computer Science** Chair of Machine Learning for Computer Vision

Task for the preparation of a Research Project

Course: M.Sc. Computational Modeling and Simulation

Name: Rajasekar Sankar

Matriculation number: 4986158

Matriculation year: 2020

Title: Camera Calibration with a Bar

Objectives of work

Write a calibration function that fits in the framework of OpenCV and uses a bar-like Object of known length as calibration target.

1. Setup a system w1th at least two cameras to capture video of a bar.
2. The videos have to be either synchronous or with precise timestamp
3. Detect the endings/markings of the bar.

Focus of work

Camera configuration

* Wiring up the Cameras to PC and Hardware trigger
* Get synchronously images

Creating a reference bar

* Build objects for the ends and paint for identification

Image Capturing for calibration process

* Take image every n seconds
* Save and label images

Extracting pairs of coordinates from synchronized images

* Find out the AoI where the objects are located and find centre coordinates
* Apply these steps for any of these n images

Calibration Process (mathematical model)

* Apply bundle adjustment to find the ex-/intrinsic parameters

Validation

* Compare the results against an existing algorithm

First referee: Prof. Dr. Bjoern Andres

Supervisor: Mr. Holger Heidrich

Issued on: 20th November 2022

Due date for submission: 2nd May 2023

Mr. Holger Heidrich

Supervisor

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**Statement of authorship**

I hereby certify that I have authored this document entitled Camera Calibration with a Bar independently and without undue assistance from third parties. No other than the resources and references indicated in this document have been used. I have marked both literal and accordingly adopted quotations as such. There were no additional persons involved in the intellectual preparation of the present document. I am aware that violations of this declaration may lead to subsequent withdrawal of the academic degree.

Dresden, 02nd May 2023

Rajasekar Sankar

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**Faculty of Computer Science** Chair of Machine Learning for Computer Vision

**Machine Learning for**

**Computer Vision**

Abstract

Fish-eye cameras are becoming increasingly popular in computer vision, but their use for three-dimensional measurement is limited partly because of the lack of an accurate, efficient and user-friendly calibration procedure. For such a purpose, the authors propose a method to calibrate the intrinsic and extrinsic parameters (including radial distortion parameters) of two/multiple fish-eye cameras simultaneously by using a wand under general motions. Thanks to the generic camera model used, the proposed calibration method is also suitable for two/multiple conventional cameras and mixed cameras (e.g. two conventional cameras and a fish-eye camera). Simulation and real experiments demonstrate the effectiveness of the proposed method. Moreover, the authors develop the camera calibration toolbox, which is available online

In computer vision, camera calibration is a necessary process when the retrieval of information such as angles and distances is required. This paper addresses the multi-camera calibration problem with a single dimension calibration pattern under general motions. Currently, the known algorithms for solving this problem are based on the estimation of vanishing points. However, this estimate is very susceptible to noise, making the methods unsuitable for practical applications. Instead, this paper presents a new calibration algorithm, where the cameras are divided into binocular sets. The fundamental matrix of each binocular set is then estimated, allowing to perform a projective calibration of each camera. Then, the calibration is updated for the Euclidean space, ending the process. The calibration is possible without imposing any restrictions on the movement of the pattern and without any prior information about the cameras or motion. Experiments on synthetic and real images validate the new method and show that its accuracy makes it suitable also for practical applications.

Abstract—Camera calibration has been studied extensively in computer vision and photogrammetry and the proposed techniques in the literature include those using 3D apparatus (two or three planes orthogonal to each other or a plane undergoing a pure translation, etc.), 2D objects (planar patterns undergoing unknown motions), and 0D features (self-calibration using unknown scene points). Yet, this paper proposes a new calibration technique using 1D objects (points aligned on a line), thus filling the missing dimension in calibration. In particular, we show that camera calibration is not possible with free-moving 1D objects, but can be solved if one point is fixed. A closed-form solution is developed if six or more observations of such a 1D object are made. For higher accuracy, a nonlinear technique based on the maximum likelihood criterion is then used to refine the estimate. Singularities have also been studied. Besides the theoretical aspect, the proposed technique is also important in practice especially when calibrating multiple cameras mounted apart from each other, where the calibration objects are required to be visible simultaneously.

An image sequence-based, fully automatic and rather flexible procedure for the calibration of stationary multi-camera systems for 3-D observation of dynamic events is presented and analysed. While conventional close-range camera calibration techniques are either based on a stable point-field with known reference coordinates or on a temporarily stationary point-field with only approximately known 3-D coordinates, which is imaged from different locations and under different orientations with one single camera, the presented technique is based on stationary cameras and moving targets, making use of the image sequence acquisition nature of most solid state cameras. In the simplest version, only one easily detectable marker has to be tracked through image sequences of multiple pre-calibrated cameras, thus avoiding the necessity of homologous feature identification for the establishment of multi-view correspondences; 3-D coordinates of the marker position are not required. This single-marker method does not allow for the determination of the interior orientation. In an extended version allowing for full camera orientation and calibration, a reference bar of known length is moved through object space, with the problem of feature identification and establishment of multi-view correspondences being reduced to the tracking of two targets. The method can only be used with multi-camera systems and is most useful for 3-D motion analysis applications, but may be adapted to a wide range of other applications. The advantages of the method over conventional self-calibration techniques are the trivial establishment of multi-view correspondences, the fact that no temporarily stable target field has to be constructed, and the fact that each camera has to be set up only once. After an explanation of the technique, its performance is examined in detail based on extensive computer simulations, and the practical effectiveness is shown in a pilot study on industrial robot calibration. Based on these studies, recommendations are given concerning the number of reference bar locations, preferable reference bar orientation schemes and the achievable

Camera calibration is an important process in the computer vision and photogrammetry, used for retrieving the information like the orientation and position of the target objects. In many industrial applications, pinhole cameras are used for 3D measurement especially for measuring the depth using the stereo system. But for accurate results it is very important to calibrate all the cameras using the calibration object. This paper describes a methodology to calibrate the intrinsic and extrinsic parameters (including distortion coefficients) of the two stationary pinhole cameras simultaneously using a 3D calibration object, the reference bar of known length is moved through the object space. N observations of the dynamic events of the bar with the detectable marker endings attached on both ends are studied using the left and right cameras at synchronous time stamps. An algorithm is defined to obtain the image points from the sphere centres, which is the marker endings on either side of the bar. The solution is developed using the bundle adjustment technique, Levenberg-Marquardt algorithm is used for minimising the least square error estimation. Experiments are performed for the planar pattern (checkerboard) and reference bar of known length using both same and different camera devices of the stereo system and the results were studied.

Introduction

Mathematically, in the image creation process, the camera accomplishes a mapping between a 3D space and the image plane. During this process, some information, e.g., angles, distances and volume are lost. If these information are needed, it becomes necessary to estimate the intrinsic and extrinsic camera parameters, through a procedure known as calibration. Usually, during this procedure, the camera captures images from an object with well known dimensions and shape (known as the calibration pattern). Afterwards, the relation between some points of the calibration pattern and their respective projections in the image plane are used to determine the camera parameters. The first calibration algorithms to become widely used were based on 3D patterns [21,14]. Over the years, new calibration methods have been proposed using 2D patterns [19,23]. More recently, Zhang [24] proposed the calibration using a single dimension pattern (consisting of a set of points in a straight line). In this, the 1D pattern should perform unknown displacements, while the camera captures images of it. The only restriction is that one of the pattern points must remain fixed during the image acquisition. However, Zhang’s work cannot be applied in practice because the method is very susceptible to noise. Therefore, only with the work of de Franc-a et al. [3], the calibration with 1D patterns could be used in practice, with an accuracy comparable to other traditional methods. This is because it was shown that the accuracy of the original method of Zhang [24] is significantly improved simply by analysing the mathematical formulation of the problem. Thus, it was possible to improve the numerical conditioning by performing a simple data normalization. The main advantage of using 1D patterns to make the calibration is the possibility to calibrate several cameras at the same time. This is because the points of the 1D pattern can be ‘‘captured’’ simultaneously by cameras even in very different points of view. However, in spite of Zhang has highlighted the advantages of using 1D patterns for calibration of multiple cameras, only after the work of Kojima et al. [13] this became possible in fact. This is because, in the case of one set of cameras, the algorithm of Kojima also estimates the extrinsic parameters of all cameras. However, unfortunately, it is necessary that at least one of the cameras, called the ‘‘reference camera’’, is already calibrated. Most calibration methods that use 1D calibration patterns assume special pattern moves or prior knowledge of some of the camera parameters. In particular, most require that a point of the pattern is always fixed. This, besides being a limitation, is one additional source of errors, because in practice it is not always easy to keep a point of the pattern fixed as the pattern moves. The work of Wang et al. [22] was the first to propose a multi-camera calibration algorithm based on a 1D pattern that moves freely and without prior knowledge of the parameters of any of the cameras. As in the algorithm of Kojima et al. [13], pattern projections are used to estimate a set of vanishing points correspondences. Thus, the infinite homography from all cameras in the set is estimated and an affine calibration can be performed. Then, the affine camera matrices can be updated to the Euclidean space, completing the calibration. However, as demonstrated empirically in Section 5.1, the estimation of vanishing points is very susceptible to noise, making these algorithms unsuitable for practical use. In this work, a different approach is proposed, where vanishing points are not necessary. Although the calibration pattern can move freely, the proposed method also does not assume prior knowledge of any intrinsic parameter. Moreover, as in any calibration algorithm using 1D calibration patterns, the proposed method has an advantage over those based on 2D plane calibration patterns, which is the possibility to calibrate two or more cameras simultaneously even if they are in very different points of view. To make this possible, in the proposed technique, the fundamental matrix of the system is initially estimated and a projective calibration of the binocular set is accomplished. Then, the plane at infinity and the intrinsic parameters of the reference camera are estimated. Thus, calibration can be updated to an Euclidean calibration. Experimental results performed on synthetic and real images show that the proposed method produces good results even in the presence of noise and thus provides a convenient and flexible approach to calibrate one or more binocular sets.

Close range photogrammetry is mostly based on the use of non-metric solid state sensor cameras today. To translate the high accuracy potential of such cameras, which is often in the order of 1r50 of a pixel, into object space, these cameras have to be modelled and calibrated thoroughly. Camera models used in digital close range photogrammetry are usually based on the collinearity condition and a number of additional parameters modelling the interior orientation, lens distortion and sometimes further distortions like effects of the image ArD conversion or sensor unflatness. Camera calibration is advantageously performed ‘on the job’ by self-calibration techniques to represent the instantaneous state of the camera. For highest flexibility and minimum effort, calibration techniques should be based on a minimum of object space information. Photogrammetric self-calibration techniques, which are only based on ray intersections at a number of object points with unknown 3-D coordinates plus one scale information, have been introduced by Brown 1971 and Ž . Kenefick et al. 1972 . In order to fully reconstruct Ž . the interior orientation of one single camera to be calibrated, a temporarily stationary target field has to be imaged by this camera under at least three different orientations, one of them preferably rotated by 1808 to reduce high correlation between parameters of interior orientation, exterior orientation and 3-D object point coordinates. The simultaneous determination of a horizontal scale factor, necessitated by different clock rates of cameras and framegrabber in systems based on standard videonorm CCD cameras Ž . e.g., El-Hakim, 1986; Beyer, 1987 , requires the acquisition of a fourth image, preferably under another camera rotation by 908. A practical scheme for self-calibration network geometry, based on the acquisition of seven images with a single camera, has been presented by Godding 1993 . The positive Ž . effect of additional exposures under the application of rotation strategies has also been shown by Grun¨ and Beyer 1992 . Due to their high degree of flexi- Ž . bility, these self-calibration techniques have become a standard for the calibration of single-camera systems, which are based on the acquisition of multiple images of a scene for 3-D object reconstruction anyway. The necessity of the establishment of a temporarily stable target field is part of the actual task in most stationary applications of digital close range photogrammetry, but may be cumbersome in dynamic applications like e.g., human motion analysis Fig. Ž 1 . Moreover, photogrammetric systems for 3-D data . acquisition in dynamic processes will usually consist