Calibration procedures for fringe projection mea ing systems in 3D

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Abstract

There are multiple applications for fringe projection systems in 3D surface measurement. The measuring system must be calibrated prior to measuring to achieve high accuracy. Several calibration methods are known all of which directly influence the measurement uncertainty. These methods can be categorized into two groups, namely physical/geometrical and "black box" calibration methods. While "black box" methods are built upon a merely mathematical basis, the first are founded on a physical/geometrical model of the fringe projection system.

1. Introduction

The advantages employing a fringe projection system are optical (i.e. non-contact) and extremely parallel measurements that provide a large number of measuring points (as a rule, almost every camera pixel corresponds to a 3D coordinate value). Thus, fringe projection systems can also be used for free-form surface measurements. The opportunity of taking fast and accurate surface measurements enables fringes projection systems to be applied in the field of coordinate metrology.
Tactile Coordinate Measuring Machines (CMM) represent an established and sophisticated metrology that allows high precision measurements. Nevertheless, high acquisition costs, required space, low measuring speed, and the indispensable contact with the measuring object are disadvantageous. Fringe projection systems, however, lend themselves to supplement CMMs. They also can be used when CMMs are not applicable due to their manner of operation.
Fringe projection systems must be calibrated prior to taking measurements. The applied calibration method establishes the relation between the coordinates of the measuring volume and the measured image plane values of the fringe projection system. Therefore, the calibration method directly influences the measurement uncertainty. In the following the currently common calibration methods are introduced. Nowadays, mainly LCD or DMD and recently LCoS [7] projectors are used in fringe projection systems. They enable the projection of free programmable patterns that allow or even support further calibration methods.

2. Measuring principle

Fringe projection systems are based upon the principle of active triangulation. Active components are the light source (projector) and one or more cameras. As a matter of simplification only one camera shall exist in the following. The existence of more than one camera is considered in the section about the calibration methods. Projector, measuring volume, and camera are the vertices of a triangle.

Fringe projection systems take optical measurements of the (as much as possible diffuse) reflecting surface of the measuring object. The surface must be located within the measuring volume. The result are 3D metric coordinate values of the surface. The reflected light is detected by the camera chip. Thus, the planar camera chip provides 2D coordinate values of the image plane.

The projector illuminates the measuring volume in a structured way that is a sequence of vertical or horizontal stripe patterns. These stripe patterns are spatially and temporally coded according to the Gray-Code (see Figure 1 left) or one of its variations. A survey of more types of structured illumination is given by [3].

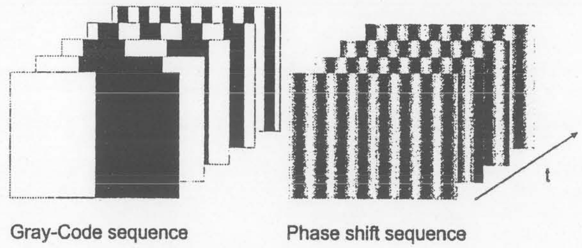

Figure 1 Gray-Code and phase shift projection

In order to increase the resolution of the stripe pattern normally the phase shift procedure is used (see Figure 1 right). On principle the phase shift is a sinusoid intensity signal. The relative phase of the signal at a certain point on the surface of the object can be precisely detected by the camera. Combining Gray-Code and phase shift attributes a definite absolute phase value ζ to each projected stripe. Monitoring the measuring object with a camera, every camera pixel p_{ij} registers one phase value ζ_{ij}. This phase value ζ_{ij} is characteristic for the place of reflection located within the measuring volume. Consequently, the phase value ζ_{ij} contains information about the altitude of the point of reflection. Altering the altitude changes the detected phase value of the pixel p_{ij}.

3. Calibration of a fringe projection system and calibration techniques

In general, having measured the phase value ζ_{ij} leads to the triple W:=(i, j, ζ_{ij}) where i, j are the pixel coordinates of the pixel p_{ij}. The task is to calculate the metric coordinate triple $\mathbf{r}=(X, Y, Z)\in\mathbb{R}^3$ (in the object coordinate system) located in the measuring volume from the triple W. The premise for an exact calculation of **r** is the calibration of the measuring system.
Mathematically speaking, the goal of calibrating a fringe projection system is to determine a calibration function f, namely $W=f(\mathbf{r})$, where the calibration function f describes the relation between the points **r** in the 3D measuring volume and the points p_{ij} on the 2D camera plane as well as their phase values ζ_{ij}. Having conducted

a measurement, in principle the inverse function of f delivers the metric coordinate **r** from the triple *W*. The calibration function itself is predetermined by the chosen calibration method. Because the calibration method establishes the relation only between *W* and **r**, it is independent from the fringe projection system itself.

Difficulties arising from non-linear influences while calibrating a fringe projection system are illustrated in Figure 2. A planar surface was measured in the reference position Z=0 with a calibrated ("black box" method) fringe projection system. Afterwards, the surface was stepped with a step length of exactly 1 mm in the direction of Z while at each step measuring Z with the fringe projection system. The measurement errors are plotted against the altitude Z in Figure 2 exhibiting a non-linear deviation.

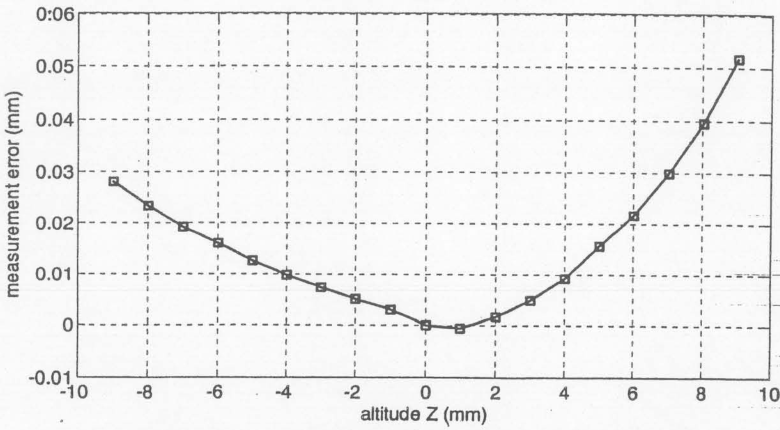

Figure 2 Non-linear distortions of a calibrated fringe projection system

Figure 3 shows only the aberration of a real camera lens system, which is mostly caused by a radial symmetric distortion. The lateral deviation of the measured points from the central projection is plotted against the x-y-plane.

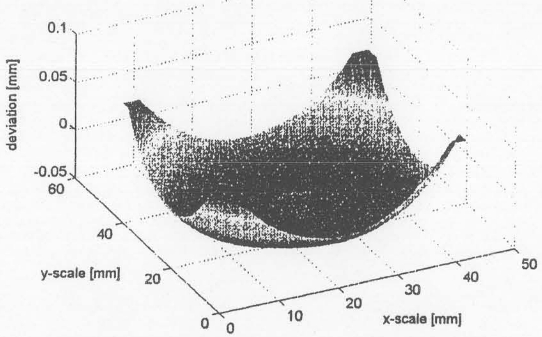

Figure 3 Lateral deviation of a camera lens system

The influence of a variety of calibration techniques on the measurement uncertainty of fringe projection systems is investigated at the Institute for Measurement and Control Engineering (IMR). The goal is to conduct a systematic study employing a variety of calibration techniques on a single fringe projection system customary to industry. The outcome of this is an evaluation of calibration techniques that is (more or less) independent from the fringe projection system. For this purpose a fringe projection system of the company GFM with one DMD projector and two cameras is used. With this flexible system it is possible to take measurements in different measuring volumes, too.
The calibration methods can roughly be categorized into two groups, namely the mathematical "black box" procedures and the physical/geometrical procedures. At first the "black box" procedures are investigated at the IMR. Later physical/geometrical models will also be examined. In this case, the influence of further parameters such as triangulation angle, measuring volume, etc. on the calibration method is investigated, too.
In order to evaluate the measurement uncertainty in general, the measurement uncertainty within the whole measuring volume must be taken into consideration. For this purpose appropriate test specimen must be developed. Particularly the surface of these test specimen must have appropriate optical characteristics.

It is assumed in the following that undercuts and shadowing effects do not occur inasmuch as every object point is always illuminated by the projector and always monitored by the camera.

3.1. Physical/geometrical calibration methods

Calibration methods of this kind are always founded on a physical or geometrical model of the measuring system. Primarily they differ in the amount of parameters of the measuring system that are taken into consideration. These parameters usually comprise distortions of both camera and projector. In this case the calibration consist of the identification of all unknown parameters of the underlying model.

The pin-hole model of a camera is the basis for all physical/geometrical models. Here the wave characteristics of light are neglected. Instead the pin-hole model is based on central perspective projection and the principles of geometrical optics. All beams of light that run through the image plane of the camera intersect at the projection center $\mathcal{P}$ of the camera (see Figure 4). The orthogonal distance of the projection center $\mathcal{P}$ to the image plane is referred to as camera constant *c*. If one knows the position of the projection center $\mathcal{P}$ and the camera constant *c*, one can calculate a beam on which the point P is located from the image coordinates p_{ij}. The point of the orthogonal projection of $\mathcal{P}$ on the image plane is referred to as principal point $H=(i_H, j_H)$. Usually the principal point does not lie on the optical axis of the camera. In photogrammetry the parameters c, i_H, j_H are called interior parameters of a camera.

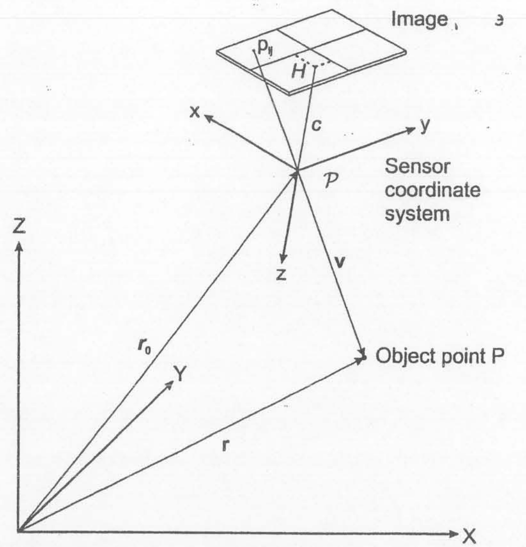

Figure 4 Image plane in the object and sensor coordinate system

Also the sensor coordinate system is introduced. Its origin is identical to the projection center $\mathcal{P}$ and its x-y-plane parallels the image plane. For a pixel coordinate p_{ij} in the sensor coordinate system $\mathbf{p}=(i-i_H, j-j_H, -c)$ shall apply.
The following equation describes the relation between the object coordinate vector $\mathbf{r}=(X, Y, Z)$ of a point P and the sensor coordinate vector $\mathbf{v}$ of the same point

$$\mathbf{r} = r_0 + m\boldsymbol{R}\mathbf{v} \qquad (1)$$

where $\boldsymbol{R}$ is a 3x3 rotation matrix with three independent rotation angels; r_0 is the position vector to the origin of the sensor coordinate system; and m is an unknown scalar value. The three rotation angles and $\mathbf{r}_0$ are the six parameters specifying the exterior orientation of the camera.
From (1) arise the non-linear collinear equations that form the basis of the calibration methods described in the following.

The pin-hole model assumes ideal projection behavior of a camera. However, real cameras have numerous distortions which can be taken into account adding further terms in (1). But every further term increases the number of model parameters that must be determined. A projector can be understood as inverse camera [4]. Consequently, the same models apply. Yet a projector can not be calibrated independently without a camera.

The determination of the unknown model parameters, e.g. interior and exterior orientation of the projector and camera(s), can be accomplished via a bundle adjustment [10, 11]. In this case all unknown parameters are determined in one single simultaneous calculation step. The object coordinate values are incorporated as unknown parameters. The measured camera coordinate values and the projector

coordinate value(s) generate a non-linear system of equations via the collinear equations. There must be four measured and independent values for each object point taken into account. The bundle adjustment determines the most probable values for the unknown parameters based on the observed values. At least one distance within the measuring volume must be known for scaling. The adjustment to the object coordinate system is accomplished using 6 further parameters. Otherwise, one can only carry out a free network bundle adjustment that does not provide spatial orientation and location [11].
Additionally, further points with known coordinate values can be positioned within the measuring volume. These so-called control points increase the number of known parameters of the systems of equations. Thus the solution becomes more stable provided that the control points are very accurately known. However, approximate values are required for each unknown parameter for a successful bundle adjustment and good results. Often appropriate approximate values are difficult to find.

Some projectors can generate two independent phase coordinate values (ζ, η) by projecting a second sequence of stripe pattern orthogonal to the first one. In this case the camera and projector can be calibrated simultaneously in one step. The reason is that one can accomplish a bundle adjustment by means of four independent coordinate values on the basis of the collinear equations. If the projector can generate only one projector coordinate value, then control points with known object coordinate values need to be positioned within the measuring volume. Thus, an over-determined system of equations is obtained. Its solution provides the unknown model parameters [11].

In the case of using two or more cameras a calibration of the projector is not necessary anymore. That is because the cameras alone already supply at least four independent values for each object point. Here the projector merely serves as signal generator in order to solve the problem of correspondence [6] (the relation between object points and measured values of different cameras (problem of correspondence) is a great problem talking of passive photogrammetry). Nevertheless, a calibration of the projector improves the accuracy of the entire system.

Further physical calibration methods are known, though they are based on special cases of bundle adjustment. For instance, in [4] the interior orientation solely of the camera is determined in the first step. For this purpose various calibration methods are known [8, 9] using photogrammetrical methods. Then a resection, which is a special case of bundle adjustment, is accomplished utilizing the calibrated camera in order to calibrate the entire fringe projection system.

Advantages:
All parameters that must be determined have a definite meaning as they directly result from the physical model. Therefore, accurate results even outside the calibrated measuring volume can be anticipated. Besides, this calibration methods provide statistical error analysis that allows an evaluation of the determined parameters.

Disadvantages:
This calibration method takes into account only the physical parameters of the measuring systems that are explicitly incorporated in the model in the first place. Other effects can not be corrected during future measurements. Moreover, these kind

coordinate values (x, y) of the object point (X, Y, Z). The calculated output of the neural network (X', Y', Z') is compared to the object coordinate values (X, Y, Z). Then the weights of the neural network can be adjusted from the difference of the output vector (X', Y', Z') and the coordinate vector (X, Y, Z). This procedure is repeated until the difference between these two vectors falls below a predetermined threshold value and thus the calibration is completed.
Additionally, further parameters such as the parameters of the network transform function or the number of layers can be adjusted during the calibration process in order to improve calibration as to be seen in [2].
Neural networks are inherent non-linear systems and, therefore, in principle take account of distortions of a fringe projection system likewise to polynomials. The problem is finding appropriate starting values for all parameters. Otherwise most of the disadvantages described for "black box" methods apply here, too. Furthermore, it seems to be difficult to theoretically anticipate the attainable measurement uncertainty.

4. Summary

The measuring principle of a fringe projection system in general has been introduced and the direct relation between calibration and measurement has been pointed out. Also, an overview of currently existing and applied calibration methods for fringe projection systems has been given. One distinguishes between model based and merely mathematical interpolation methods that use a totally different approach.
As a rule "black box" calibration methods do not require exact knowledge of the measuring system but only an appropriate calibration object instead. However, the result of the calibration does not provide any information about the measurement accuracy. In contrast, physical/geometrical calibration methods are model based procedures that become complicated and thus pose a difficult to solve calibration problem for even slight deviations from the ideal pin-hole camera model though.

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