# 3D Spatial Measurements by Means of a Prism-based Endoscopic Imaging System

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## Abstract

Prism-based endoscopic passive imaging systems are widely used for simultaneous visual inspection and 3D spatial measurements of the detected defects. We analyzed conventional calibration methods for the pinhole camera model with polynomial distortion approximation and compare them to the ray tracing model based on the vector form of Snell's law. In order to evaluate the effectiveness of the models, the software for the imitation of various calibration procedures has been developed. The experimental data was based on the images of the test-charts acquired with two industrial videoendoscopes and prism-based stereoscopic adapters. Our analysis confirmed that the ray tracing model demonstrates significantly better measurement accuracy in a large distance range. The results may be useful for the development of the new tools for remote visual inspection in industrial and medical applications.

***Keywords:*** *Remote visual inspection, 3D spatial measurements, Geometric calibration, Polynomial distortion model, Prism distortion.*

## 1. INTRODUCTION

Endoscopic systems are widely used for remote visual inspection of aviation and car engines, pipelines, nuclear equipment and many other industrial objects, as well as in medical applications. Endoscopic measurement technologies based on stereoscopic and other methods allow simultaneous visual inspection and 3D spatial measurements of the detected defects.

The stereoscopic technique requires at least two images registered from different viewpoints by two imaging devices or one moving device [2,5,8]. At the moment, placing two separate lenses and two CCD chips in the head part of endoscope with a diameter less than 8 mm is challenging. Therefore, modern industrial endoscopes may be equipped with the attachable stereo adapters which make it possible to obtain images from two different viewpoints on a single CCD sensor [3,15]. This adapter contains a biprism and an auxiliary lens as shown in figure 1 [13].

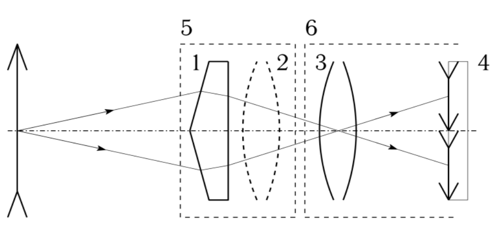


**Figure 1:** Imaging system with prism-based stereo adapter: 1 — biprism, 2 — auxiliary lens, 3 —main lens, 4 — CCD sensor, 5 — attachable adapter, 6 — endoscope camera head.

The conventional calibration methods assume projective camera and polynomial distortion model [16,19]. The prism-based stereoscopic device can be considered as two virtual pinhole cameras. The intrinsic and extrinsic parameters can be derived from the prism and main lens parameters as shown in [11,12,18]. This approach is unsuitable for precise measurements because of the optical distortion introduced by the prism. The alternative model was presented in the paper [17] for the image distortion correction method and applied for the complicated optical system with two rotating prisms in front of the main lens. Additionally, the camera model and the calibration procedure should be adapted for endoscope with attachable stereoscopic adapter to consider the uncertainty of the attaching mechanism and the fact that simultaneous calibration of the adapter and the camera head is not always available [14].

This work is dedicated to the theoretical and experimental study of a few mathematical models and calibration algorithms for the prism-based stereoscopic imaging device.

## 2. MATHEMATICAL MODELS

The registration channels of the stereoscopic system may be represented by the simplified geometric model of the image formation [2,5,8,19]. This mapping determines the unique correspondence of rays in the object space and points on the image plane. The mapping described by the "pure" pinhole model (used in [11,12,18]) is unsuitable for precise measurements. Therefore, we should complete it with an additional transformation to consider distortion caused by the prism and the main lens. The most common model [1,19] represents distortion as the combination of radial (3rd, 5th and 7th orders) and tangential ("thin prism") parts in order to consider lens decentering. We further refer to this model as 'model #1' and use 26 parameters to describe it.

We can extend the polynomial distortion model using the generic polynomial of two variables with $2(B + 1)$ coefficients. The point coordinates in the unit plane are the variables and $B$ is the highest degree of the polynomial. This universal equation represents many particular distortion models, such as polynomial model [14]. We further refer to the extended polynomial model as 'model #2'. Generally, we should limit the number of distortion coefficients to simplify optimization procedures on the calibration stage. Total number of parameters for model #2 is equal to $(16 + 2(B + 1)^2)$, but in practice significantly less parameters are used.

In order to implement 3D reconstruction by triangulation, camera model should be invertible and provide the back-projection transformation. The considered models do not allow finding a closed-form solution for the inverse transformation. That is why an iterative solver or look-up-table should be used in this case.

The alternative model based on a ray tracing from the image plane to the object space is formulated similar to the paper [17]. We describe the refraction of each ray on both surfaces of the prism according to the vector form of Snell's law. The prism refraction should be complemented with the model of the main lens in order to find the ray coordinates after the prism for each image pixel. Ray tracing through the prism is shown in figure 2. We use the pinhole model with distortion similar to model #1 for the main lens. Hence, we have 30 parameters to describe the ray tracing model ('model #3') [7].

In contrast to the previous model, the ray-tracing model cannot provide closed-form solution for the forward transformation because it requires initially unknown direction vector of the line from 3D object point (shown in red in figure 2). This problem is usually solved by the iterative technique called the ray aiming.

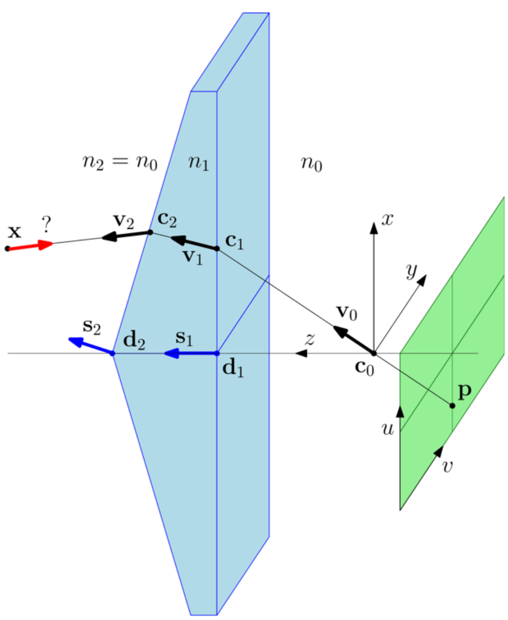


**Figure 2:** Ray tracing through the prism.

Next, we consider the reconstruction of 3D coordinates from $N$ projections as the ray intersection problem and use the maximum likelihood estimation to solve it [5,8,10]. The same approach is applied to form the cost function for the optimization on calibration stage [7].

## 3. COMPUTER SIMULATION

In order to evaluate each of the proposed models we have developed the software for the imitation of various calibration procedures using different types of calibration targets (such as boards and corners [2,19] or steps [4]). The input data (2D image coordinates) for calibration procedures was generated with full ray tracing model and high-order polynomial distortion model and additive noise. Then the estimated parameters for every model were used to calculate the uncertainty of 3D coordinates for the set of points distributed in the working volume. The average deviation and the maximum absolute deviation were chosen as the main criteria for model optimality. Additionally, the estimated 3D point coordinates were used to calculate the geometric parameters such as distances or areas. The criteria based on deviations of length or area are very useful for the evaluation of calibration models for these systems [3,5,6,15].

We performed this evaluation for the parameter values typical for the industrial endoscope with the prism-based stereoscopic adapter. Main results and conclusions of this simulation are the following: first, using the pinhole models leads to an unacceptable bias, model #1 and #2 cannot be equal to model #3 under specified conditions; second, increasing the number of degrees for polynomial distortion model as the 2D transformation does not lead to better results. Detailed results were presented in our recent paper [7].

The proposed method is flexible and suitable for different calibration algorithms and calibration targets. It can also be used to test stability and convergence for parameter optimization during the calibration procedures and to compare calibration targets and strategies.

## 4. EXPERIMENTAL RESULTS

We conducted the series of experiments using two different industrial videoendoscopes with 6 mm probe diameter and attachable stereo adapters. We utilized plane calibration targets with circular dots and chessboard markers to acquire images for calibration and tests. Three calibration targets with 0.5, 1 and 2 mm distance between the markers were placed at the distances from 10 to 40 mm from the probe. The image of the calibration target with circular dots is shown in figure 3.

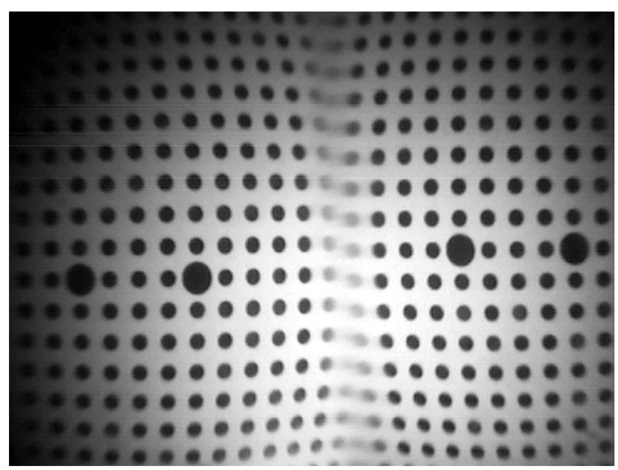

**Figure 3:** The image of the calibration target with circular dots.

First, the images of the calibration set (about 20 images) were processed to estimate parameters for three analyzed models. Next, the images of the test set (also about 20 images) were used to calculate the 3D coordinates for each marker and the geometric parameters such as a length of a segment or an area of a figure. The calculated deviations of the length for 2 mm segment are indicated by dots color in figure 4 for model #1 and in figure 5 for model #3. The data set included segments roughly perpendicular to the z-axis of the probe and slanted segments.

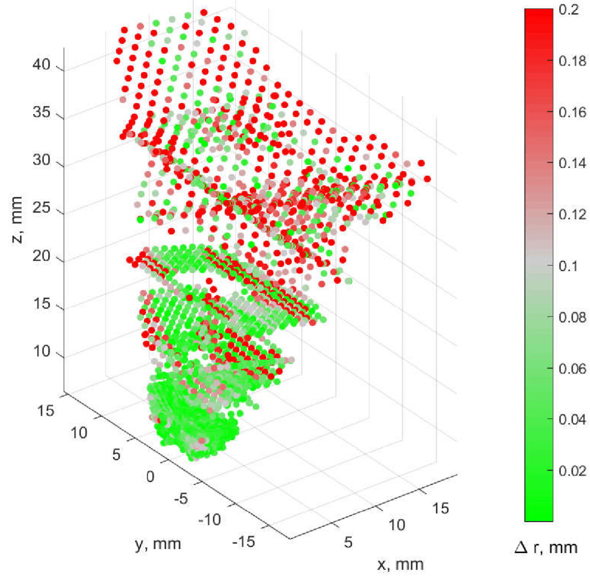


**Figure 4:** Absolute deviation of length for 2 mm segments estimated with model #1.

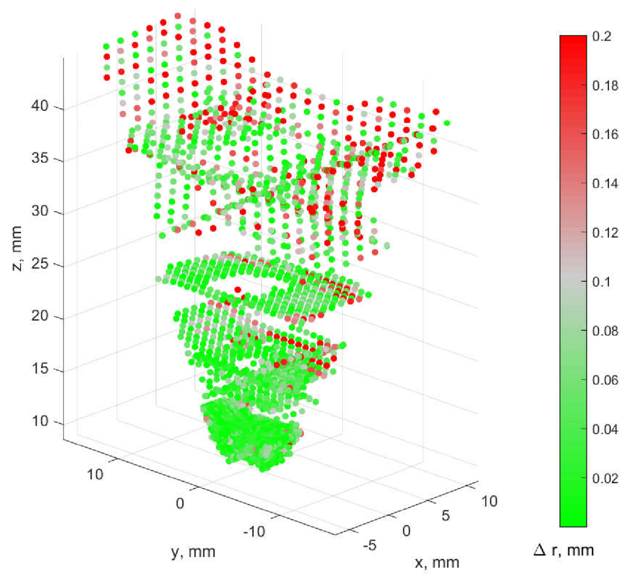


**Figure 5:** Absolute deviation of length for 2 mm segments estimated with model #3.

In order to perform quantitative analysis, we divided the obtained data set into zones according to the distance from the coordinate origin and calculated mean and standard deviation of the segment length for every zone. The resulting graphs for 2 mm segment (figure 6) show that model #3 demonstrates significantly better measurement accuracy than model #1 when the distance is over 15 mm. We also used the estimated parameters of the models, positions of calibration target and 3D coordinates of markers as the input data for the computer simulation. The developed software allowed to predict the measurement uncertainty caused by pixel coordinate errors of corresponding points using the unscented transformation [9]. The calculated deviation of the length corresponding to the standard deviation of pixel coordinates 0.2 pix for the same data set is shown in figure 6 for comparison.

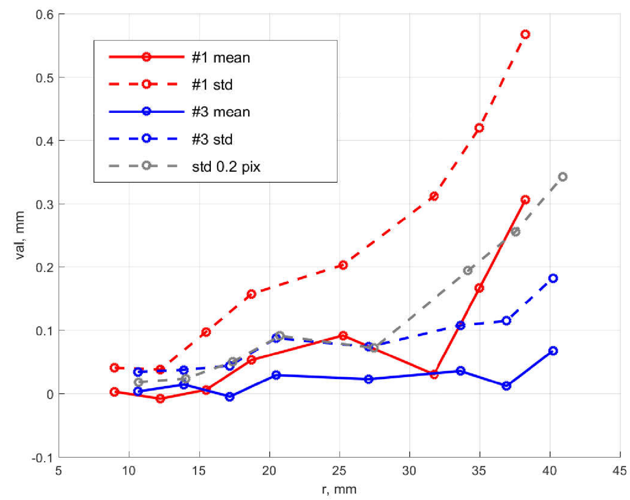


**Figure 6:** Mean and standard deviation of length for 2 mm segments estimated with model #1 and #3 compared to computer simulation

## 5. CONCLUSION

We analyzed the conventional calibration methods for the pinhole camera model with polynomial distortion approximation and compared them to the ray tracing model based on the vector form of Snell's law. Our analysis identified the main problems for three considered models: entrance pupil shift, non-homocentric beams and unknown required number of coefficients for polynomial models and the iterative forward ray aiming for the ray tracing model. In order to evaluate each of the proposed models we have developed the software for the imitation of various calibration procedures and used it to prove that the pinhole camera models cannot be equal to the ray tracing model under specified conditions. Finally, we conducted the experiments with two industrial videoendoscopes and attachable stereo adapters to validate the proposed method and confirmed its accuracy and effectiveness by comparison of the experimental results and computer simulation.

## 6. AKNOWLEDGEMENTS

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