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Calibration of an Industrial Robot using a Stereo Vision System

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Abstract

Industrial robots have very good repeatability but still lack good absolute accuracy. The main reason is difference between the ideal robot kinematic model integrated in the robot controller and actual robot parameters. A method for identifying certain parameters of the robot model has been proposed. A noncontact method using a stereovision system attached to the robot arm is utilized for providing measurements of calibration points in space. Points are represented as spheres which localized by the stereo vision system project a circle in two image capture planes independent of the viewing angle. Spatial coordinates of each sphere center are acquired in different robot configurations. From these readings errors of robot absolute positioning are measured. The standard Denavit-Hartenberg (DH) notation is used when the modified model parameters containing joint encoder offset values are directly input to the robot controller. Calibration experiments carried out on a KUKA KR 6 R900 industrial robot show improved accuracy results. The maximum positioning error around calibration points was decreased from 3.63 mm prior to calibration, to 1.29 mm after the calibration procedure.

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Keywords: Robot calibration; absolute accuracy

1. Introduction

Industrial robots have a very broad field of application ranging from assembly, manufacturing, and other technologies. Industrial robots mostly deal with processes in known and structured environments where robot motion is preprogrammed and executed, continuously repeating the same paths and motions. For this reason industrial robots are designed and manufactured to provide very high repeatability for successful execution of predefined tasks.

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The aspect, in which industrial robots are still not able to provide satisfactory results, when delivered to end customers, is absolute accuracy. In 6 degree of freedom (DOF) serial link manipulators [1] this problem is emphasized. As every industrial robot is manufactured in a certain tolerance range there are no two identical mechanical units. On the other hand each robot controller utilizes the same control model with ideal DH [2] parameters (link lengths, offsets, twist, etc.). For this reason there always exists a certain error describing the difference between the ideal position in the robot model and the actual position of the robot in some reference frame.

Research in the field of robot calibration shows different calibration methods and algorithms which evaluate DH parameters of the robot model or describe novel kinematic robot models with additional parameters for improving accuracy results. In [3] a calibration method is proposed utilizing a virtual closed kinematic chain method. A laser spot is projected on a distant plane and small robot motions are magnified. A calibration method for identification of 36 independent parameters of a robot arm is described in [4]. Authors apply a principle of moving the robot endpoint around spherical shells centered on a fixed point, collect data and perform identification of robot kinematic parameters. Another calibration approach utilizing cooperative coevolutionary networks and pseudoerror theory is described in [5]. Measurement methods in robot calibration range from theodolite [6], laser beam projection [3], 2D machine vision [7], portable coordinate measuring machines [8] and other.

From the robot kinematic model overview industrial robot calibration methods can roughly be distinguished in three categories:

- Error registration – the robot is viewed as a black box where compensation factors and values are given for every robot pose
- Static calibration – identification of time invariant robot parameters
- Dynamic calibration – identification of robot motion parameters

Duelen and Schroer [9] suggest that all parameters of the kinematic robot model could be identified only by measuring the position of a certain point of the robot end effector. Applying this principle, in this research a static noncontact closed chain calibration method using stereovision is presented for evaluating robot kinematic parameters that can be embedded directly in KUKA robot controllers. With this approach the control hierarchy and structure of a robotic system is left intact and the usability of an industrial robot is not altered. In following sections the experimental setup is described, methods and algorithms are presented and preliminary results are discussed.

2. System setup

The system consists of a 6 DOF KUKA KR 6 R900 robot arm with declared repeatability of ±0.03 mm and payload of 6 kg. DH parameters of the robot are depicted in Table 1.

Table 1. Original values of DH robot parameters.

	d (*mm*)	**θ** (*deg*)	**a** (*mm*)	**α** (*deg*)
Link 1	400	θ_1	25	90
Link 2	0	θ_2	455	0
Link 3	0	θ_3	35	90
Link 4	420	θ_4	0	-90
Link 5	0	θ_5	0	90
Link 6	80	θ_6	0	180

The robot has a tool changing device which allows flexible automatic tool exchange. The stereo vision system (as shown in Fig.1 a) consists of two perpendicular CCD cameras which form a virtual robot tool center point (TCP). The two CCD cameras have macro lenses and allow high magnification of the viewed object. For the calibration purpose a black polymer sphere was used. One pixel is roughly mapped to 0.05mm and the vision system allows high resolution and accurate readings of sphere center.

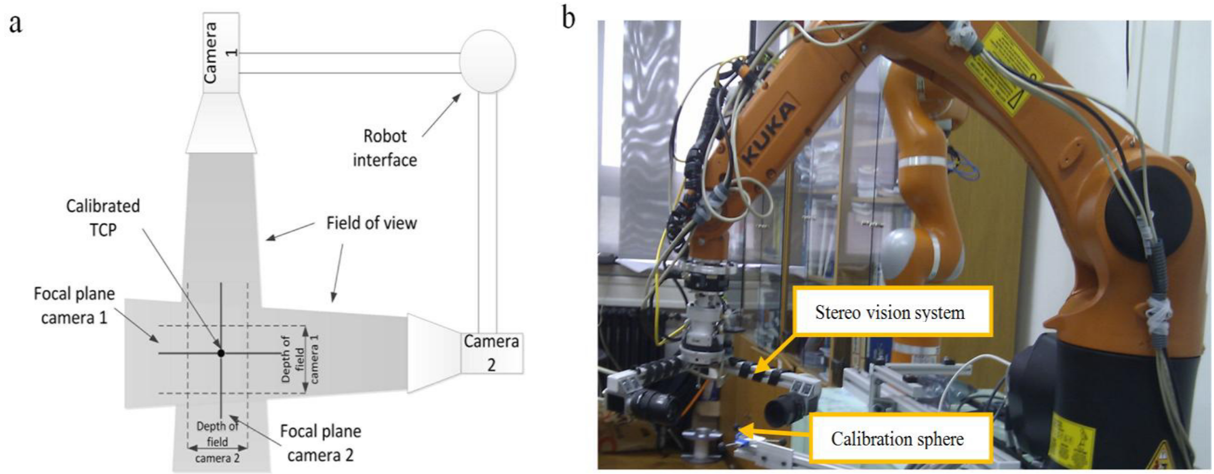

Fig. 1. (a) Schematic overview of the stereovision system; (b) Calibration procedure experimental setup.

2.1. Calibration procedure

The virtual TCP is manually guided to desired positions and orientations where the calibration sphere is located (Fig 1. b). The machine vision algorithm adjusts robot position with respect to the calibration sphere in the camera reference frame. Robot joint states are recorded for later use in the parameter optimization algorithm. After an adequate number of measurements are made the recorded joint states for each calibration point are compared.

The transformation matrix as shown in equation (1), with six joint states (**θ**) as variables, is composed of six respective transformation matrices containing the DH parameters previously noted in Table 1. and information about the robot TCP (tool).

$$T = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6 \cdot tool \tag{1}$$

The maximum error for each calibration sphere position is calculated. The iterative algorithm minimizes the maximum errors and applies new values for joint offset values. The algorithm searches the state space of vector **Δθ** to find the minimum of the function around calibration points (n_i) containing different robot configurations (c_k) as shown in equation (2):

$$\forall n_i \in c_k : \max(T_{ik}) - \min(T_{ik}) \rightarrow \min \tag{2}$$

Purpose of the algorithm is to find the best match of parameters **Δθ** for all calibration points c. A least square (LS) method was not used mainly because it yields results that might have higher maximum errors opposed to the iterative method. The least squares method yields better results over the average error than the iterative algorithm. The main purpose of the developed algorithm was to minimize the overall maximum error around each calibration point. In order to improve overall accuracy more calibration points provide a larger sample and therefore ensure more reliable and accurate correction factors.

3. Results

Optimized joint offset values **Δθ** were acquired from 24 calibration points and are shown in Table 2. Constant offset values compensate for the difference between the ideal kinematic model and the actual robot and are added to the joint vector **θ**.

Table 2. Calibrated joint offset values.

$\Delta\theta_1$ (*deg*)	$\Delta\theta_2$ (*deg*)	$\Delta\theta_3$ (*deg*)	$\Delta\theta_4$ (*deg*)	$\Delta\theta_5$ (*deg*)	$\Delta\theta_6$ (*deg*)
-0.538	+1.077	-0.163	+1.090	-0.286	+0.559

The maximum error prior to calibration was reduced after optimizing the offset values of the initial kinematic model as shown in Table 3. A comparison between errors in the robot reference frame around calibration points is presented.

Table 3. Absolute positioning errors prior and after calibration.

	x (*mm*)	y (*mm*)	z (*mm*)	E (*mm*)
Initial kinematic model	2.01	1.25	2.75	3.63
Optimized kinematic model	0.80	0.66	0.76	1.29
Δ (initial – optimized)	1.21	0.59	1.99	2.34

Absolute positioning errors take into account translational displacements (x, y, z) and Euclidian distances (E) of the maximum deviation around each calibration point. Angular displacements of ideal robot pose and actual robot pose will be part of future research.

4. Conclusion and future work

The proposed approach for robot calibration to increase absolute accuracy has proven good results. Maximum error prior to calibration was 3.63 mm and 1.29 mm after optimizing the offset values of the initial robot kinematic model.

The optimizing procedure of offset values, which can be directly imported in the KUKA robot controller, has a limited possibility of minimizing the absolute positioning error. In Table 4. preliminary simulation results are shown where 30 robot kinematic parameters were optimized. Six new parameters were introduced, an encoder scale factor for each robot joint reading.

Table 4. Calibrated values of all robot DH parameters with supplied encoder scale values.

	d (*mm*)	**θ** (*deg*)	**a** (*mm*)	**α** (*deg*)	encoder scale
Link 1	400.51	θ_1-0.753	23.65	90.43	0.99908
Link 2	0.16	θ_2+0.969	456.95	-0.28	0.99871
Link 3	0.41	θ_3-0.235	35.95	89.81	0.99883
Link 4	420.28	θ_4+1.090	0.25	-89.97	1.00025
Link 5	0.05	θ_5-0.286	-0.95	89.97	1.0000
Link 6	80.09	θ_6+0.404	0.80	180.19	0.99908

With the optimized model the accuracy around calibration points has been further improved, with a maximum error of 0.74 mm. Parameters from Table 4. cannot be directly imported to the robot controller. A kinematic solver needs to be developed for processing the new model definition. The error of 0.74 mm was obtained as a simulation result from MATLAB software and still needs to be validated on the actual setup. In Fig. 2. an overview of all calibration accuracy results is presented.

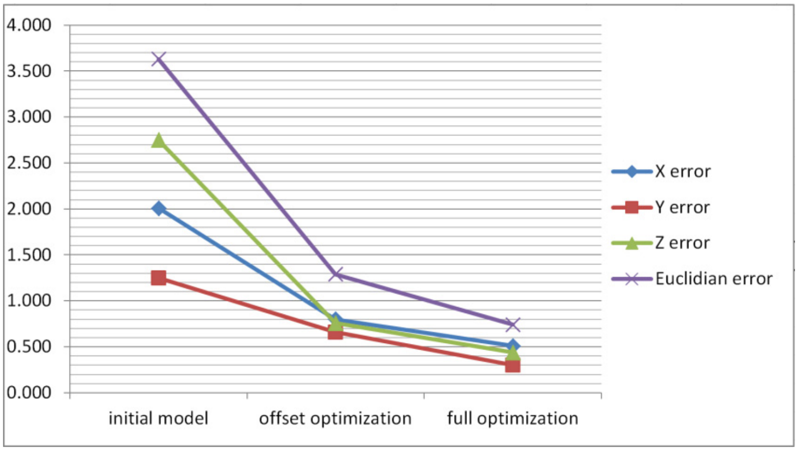

Fig. 2. Calibration results overview (values in mm).

As calibration requires manual adjustment of different poses it is a time consuming process. Future development of the calibration procedure will include automatic calibration in a multiagent robot system [10,11,12]. The calibration sphere will be manipulated by another robot and the calibration procedure will be done autonomously.

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