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Optical measuring equipments. Part I: Calibration model and uncertainty estimation

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ABSTRACT

This study aims to propose and describe a procedure for calibrating the "vision subsystem" of digital optical machines, based on the affine camera model, valid for telecentric optical equipment. From this procedure, it is possible to systematise the calculation of the uncertainty of the calibration parameters associated with the "vision subsystem" by using the Monte Carlo method. The identification and characterisation of the calibration parameters of the "vision subsystem" and its associated uncertainty, obtained through this study, make it possible to characterise the metrological properties of the indicated optical equipment and ensure the metrological traceability of the measurements that have been subsequently taken.

This work is divided into two parts. Part I focuses on developing a mathematical model of the "vision subsystem" and calculating the uncertainties of its parameters. Part II develops an example of measuring and calculating measurement uncertainty, based on the theoretical development of Part I.

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1. Introduction

The use of digital optical measuring systems has been widely distributed in the industrial area, due to its advantages such as: the speed of data acquisition, measuring function automation, precision, and, above all, the absence of contact [1]. In parallel to the use and development of such equipment in industry [2] there has been a growing interest in the field of scientific research. These optical instruments can be divided into two subsystems, a 'machine subsystem' and a "vision subsystem". The first contains the measuring table and the second contains the camera and optics associated with it [1]. At present there is no general procedure for calibrating this equipment established by national metrology institutes, although work has been carried out in this field [1,3]. In particular, there is abundant scientific literature where you can find different proposals for calibration procedures or verification of the vision system (camera) as well as for the machine system based on verification procedures commonly used in the CMMs [4–6].

In 2004 Lazzari and Iuculano [1] developed a mathematical model to evaluate measurement uncertainties obtained by an optical machine equipped with a CCD (charge coupled device) camera. The study is based on the two aforementioned subsystems, making it possible to model them and obtain a first metrological characterisation of this type of machine, only valid for determining lengths and coordinates of points, with their associated uncertainties. These authors consider a number of sources of type B uncertainty for determining the uncertainty associated with the "vision subsystem", without considering a camera model with its corresponding parameters. However, most studies found in scientific literature focus on the vision system, developing theoretical camera models for determining their intrinsic and extrinsic parameters. The "*pin-hole camera*" model [7–11], probably the simplest of those known, represents an ideal and distortion-free camera, which has its optical centre located at a finite point.

Using the above camera model, Chatterjee et al. [12] conducted a study based on the concept called "*coplanar camera calibration*", where the extrinsic and intrinsic parameters of the camera are calculated from a series of images and the coordinates of different points in space, which are considered to be located in a two dimensional plane; this consideration is verified in most applications of digital optical machines. In the same vein, Luo et al. [13] have developed a calibration technique considering that the condition of the measuring table is parallel or nearly parallel to the image plane (sensor CCD).

Other camera models are based on the "*affine camera*", which has the optical centre located at an infinite point [14]. These models allow us to represent systems with telecentric lenses that, unlike

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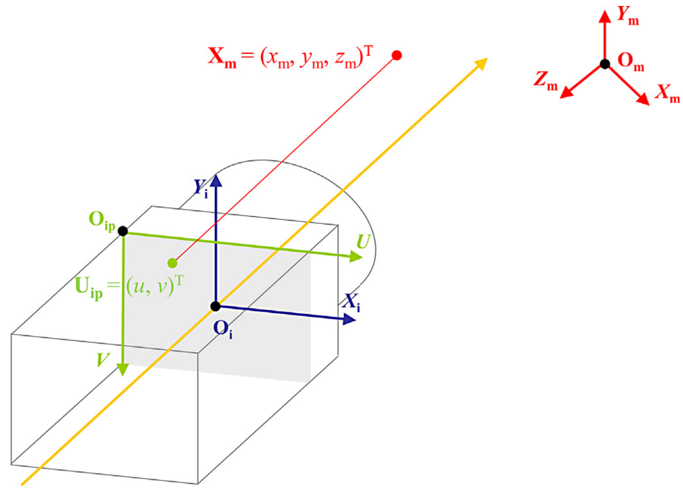

Fig. 1. Affine camera model.

traditional "*pin-hole camera*" systems founded on a perspective projection, are based on orthogonal parallel projections. The study by Li and Tian [15] uses this camera model while also including the main sources of geometric distortion of the lenses. Previous camera models use linear and nonlinear solving methods for calculating the parameters.

The various studies of scientific relevance represent important advances, but most do not define mathematical models to calculate the uncertainty associated with their parameters, i.e. they deal with verifications rather than calibrations so to speak, according to its definition in the VIM [16].

The main objective of the study carried out on this work is to define a "vision subsystem" calibration procedure of digital optical equipment able to determine the values of the uncertainty associated with the parameters of the camera. For this a behaviour model of the "vision subsystem" is defined based on the *affine camera*, valid for equipment using telecentric optical systems. This model incorporates five intrinsic parameters as well as the possible geometric lens distortion. Based on this model, a procedure has been developed to determine the parameters of the model and its associated uncertainty by using the Monte Carlo method. A fixed frequency grid distortion target is used for calibration. The development of this calibration procedure ensures the traceability of the measurements of the "vision subsystem" that are subsequently made. The validity and robustness of the procedure has been proven through experimental tests on calibrated fixed frequency grid distortion target.

2. Camera model

The camera model used in this study is the so-called *affine camera*, of which optical centre at infinity [14]. It is used to model optical systems equipped with telecentric lenses/objectives [15], making it possible to transform the coordinates of a point in space (3D) "world system coordinates" (axis X_m, Y_m and Z_m), into the coordinates of a point in an image (2D) "coordinates of the digitised image system" (axis U, and, V) through an orthogonal projection, a translation and a rotation (Fig. 1). This transformation is shown as a matrix by:

$$\begin{aligned}\mathbf{U}_{hpi} &= \mathbf{K}[\,\mathbf{R} \quad | \quad \mathbf{t}\,] \cdot \mathbf{X}_{hm}\\ \mathbf{U}_{hpi} &= \mathbf{P} \cdot \mathbf{X}_{hm}\end{aligned} \tag{1}$$

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha_x & s & x_0 \\ 0 & \alpha_y & y_0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} r_{11} & r_{12} & r_{13} & -t_x \\ r_{21} & r_{22} & r_{23} & -t_y \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x_m \\ y_m \\ z_m \\ 1 \end{pmatrix} \tag{2}$$

where $\mathbf{X}_{hm} = (x_m, y_m, z_m, 1)^T$ are the coordinates of a point in the world system, $\mathbf{K}$ is the calibration matrix of the system, $U_{hpi} = (u, v, 1)^T$ are the pixel coordinates of the digitised image system, $\mathbf{R}$ is a rotation matrix 3×3 orthogonal with the elements of its last row being zeros and $\mathbf{t} = (-t_x, -t_y, 1)^T$ are the coordinates of the optical centre O_c with respect to the origin of the world coordinate system O_m and $\mathbf{P}$ is defined as the matrix of the camera. s represents the obliquity parameter of the axes, x_0 and y_0 represent the coordinates of the image centre and α_x and α_y represent the effective focal length (along the X and Y axes) of the camera based on the size of the pixels.

It begins with the plausible assumption that the optical system has geometric distortion. This distortion manifests itself in the change of position of the image points, as a result of different types of imperfections in the design, manufacture and assembly of lenses. The coordinates of a point, expressed in the digitised image system and taking into account the geometric distortion, may be reported as:

$$\begin{aligned}u &= u' - \delta_{u'}\\ v &= v' - \delta_{v'}\end{aligned} \tag{3}$$

where u and v represent distortion-free coordinates, u' and v' are the coordinates observed with distortion and $\delta_{u'}$, $\delta_{v'}$ represent the geometric distortion of coordinates u' and v'.

In this study, based on the criteria used by other authors [8,13], three types of geometric distortion are going to be considered: radial, decentering and thin prism. Total effective distortion can be calculated as the sum of the three aforementioned types:

$$\begin{aligned}\delta_{u'} &= \overbrace{k_1 \Delta u'(\Delta u'^2 + \Delta v'^2) + k_2 \Delta u'(\Delta u'^2 + \Delta v'^2)^2}^{\text{Radial}} + \overbrace{p_1(3\Delta u'^2 + \Delta v'^2) + 2p_2 \Delta u' \Delta v'}^{\text{Decentering}} + \overbrace{s_1(\Delta u'^2 + \Delta v'^2)}^{\text{Thin prism}}\\ \delta_{v'} &= k_1 \Delta v'(\Delta u'^2 + \Delta v^2) + k_2 \Delta v'(\Delta u'^2 + \Delta v'^2)^2 + 2p_1 \Delta u' \Delta v' + p_2(\Delta u'^2 + 3\Delta v'^2) + s_2(\Delta u'^2 + \Delta v'^2)\end{aligned} \tag{4}$$

where $\Delta u' = u' - u_r$, $\quad \Delta v' = v' - v_r$ and $k_1, k_2, p_1, p_2, s_1, s_2$ represent the geometric distortion coefficients and (u_r, v_r) represents the distortion centre.

3. Developed calibration procedure

The developed calibration procedure uses a fixed frequency grid distortion target. By acquiring an image of this target (Fig. 2a), captured by the optical equipment, the intrinsic parameters of the camera may be obtained and it can be determined whether this optical system has some type of geometric distortion, based on the camera model defined in the previous section. The solving method is divided into two stages:

- In the first, it is considered that the optical system has no distortion and an initial solution $\mathbf{P}_0$ of the camera matrix is obtained by a linear solving method.

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