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Geometric calibration of industrial robots using enhanced partial pose measurements and design of experiments

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ABSTRACT

The paper deals with geometric calibration of industrial robots and focuses on reduction of the measurement noise impact by means of proper selection of the manipulator configurations in calibration experiments. Particular attention is paid to the enhancement of measurement and optimization techniques employed in geometric parameter identification. The developed method implements a complete and irreducible geometric model for serial manipulator, which takes into account different sources of errors (link lengths, joint offsets, etc). In contrast to other works, a new industry-oriented performance measure is proposed for optimal measurement configuration selection that improves the existing techniques via using the direct measurement data only. This new approach is aimed at finding the calibration configurations that ensure the best robot positioning accuracy after geometric error compensation. Experimental study of heavy industrial robot KUKA KR-270 illustrates the benefits of the developed pose strategy technique and the corresponding accuracy improvement.

1. Introduction

In robotic literature, the problem of geometric calibration is already well studied and has been in the focus of the research community for many years [1–8]. As reported by a number of authors, the manipulator geometric errors are responsible for about 90% of the total positioning error [9]. Besides of the errors in link lengths and joint offsets, the end-effector positioning errors can be also caused by the non-perfect assembling of different links and arise in shifting and/or rotation of the frames associated with different elements, which are normally assumed to be matched and aligned [10]. It is clear that the geometric errors do not vary with the manipulator configuration, while their influence on the positioning accuracy depends on the latter. At present, there exist various calibration techniques that are able to calibrate the manipulator geometric model using different modeling, measurement and identification methods [11–16]. The identified errors can be efficiently compensated either by adjusting the controller input (the target point) or by direct modification of the model parameters used in the robot controller.

The classical calibration procedure usually includes four steps: modeling, measurement, identification and implementation. The *Modeling* step focuses on the development of proper geometric model of robotic manipulator. In the pioneer works [14], researches have used the classical DH convention for robot calibration. However, this model turned out to be discontinuous in some cases and may lead to unacceptable identification results [17]. So, several alternative approaches have been proposed to overcome these difficulties by means of introducing extra parameters [18,19]. Since the inclusion of additional parameters causes redundancy, these methods raise the problem of parameter non-identifiability, which leads to the necessity of investigating the model completeness, irreducibility and continuity. For example, in [20], the authors proposed a complete and parametrically continuous (CPC) model and further its modified version (MCPC) for robot calibration. Besides, there have been also proposed some analytical/numerical techniques for elimination of the non-identifiable parameters. For example, in [18], the authors used QR decomposition of the identification Jacobian for model reduction and in [21], the authors used straightforward evaluation of the Jacobian matrix rank.

The *Measurement* step involves data collecting of robot link and end-effector position/orientation. Generally, six parameters are required to specify the manipulator end-effector location (three translations and three rotations) [12,22], but sometimes the end-effector position is measured only [23]. Various calibration methods based on different measurement techniques were

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proposed, they are usually categorized as closed-loop and open-loop ones. The closed-loop calibration uses physical constraints on the manipulator end-link (point, line or plane constraints, for instance). It is claimed to be autonomous and does not require any external device [13,21,24]. However in this case, the manipulators must have some redundancy to perform self-motion, and the robot configuration should be carefully selected to satisfy particular constraints. Therefore, the open-loop methods have found wide applications; they are based on the full or partial pose measurements of the end-effector location using external devices. In practice, the partial pose information is often used and provides from one to five dimensional measurements [11,25,26] instead of the full pose information (6-dimensional location). In general, the lower dimensional measurement is more attractive due to simplicity of calibration experiment setup. For this so-called *partial pose measurement* technique, various external devices can be applied, such as laser tracking system [23], the ball-bar system [27] and wire potentiometer [22], etc.

The *identification* step in robot calibration can be treated as the best fitting of the experimental data (given input variables and measured output variables) by corresponding models. This problem has been addressed by a number of researchers who have used various modeling methods and identification algorithms, such as linear least square technique, Levenberg–Marquardt algorithm, Kalman filtering technique and maximum likelihood estimator etc. [16,28]. Among them, the least square technique is the most often applied one, which aims at minimizing the sum of squared residuals [29]. An important problem here is non-homogeneity of the residual errors (distances and angles, for instance). To solve this problem, usually a straightforward solution is applied: assigning weights or normalization, but this weight assigning procedure is very non-formal and not rigorous (while being essential for the final results). To solve the corresponding optimization problem, there exist various numerical algorithms such as gradient search [27,30], heuristic search and the others [31]. However, these numerical techniques are often difficult to apply due to large number of parameters to be tuned, that often lead to low convergence. Nevertheless, for the case of geometric calibration, the errors in the parameters are relatively small, so the linearization technique can be successfully applied. In this case, the solution of a linear least square problem can be found straightforwardly (i.e., via the pseudo-inverse of Moore–Penrose) [32,33]. It should be mentioned that in some particular cases, for instance, when the geometric errors are relatively large, the solution can only be found iteratively [15].

The most essential works on the above mentioned calibration methods in robotics literature are summarized in Table 1. Among these publications, limited number of works directly addresses the problem of parameter identification accuracy and reduction of the impact of measurement errors. Although the calibration accuracy may be improved by straightforwardly increasing the number of experiments [27], the measurement configurations may also affect the robot calibration [34]. It has been shown that the latter may significantly improve the identification accuracy [35]. Intuitively, using diverse manipulator configurations for different experiments seems perfectly corresponds to the basic idea of the classical experiment design theory, which intends to spread the measurements as much distinct as possible [15]. However, the classical results are mostly obtained for very specific models (such as the linear regression) and cannot be applied directly due to non-linearity of the relevant expressions of robot geometric model.

At present, there are few works where the problem of optimal pose selection for robot calibration has been discussed [39,40]. In these works, in order to compare the plans of experiments, several quantitative performance measures have been proposed and used as the objectives of the optimization problem associated with the optimal sets of measurement poses. In defining the objectives, the authors in [35,40–42] proposed some observability indices, which are based on the singular values of the identification Jacobian (condition number, for instance). These indices have been examined and compared in [38,39,43,44], where the authors paid more attention to developing efficient numerical algorithms, such as genetic algorithm, Tabu search, DETMAX and also hybrid methods in order to obtain the optimal measurement configurations. However, these approaches deal with rather abstract notions that are not directly related to the robot accuracy and may lead to some unexpected results, for example, when the condition number is good, but the parameter estimation errors are rather high. Besides, it usually requires very intensive and time consuming

Table 1
Summary of related works for geometric calibration

Application (Manipulator)	Number of model parameters	Number of measurement configurations	Measurement device	Identification algorithm	Achieved accuracy, [mm]
6-dof parallel robot [25]	35	80[1]	Two inclinometers[a]	Levenberg–Marquardt method	0.40
Stewart platform [36]	42	15[1]	Single theodolite[a]	Non-linear LS	0.50
PUMA 560 [23]	27	25[1]	Laser tracking system[a]	–	0.10
PUMA 560 [27]	36	800[1]	Ball-bar system[a]	Gradient search method	0.08
PUMA 560 [22]	24	48[1]	Wire potentiometer[a]	Non-linear LS	0.50
PUMA 560 [13]	23	100[3]	–[b]	Non-linear LS	0.25
Schilling Titan II [37]	42	800[2]	–[b]	Linear LS	5.70
Stäubli TX90 [15]	23	100[2]	Touching probe[b]	Weighted pseudo inverse	0.22
SCARA robot [38]	30	10[4]	–[b]	Genetic algorithm	3.60
Gough platform [39]	42	18[5]	Vision system[c]	Heuristic search	1.30

Selection of measurement configurations:

[1] Random configurations.
[2] Well distributed configurations.
[3] Noise amplification index.
[4] Minimum condition number.
[5] Several observability indices.

Measurement technique:

[a] Open-loop measurement.
[b] Closed-loop measurement.
[c] Simulation.