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Optimal pose selection for calibration of planar anthropomorphic manipulators

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ABSTRACT

The paper is devoted to the calibration experiment design for serial anthropomorphic manipulators with arbitrary number of links. It proposes simple rules for the selection of manipulator configurations that allow the user to essentially improve calibration accuracy and reduce identification errors. Although the main results have been obtained for the planar manipulators, they can be also useful for calibration of more complicated mechanisms. The efficiency of the proposed approach is illustrated with several examples that deal with typical planar manipulators and an anthropomorphic industrial robot.

1. Introduction

The standard engineering practice in industrial robotics assumes that the closed-loop control technique is applied only on the level of servo-drives, i.e. for actuating the manipulator joints. In such systems, the Cartesian space control is based on the open-loop method that incorporates numerous direct/inverse kinematic transformations derived from the manipulator geometric model. These transformations define correspondence between the manipulator joint coordinates and the Cartesian coordinates of the end-effector. Hence, to achieve desired accuracy, manipulator geometric model employed in the control algorithm should be carefully tuned (calibrated) to take into account manufacturing tolerances and parameter variations from manipulator to manipulator [1].

The problem of robot calibration has already been well studied and it has been in the focus of research community for many years [2]. In general, the calibration process is divided into four sequential steps [3]: modeling, measurements, identification and compensation. The first step focuses on the design of the appropriate (complete but non-redundant [4]) mathematical model. At the second step, related measurements (calibration experiments) are carried out using commercially available or custom-made equipments [5,6]. The third step usually deals with the identification of the Denavit–Hartenberg parameters [7], which may provoke numerical instabilities for the manipulators with collinear successive axes considered in this paper. For this particular but very common case, some authors (Hayati [8], Stone [9], and Zhuang [10]) proposed some modifications, but here we will use a more straightforward approach that is more efficient for the planar manipulators. The last step is aimed at compensating identified parameter variations [11–13].

Among numerous publications devoted to the robot calibration, there is a very limited number of works that directly addresses the issue of the identification accuracy and reduction of the calibration errors. In particular, Ikits and Hollerbach [14] used noise amplification index to estimate the errors in the identified parameters of Puma 560 robot. Mirman and Gupta [15] proposed compensation algorithm using position-independent parameter error values. In [16] the authors assessed backlash error for an ABB IRB 1600 6-dof serial industrial robot. Five different observability indexes were compared in [17] and the authors detected that all of them are related to each other. In [18] the determinant-based observability index was used to evaluate the performance of active robot calibration algorithm applied to a 6-dof PUMA 560 robot. In further comparison study, Hollerbach et al. [19] proposed to treat all calibration methods as closed-loop ones and introduced the calibration index that categorizes all calibration methods in terms of number of equations per pose. Zhuang et al. [20] used the condition number of the identification Jacobian to compare the identification accuracy impact of different measurement configurations. In [21] the authors

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used iterative one-by-one pose search algorithm in order to minimize the influence of measurement noise on the identification of geometrical parameters of a Gough-Stewart Platform.

It is clear that the calibration accuracy may be straightforwardly improved by increasing the number of experiments (with the factor $1/\sqrt{m}$, where m is the number of experiments [22]). Besides, using diverse manipulator configurations for different experiments looks also intuitively promising and perfectly corresponds to some basic ideas of the classical theory of experiment design [19] that intends to use experiments that are as much distinct as possible. However, the classical results are mostly obtained for very specific models (such as the linear regression) and cannot be applied here directly due to the non-linearity of the relevant equations. There are few research works in the literature that deal with the optimal pose selection for robot calibration. For example, Borm and Menq [23] have investigated the implications of different observability measures in the robot position error and influence of the measurement configurations number on the final accuracy. They concluded that the number of measurements is less important than proper selection of measurement configurations. In [24] the authors defined the set of optimal measurement configurations by minimizing the condition number of the observation matrix. Daney [25] used the constrained optimization algorithm based on the minimization of the singular values root-product for optimal measurement configurations selection for Gough platform calibration. The noise amplification index was used in [26] to quantify measurement configurations and to select the best one. In [27] authors used D-optimality criteria to determine optimal measurement configurations for planar anthropomorphic manipulators. Zhuang et al. [28] applied simulating annealing to obtain optimal or near optimal measurement configurations, which minimize at least one of two considered performance measures. Imoto et al. [29] proposed to use the end-effector position accuracy after calibration as a performance measure in order to generate measurement configurations. Similar idea was used in [30] where the authors introduced test configurations related to the technological process, which allowed them to define the performance measure as the positioning accuracy after calibration that is also related to the weighted trace of the covariance matrix.

As follows from detailed analysis, all previous works in the area of calibration experiment design provide user with an iterative scheme that aims at minimizing an objective function that depends on the singular values of the identification Jacobian (condition number, for instance). However, this approach does not consider directly the identification accuracy and may lead to some unexpected results (where the condition number is perfect, but the parameter estimation errors are rather high). Besides, it requires very intensive and time consuming computations caused by a poor convergence and high dimension of the search space (number of calibration experiments multiplied by the manipulator joint number). Hence, to apply this technique in industry, strong mathematical background and good experience in the numerical optimization are required. It is obvious that practical engineers need some type of a "rule of thumb", which allows them to select measurement configurations without tedious computations.

In this paper, the problem of optimal design of the calibration experiments is studied for the case of a planar manipulator with arbitrary number of links. Such manipulators do not cover all architectures used in practice, but nevertheless this model allows us to derive some very useful analytical expressions and to propose some simple practical rules defining optimal configurations with respect to the calibration accuracy. In the following sections, particular attention will be given to planar manipulators with 2 and 3 d.o.f. that are essential components of all existing anthropomorphic robots. Practical significance of the obtained results will be illustrated by a case study that deals with the calibration experiment design for a 6-d.o.f. KUKA industrial robot, which is presented as a set of simple planar sub-manipulators.

The remainder of this paper is organized as follows. Section 2 defines the research problem and contains basic assumptions. Section 3 presents a motivation example that shows the importance of measurement pose selection in robot calibration. In Section 4, the identification algorithm is presented. Section 5 deals with the evaluation of the identification accuracy. Section 6 contains the main theoretical contributions that allow the user to generate desired measurement configurations without straightforward numerical optimization, using proposed rule of thumb. Sections 7 and 8 illustrate advantages of the developed approach and contain some simulation results. In Sections 9 and 10, the proposed technique is extended to the case of spatial manipulator and is applied to a 6-dof serial industrial robot. Section 11 contains discussion where weak and strong sides of the developed approach are considered. Finally, Section 12 summarizes the main contributions of the paper.

2. Problem statement

Let us consider a general planar serial manipulator consisting of n rigid links connected by the corresponding number of revolute joints. For this manipulator, the end-effector position (x, y) can be defined as follows:

$$\begin{aligned} x &= l_1 \cos\, q_1 + l_2 \cos\,(q_1+q_2) + \cdots + l_n \cos(q_1+q_2+\cdots+q_n) \\ y &= l_1\, \sin q_1 + l_2 \sin(q_1+q_2) + \cdots + l_n \sin(q_1+q_2+\cdots+q_n) \end{aligned} \tag{1}$$

where $l_1, l_2, \ldots, l_n$ are the link lengths, $q_1, q_2, \ldots, q_n$ are the actuated joint coordinates, n is the number of links. In practice, the actual values of the link length l_i and the joint coordinates q_i differ from the nominal ones $l_i{}^0$ and q_i^0 by some offsets Δl_i and Δq_i to be identified:

$$l_i = l_i^0 + \Delta l_i; \quad q_i = q_i^0 + \Delta q_i \tag{2}$$

For further convenience, let us introduce the notations

$$\theta_i^0 = \sum_{k=1}^{i} q_k^0; \quad \Delta\theta_i = \sum_{k=1}^{i} \Delta q_k \tag{3}$$

that allow us to rewrite (1) as

$$\begin{aligned} x &= \left(l_1^0 + \Delta l_1\right) \cdot \cos\left(\theta_1^0 + \Delta\theta_1\right) + \cdots + \left(l_n^0 + \Delta l_n\right) \cdot \cos\left(\theta_n^0 + \Delta\theta_n\right) \\ y &= \left(l_1^0 + \Delta l_1\right) \cdot \sin\left(\theta_1^0 + \Delta\theta_1\right) + \cdots + \left(l_n^0 + \Delta l_n\right) \cdot \sin\left(\theta_n^0 + \Delta\theta_n\right) \end{aligned} \tag{4}$$

Below, the system (4) will be used to generate the set of calibration equations where the offset variables $\{\Delta l_i, i = \overline{1, n}\}$ and $\{\Delta\theta_i, i = \overline{1, n}\}$ are treated as unknowns.

To find the desired offsets, a number of experiments are carried out providing a set of Cartesian coordinates $\left\{x^k, y^k\right\}$ and corresponding joint angles $\left\{q_1^k, q_2^k, \ldots, q_n^k\right\}$ that theoretically satisfy the system of Eq. (4). However, due to measurement errors, the number of experiments should be excessive and the set of the calibration equations cannot be satisfied simultaneously. Hence, the identification procedure may be treated as the best fitting of the experimental data by the geometrical model (2), i.e. by minimizing the corresponding positional residuals.

To take into account the impact of the measurement noise, the calibration equations derived from (4) can be written in the following form:

$$\begin{aligned} x^k &= \sum_{i=1}^{n} \left(l_i^0 + \Delta l_i\right) \cdot \cos\left(\theta_i^{0k} + \Delta\theta_i^k\right) + \varepsilon_x^k \\ y^k &= \sum_{i=1}^{n} \left(l_i^0 + \Delta l_i\right) \cdot \sin\left(\theta_i^{0k} + \Delta\theta_i^k\right) + \varepsilon_y^k \end{aligned} \tag{5}$$