Self-Calibration of a Camera Equipped SCORBOT ER-4u Robot

Gossaye Mekonnen Alemu and Sanjeev Kumar
Department of Mathematics
IIT Roorkee
Roorkee-247 667, India
gossayemekonnen@gmail.com
malikfma@iitr.ac.in

Pushparaj M. Pathak
Department of Mechanical and Industrial Engineering
IIT Roorkee
Roorkee-247 667, India
pushpfme@iitr.ac.in

***Abstract*—This paper presents a vision based self-calibration method for a SCORBOT ER-4u robot manipulator. Here, only a ground-truth scale in the reference frame is required to achieve self calibration instead of external expensive calibration apparatus. A set of stereo images captured by a camera which is attached to the robot end-effector is used as input of the algorithm. These images contain the pose of the manipulator with the pose of the camera for a manipulator movement trajectory. The camera poses are estimated up to a scale factor at each configuration with an existing factorization method, where a nonlinear optimization algorithm is applied to improve the robustness. Simulations results are obtained by using the proposed model for a number of trajectories. For simulation purpose, a program MATLAB 7.12.0 is used for the given set of parameters. Moreover, experimental studies by ViewFlex software for the calibration of a SCORBOT ER-4u robot (a vertical articulated robot, with five revolute joints, stationary base, shoulder, elbow, tool pitch and tool roll) are carried out. Finally, experimental and simulation results are compared to check the validity of the proposed algorithm.**

Keywords – Epipolar geometry; Robot kinematics; Self-calibration; Stereo vision; ViewFlex

I. Introduction

Camera calibration is considered to be a fundamental task for computer vision and its applications. The existed methodologies of camera calibration can be divided into two categories such as traditional calibration [1], [2] and self-calibration [3]. In traditional calibration methods, the intrinsic and extrinsic parameters are computed of stationary cameras with 3D or 2D references placed at several positions. In this, one can obtain more accurate parameters with high-precision references. Self-calibration [4], [5] of any system is the capability of performing calibration without any external expensive calibration apparatus setup. These are useful when a system is functioning in a dynamic environment.

Mainly, self-calibration techniques can be classified into two broad categories: redundant sensor approach and motion constraint approach. However, both these approaches are having certain advantages and limitations [6]. The main drawback of sensor based approaches is that some of the kinematic parameters are not independent of the error models, and therefore, position and/or orientation of the tool on the platform cannot be calibrated. In the later category, it is not possible to calibrate the position and/or orientation of the tool resulting that the error in locked passive joints may become unobservable.

To overcome the above mentioned drawbacks, vision based robot calibration methods come in to picture. Vision-based robot calibration methods [7], [8] requests the precise 3D fittings measured in a reference coordinate system. Due to the lack of high-accuracy measuring devices, such measurement procedure may not be feasible in certain applications, and hence, having limitations such as time consuming, inconvenient etc. In some cases, where a precisely measured fixture is available, the dimension of such a fixture often restricts calibrated robot workspace.

However, dependency on a precise fixture turns out as a limitation of these vision based techniques. In this context, camera self-calibration based techniques [9] was the new development in this paradigm. The idea is that if the camera can be self-calibrated, one can then collect robot end-effector poses without using precise calibration fixtures. In this paper, we propose an efficient means for camera self-calibration of a SCORBOT ER-4u Robot based on the camera self-calibration method proposed in [9]. The main advantage of this method is that there is no need of multiple precise 3D feature points on the reference coordinate system. Here, only requirement is a precise scale length on the reference coordinate system. Here, we have given simulations results using the above mentioned model for a number of trajectories. For simulation purpose, a MATLAB program is used for the given set of parameters. Moreover, experimental studies by ViewFlex software [10] for the calibration of a SCORBOT ER-4u robot (a vertical articulated robot, with five revolute joints, stationary base, shoulder, elbow, tool pitch and tool roll) are carried out. Finally, experimental and simulation results are compared to check the validity of the proposed algorithm.

II. Preliminaries

In this section, we have described the fundamental models related to robot kinematics. A description about camera projective geometry and their role in calibration is given in the subsequent subsections.

A. The Modified complete and perametrically continuous (MCPC) model

In robot kinematics, we study the relation between the joints and the robot end-effector. In terms of vision guided robot, this relation tells us the relation between the outputs of robot joint sensors to the pose of a robot end-effector. Extensive research has been done in this direction to develop different kinematic models for various robot arms since 1980. Paul [11] has contributed significantly in area of kinematic modeling, robot path planning and control.

The MCPC model is an extension of a complete and parametrically continuous (CPC) type model [12]. The CPC model is a natural evolution of models and inspired by computer vision techniques. The MCPC model uses four parameters to represent the internal link transformation of a robot and separates joint variables from link parameters. In this model, each link transformation B_i has the following basic structure:

$$B_i = Q_i V_i, \; i = 0, 1, 2, 3, ...n \tag{1}$$

where n is the number of links, Q_i is the motion matrix and V_i is shape matrix and defined in the following form:

$$Q_i = Rot(z, \theta_i) \;\; \text{for a revolute joint,} \tag{2}$$
$$Q_i = Trans(0, 0, d_i) \;\; \text{for prismatic joint,} \tag{3}$$
$$V_i = Rot(x, \alpha)Rot(y, \beta)Rot(z, \gamma)Trans(l_{i,x}, l_{i,y}, l_{i,z}) \tag{4}$$

The 4×4 homogeneous transformations T_n which relate the pose of an end-effector to the reference coordinates by following the above definition expressed in the form of:

$$T_n = B_0 B_1 B_2, ..., B_{n-1} B_n. \tag{5}$$

To derive the MCPC error model [13], let dT be the additive differential transformation of T given by

$$dT = T - T^0, \tag{6}$$

where T^0 is a transformation that is a function of the nominal kinematic parameters, which are normally provided by the manufacturer, and is a function of the actual kinematic parameters. To a first-order approximation

$$dT = T^0 \delta T, \tag{7}$$

where δT has the structure of the form [1] :

$$dT = \begin{bmatrix} \Omega(\delta) & d \\ 0_{1\times 3} & 0 \end{bmatrix} = \begin{bmatrix} 0 & -\delta_z & \delta_y & d_x \\ \delta_z & 0 & -\delta_x & d_y \\ -\delta_y & \delta_x & 0 & d_z \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{8}$$

where d the translational error and δ rotational error. Consider y_j and ρ be the pose error vector of end-effector and the independent link parameter error vector, respectively. That is,

$$y_j = \begin{bmatrix} d^j \\ \delta^j \end{bmatrix} \tag{9}$$

where d^j and δ^j are the jth measurement of d and δ , respectively; and,

$$\rho \equiv \begin{bmatrix} \Delta\alpha^T & \Delta\beta^T & \Delta\gamma_n & \Delta x^T & \Delta y^T & \Delta z_n \end{bmatrix}^T \tag{10}$$

where

$$\Delta\alpha = [\Delta\alpha_0, \Delta\alpha_1, \ldots \Delta\alpha_n]^T ,$$

$$\Delta\beta = [\Delta\beta_0, \Delta\beta_1, \ldots \Delta\beta_n]^T ,$$

$$\Delta\gamma = [\Delta\gamma_0, \Delta\gamma_1, \ldots \Delta\gamma_n]^T ,$$

$$\Delta x = [\Delta l_{0,x}, \Delta l_{1,x}, \ldots \Delta l_{n,x}]^T ,$$

$$\Delta y = [\Delta l_{0,y}, \Delta l_{1,y}, \ldots \Delta l_{n,y}]^T$$

and

$$\Delta z = [\Delta l_{0,z}, \Delta l_{1,z}, \ldots \Delta l_{n,z}]^T$$

are MCPC error parameters. If J_j be the identification Jacobian evaluated at j_{th} robot configuration, then the robot error model can be written as [9]

$$y_j = J_j \rho, j = 1, 2, ..., m, \tag{11}$$

where m is the number of measurements. In a compact form

$$y = J\rho, \tag{12}$$

where

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} \; and \quad J = \begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ J_m \end{bmatrix} \tag{13}$$

where ρ can be solved by a least-squares method.

B. Kinematic identification

By using a number of end-effector pose measurements and the corresponding joint position values, the process of kinematic identification provides the kinematic model parameters of a manipulator. This reduces the error between the computed and measured robot poses by selecting the kinematic parameter vector. The process of kinematic identification is done by designing an error function $\|y - Jd\rho\|$, where y represents the pose error vector and ρ is the parameter error vector. An optimal set of ρ is computed so that the above mentioned error function minimize.

C. Camera Model

Here, the camera model is considered a pinhole camera that use perspective projection in image formation. The camera matrix P can be modeled as the product extrinsic and intrinsic camera parameters matrices as:

$$P \approx A * [Rt], \tag{14}$$

where $\approx$ means that the equality holds up to a nonzero scale factor. The matrix R represents the orientation of the camera and given by a 3×3 orthogonal matrix and t is the extrinsic parameters (translation vector) of representing the camera's position. The matrix A is the intrinsic calibration matrix and given by

$$A = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \tag{15}$$

where (c_x, c_y) are the coordinates of the principal point at which the optical axis passes through the sensor plane. f_x and f_y are the scale factors along the x and y axes of the image plane, which are related to the focal length f of the camera, and s is the parameter describing the skewness of the two image axes.

In a stereo vision system, we use two identical cameras placed at a distance (along a chosen direction) from each other. The relation between the various pixels in the two camera image planes is a 2-D search problem. However, this correspondence problem can be reduced to 1-D search by making use of epipolar constraint. Let a camera take two images by linear projection from two different locations, as shown in Figure 1. Let c be the optical center of the camera when the first image is obtained, and let c' be the optical center for the second image. where $< c, c' >$ projects a point r as m in the first image plane and to a point m' in the second image plane. The fundamental matrix describes this correspondence: $l' = F\ m$. Since, the point m' corresponding to m belongs to a line l' by definition, it follows that F denotes the fundamental matrix:

$$m'^T F m = 0, \tag{16}$$

where

$$F = A^{-T}[t]_\times R A^{-1} \tag{17}$$

with $[t]_\times$ being an antisymmetric matrix which is defined as

$$[t]_\times = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} \tag{18}$$

III. Adopted Pose measurement with customized factorization method

A. Factorization method

Here, we have adopted an approach given in [9]. By taking some assumptions such as the lens distortion does not change for a fixed length, the two image axes are considered to be perfectly perpendicular to each other and the calibration outcomes are not very sensitive to the principal point, the intrinsic matrix is stated in the following simple form:

$$A = \begin{bmatrix} f_x & 0 & 0 \\ 0 & \mu f_x & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{19}$$

In order to obtain the pose data with an uncalibrated camera with the above form of intrinsic matrix, Hartley's factorization method [14] can be used. The only modification with the original method requires that the number of cameras become two instead of one. Both linear as well as nonlinear factorization approaches can be used in the self-calibration of cameras placed at the end-effector of a robot manipulator.

B. Determination of the Scale Factor

Using the above mentioned factorization method, one can compute the position vectors up to an unknown scale factor. This scale factor k_i can be defined as

$$k_i = \pm \frac{\|t_i\|_2}{\|\hat{t_i}\|_2} \qquad i = 1, 2, 3, ...m, \tag{20}$$

where $\|t_i\|_2$ and $\|\hat{t_i}\|_2$ represent the actual and estimated relative position vectors of the camera at robot configuration i, respectively, under l_2 norm. The parameter m represents the total number of configurations related to robot measurement. The main aim is to determine the sign of (20). The assumption required is that the actual distance d between the two object points is given for estimating the scale factor. The unknown scale can be expressed with this distance d. If d and $\hat{d_i}$ denote the measured distance (the known scale) and the estimated distance value, respectively at any robot configuration measurement i, then the ratio given by

$$\lambda_i = \pm \frac{d_i}{\hat{d_i}} \qquad i = 1, 2, 3, ...m, \tag{21}$$

Now the question arises whether λ_i is equal to the unknown scale factor k_i or not. The following lemma and theorem from [9] give an explanation to this question.

Lemma 1. *The ratio between the actual and the estimated distances is equal to the ratio of the l_2 norm of the actual the estimated relative position vectors obtained with the factorization method, i.e.,*

$$\lambda_i = \pm \frac{\|t_i\|_2}{\|\hat{t_i}\|_2} \qquad i = 1, 2, 3, ...m, \tag{22}$$

Theorem 1. *The absolute value of the scale factor k obtained from the factorization method is equal to the ratio of the actual and the estimated distances λ, i.e.,*

$$k_i = \pm \frac{d_i}{\hat{d_i}} \qquad i = 1, 2, 3, ...m, \tag{23}$$

Applying theorem 1, the position vector can be solved by

$$t_i = \pm \frac{d_i}{\hat{d_i}} \qquad i = 1, 2, 3, ...m, \tag{24}$$

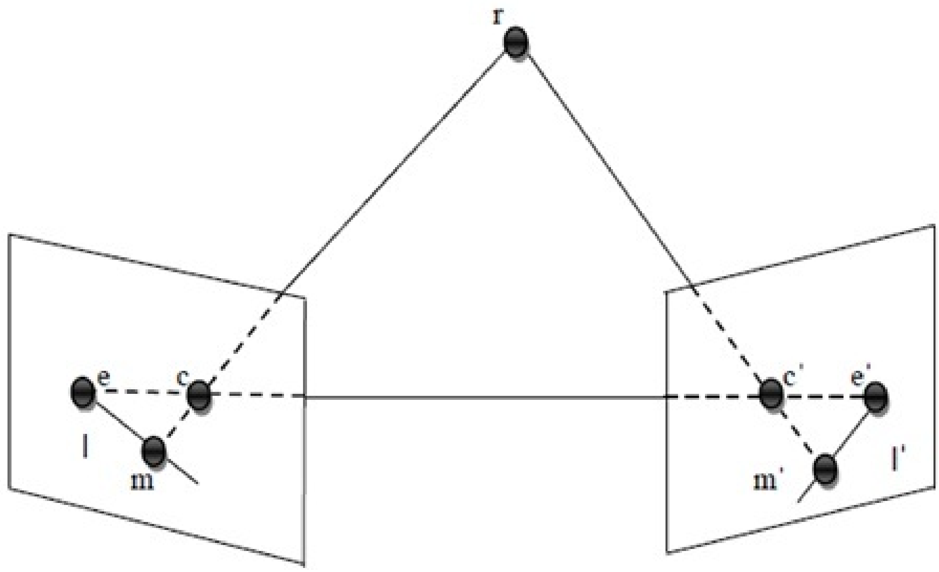

Fig. 1. The epipolar transformation.

Since the above theorem lemma and theorem reveals that two signs are possible for the calculated completed translation vector t from (24). Since the actual robot link parameters and the nominal values are very close, the nominal position and orientation of the camera can be approximated by the actual camera pose. Consequently, the nearest position vector to the nominal one should be chosen.

IV. Simulation and Experimental Results

In order to evaluate the above described self-calibration method for a SCORBOT ER-4u robot, we have conducted simulation as well as experimental studies. The SCORBOT-ER 4u was designed and developed to emulate an industrial robot. It is a vertical articulated robot, with five revolute joints. With gripper attached, the robot has six degrees of freedom. This design permits the end-effector to be positioned and oriented arbitrarily within a large work space. It has a servo jaw gripper fitted with rubber pads. These pads can be removed to allow the attachment of other end effector devices, such as suction pads. The nominal link parameters of the SCORBOT ER-4u are listed in Table I

TABLE I. Nominal D-H Parameter for Scorbot ER-4u

Joint i	α_i (deg)	a_i (mm)	d_i (mm)	θ_i (deg)	Operating range
1	$\pi/2$	101.25	334.25	38.15^o	$-155^o to + 155^o$
2	0	220	0	-30^o	$-35^o to + 130^o$
3	0	220	0	45^o	$-130^o to + 130^o$
4	$\pi/2$	0	0	-63.54^o	$-130^o to + 130^o$
5	0	0	137.35	0^o	$-570^o to + 570^o$

TABLE II. Expected values of the end-effector

Tool-tip pos. i	p_x (mm)	p_y (mm)	p_z (mm)	Pitch (θ_4)	Roll (θ_5)
1	315.60	247.90	190.30	-63.54^o	0.0^o
2	320.80	252.00	182.80	-63.54^o	0.0^o
3	310.40	243.80	197.70	-63.54^o	0.0^o
4	309.70	243.30	183.60	-63.54^o	0.0^o
5	321.80	240.10	190.30	-63.54^o	0.0^o

Table II gives the simulated values of SCORBOT ER-4u obtrained with the simulation study done on MATLAB 7.12.0 platform. The graphically visualization of the robot obtained in simulation study has been shown in Figure 2, where visualization has been shown in a 3-D environment.

The experimental setup consisted of a SCORBOT ER-4u robot, a CCD camera, an RGB color frame grabber and a PC based image processing system using ViewFlex software [10]. The resolution power of CCD camera is $640H \times 480V$ pixels. The actual value, for the given coordinates of the

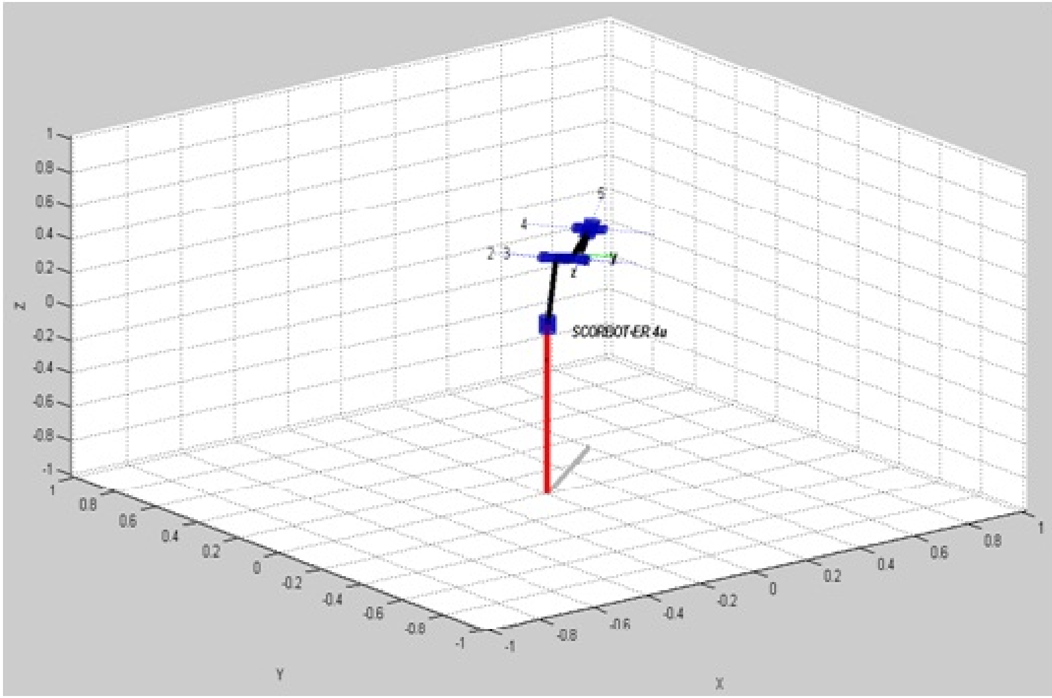

Fig. 2. SCORBOT ER-4u position with nominal values.

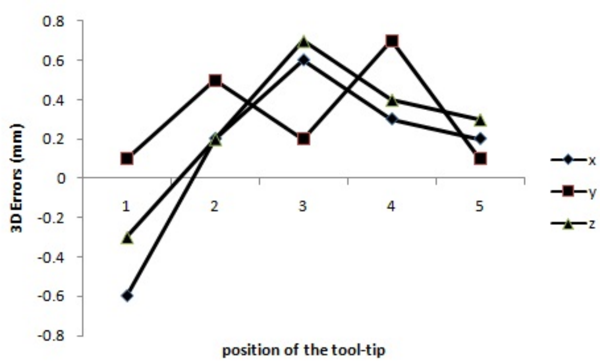

Fig. 3. The position measurements of the tool-tip and their relative errors.

TABLE III. MEASURED VALUES OF SCORBOT ER-4U ROBOT

Tool-tip pos.	p_x (mm)	p_y (mm)	p_z (mm)	Pitch (θ_4)	Roll (θ_5)
1	315.00	248.00	183.00	-63.54^o	0.0^o
2	321.00	252.50	182.80	-63.54^o	0.0^o
3	311.00	244.00	198.00	-63.54^o	0.0^o
4	310.00	244.00	184.00	-63.54^o	0.0^o
5	322.00	240.20	190.60	-63.54^o	0.0^o

origin, of the robot end-effector pose is shown in Table III. In experimental study, the measured values compared with the simulated values of the tool tip and the result is listed in the Table IV.

For visualization purpose, a graph has been plotted to represent the relationship between the pose measurements of points and the errors. Figure 3 illustrates this graph for the employed SCORBOT ER-4u robot.

V. CONCLUSIONS

Self-calibration of a camera-equipped SCORBOT ER-4u robot manipulator with a minimum amount of ground truth has been presented by adopting a recently developed approach of finding scale factor. This approach relies on the camera to capture robot poses at each robot measurement configuration. The method has been evaluated through simulation as well as experimental studies. It has been found that the adopted approach is well suited in case of SCORBOT ER-4u robot and the results are quite encouraging. The implementation procedure is easy and can be applied to

TABLE IV. THE MEASURED VALUES COMPARED WITH THE SIMULATED VALUES OF THE ROBOT TOOL TIP

Position of the Tool-tip	Position values	$^0T_5$ desired values (mm)	Measured Values (mm)	Error (mm)
1	p_x	315.60	315.00	-0.60
	p_y	247.90	248.00	0.10
	p_z	190.30	190.00	-0.30
2	p_x	320.80	321.00	0.20
	p_y	252.00	252.50	0.50
	p_z	182.80	183.00	0.20
3	p_x	310.40	311.00	0.60
	p_y	243.80	244.00	0.20
	p_z	197.70	198.00	0.70
4	p_x	309.70	310.00	0.30
	p_y	243.30	244.00	0.70
	p_z	183.60	184.00	0.40
5	p_x	321.80	322.00	0.20
	p_y	240.10	240.20	0.10
	p_z	190.30	190.60	0.30

many other situations, such as mobile robot, remote control robot, and autonomous vehicles, due to its minimum usage of the external ground truth data. Further, we will work to modify the adopted algorithm in case of noisy data (images). Moreover, we will work to make the method more faster so that one can use it in real time for the calibration of camera equipped robots.

REFERENCES

[1] Faugeras, O.D., Toscani, G.: The Calibration Problem for Stereo. In: IEEE international Conference on Computer Vision and Pattern Recognition, pp. 1520. IEEE Press, Florida (1986)

[2] Zhang, Z.: A Flexible New Technique for Camera Calibration. IEEE Transactions on Pattern Analysis and Machine Intelligence 22(11), 1330-1334 (2000)

[3] Gong C., Yuan J., Ni J.: A Self-Calibration Method for Robotic Mesurement System. Journal of Manufacturing Science and Engineering, 122(1), 174–181 (1999).

[4] Hartley, R.I.: Self-calibration from Multiple Views with a Rotating Camera. In: 3rd European Conference on Computer Vision, Stocklholm, pp. 471-478 (1994)

[5] Quan, L.: Self-calibration of an Affine Camera from Multiple Views. International Journal of Computer Vision 19(1), 95-105 (1996)

[6] Vincze M., Prenninger J.P., Gander H.: A laser tracking system to measure position and orientation of robot end effectors under motion. Int J Robotics Res 13(4), 305-14 (1994)

[7] Renaud P, Andreff N, Marquet F, Martinet P.: Vision-based kinematic calibration of a H4 parallel mechanism. IEEE Int Conf Robotics Automation 1191-1197 (2003).

[8] Daney D, Andreff N, Papegay Y.: Interval method for calibration of parallel robots: a vision-based experimentation. Computational Kinematics, Cassino (2005).

[9] Meng, Y., Zhuang, H.: Autonomous robot calibration using vision technology, Robotics and Computer-Integrated Manufacturing 23, 436-446 (2007).

[10] ViewFlex User Manual, Version 3.2, Intelitek Inc., Catalog ♯ 100299 Rev. G, (2008).

[11] Paul B.P.: Robot manipulators: mathematics, programming, and control. Cambridge, MA: MIT Press (1981).

[12] Zhuang H., Wang K., Roth Z.S.: Error-model-based robot calibration using a modified CPC model. Int J Robotics Computer-Integrated Manuf, 10(4), 287-299 (1993).

[13] Zhuang H., Roth Z.S.: Camera-aided robot calibration. Boca Raton, FL: CRC Press (1996).

[14] Hartley R., Zisserman A.: Multiple view geometry in computer vision. Cambridge: Cambridge University Press (2000).