Robotics and Computer-Integrated Manufacturing 37 (2016) 33–48

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Computationally efficient and robust kinematic calibration methodologies and their application to industrial robots

Temesguen Messay [a,*], Raúl Ordóñez [a], Eric Marcil [b]

[a] Department of Electrical and Computer Engineering, University of Dayton, 300 College Park, Dayton, OH 45469-0232, United States
[b] Yaskawa America, Inc., Motoman Robotics Division, Headquarters and Manufacturing Facility, 100 Automation Way, Miamisburg, OH 45342, United States

ARTICLE INFO

Article history:
Received 14 December 2014
Received in revised form
24 May 2015
Accepted 17 June 2015

Keywords:
Kinematic calibration
Optimization
Simulated annealing
Trust region
CompuGauge
MotoCal
Industrial robots
Yaskawa Motoman Robotics, Inc

ABSTRACT

In this paper, we present new computationally efficient and robust kinematic calibration algorithms for industrial robots that make use of partial measurements. These include a calibration method that requires the supply of Cartesian coordinates of the calibration points (3DCAL) and another calibration technique that only requires the radial measurements from the calibration points to some reference (1DCAL). Neither method requires orientation measurements nor the explicit knowledge of the whereabout of a reference frame. Contrary to most other similar works, both methods make use of a simplified version of the original Denavit–Hartenberg (DH) kinematic model. The simplified DH(-) model has not only proven to be robust and effective in calibrating industrial manipulators but it is also favored from a computational efficiency viewpoint since it consists of comparatively fewer error parameters. We present an analytical approach to develop a set of guidelines that need to be considered in order to properly construct the DH(-) model such that it is parameterically continuous and non-redundant. We also propose an automated method to provide a characterization of the error parameters that is insightful so as to correctly deduce the DH(-) error model of a manipulator. The method makes use of a novel hybrid optimization scheme to conduct a statistical analysis of the error parameters that is indicative of their relevance. We made note that, for the industrial robots used in this paper and similar ones, calibrating the home position only is sufficient to attain adequate results for most robotic applications. Hence, we put forward for consideration a yet simpler calibration model; the DH(-)(-) model. We employ the Trust Region (TR) method to minimize the objective functions of both frameworks (3DCAL and 1DCAL). The performance of the proposed methods is compared to that of a state-of-the-art commercial system (MotoCal) using the same materials, data and internationally recognized performance standards. Our experimental results suggest that our methods yield improved results compared to that of MotoCal.

1. Introduction

Repeatability (also known as test–retest reliability) and accuracy are important characteristics of industrial robots [1–5]. The demand of improving those two qualities of industrial robots has therefore been growing continuously over the past two decades. It is a known fact that today's industrial manipulators have satisfactory repeatability (better built) but poor accuracy due to numerous sources of errors [3,6–9]. Robot calibration is the process of enhancing the positioning accuracy of a manipulator through software rather than modifying the mechanical structure (i.e., design) of the robot itself [10–12]. The leading source of lack of accuracy is the discrepancy between the mathematical model of the manipulator in the controller and the actual geometry of the structure [2,3,6,8,13,14]. An accurate representation of the geometry of a robot is very crucial because the efficiency of methods for planning and controlling robot motions is highly dependent on such a mathematical model [12,15–19]. Hence, in this paper, we present computationally efficient and robust kinematic calibration techniques for industrial robots. A kinematic calibration procedure involves *modelling*, *measuring*, *identifying parameters*, *implementing compensation* and *validating* [10,20,21].

1.1. Modelling

The first procedural step is to derive a mathematical model that relates the robot's joint angles to the pose of its end-effector and that takes into account the geometric error parameters that need to be identified. The standard Denavit–Hartenberg (DH) convention [22] is universally used for kinematic modelling in robotics [3,22–24,16,18]. However, a standard DH based kinematic

---

[*] Corresponding author.
E-mail addresses: tmessay1@udayton.edu (T. Messay), rordonez1@udayton.edu (R. Ordóñez), eric.marcil@motoman.com (E. Marcil).

http://dx.doi.org/10.1016/j.rcim.2015.06.003
0736-5845/

calibration model is singular for manipulators with two consecutive parallel (or near parallel) joint axes [25–27]. Since the majority of industrial robots possess at least two parallel joint axes, significant efforts were made to solve such a problem. Authors either proposed to use a modified version of the standard DH convention (e.g., adding an extra parameter to the original DH model) or introduced their own model to resolve the presented challenge [10,20,25,26,28–33]. However, a potential drawback of some of those alternate solutions is that the compensation is not directly implementable in controllers of existing industrial manipulators.

In this paper, we propose to "simplify" the standard DH based kinematic calibration model so as to make it continuous and non-redundant (i.e., we opt to not consider some of the DH error parameters deemed redundant and hence irrelevant). Our approach has not only proven to overcome the problem of discontinuity [3,6,25–27] and redundancy [3,6] but it is also favored from a computational efficiency viewpoint since it consists of comparatively fewer error parameters. Furthermore, we believe that it is applicable and well-suited to calibrate industrial manipulators like those of Yaskawa Motoman Robotics, Inc. (or other similar manipulators) because not all DH parameters are accessible to be modified [34–36]. We have established useful rules/guidelines based on empirical studies and generalized geometric knowledge of kinematic modelling that need to be considered in order to make the error model non-redundant. We shall show that the resultant simplified DH(-) model is more robust compared to existing calibration methods as it ensures that a reliable end-result is attained.

We have also devised an automated method to provide a parameter assessment that is greatly insightful in identifying irrelevant parameters (i.e., that is helpful to properly construct the DH(-) model of a given manipulator). In particular, we believe that this automated assessment to be greatly advantageous when calibrating manipulators of complex geometry (e.g., structures with higher Degree of Freedom (DOF) compared to the ones considered in this work). The method makes use of a novel hybrid optimization scheme composed of the Simulated Annealing (SA) algorithm [37–41] and the Trust Region (TR) algorithm [42–46]. It provides a statistical analysis on the estimates of a given error parameter that is suggestive of its relevance. Thus, for the error parameters that the auto-rating is above a given threshold or the end-user so designates, only a basic understanding of the geometry of the robot is required from the user to determine which ones are non-pertinent (i.e., that consequently need to be discarded in order to correctly derive the DH(-) kinematic calibration model for the manipulator at hand).

Additionally, we shall demonstrate that, for the type of robots (e.g., [47–49]) and controllers (e.g., [34–36]) that are put to use in this work, precision inaccuracy is mostly due to incorrectness of the offset values used to describe the manipulator's home position (also known as Absolute [ABS] data [34–36]). Hence, we further simplify the DH(-) model and introduce the DH(-)(-) model, a simpler model that consists of calibrating the home position (and tool if applicable) only. We shall demonstrate that, although incomplete, the DH(-) and DH(-)(-) kinematic calibration models are capable of exceptional performance and can be used to calibrate a wide range of industrial robots provided that the models are accurately constructed.

1.2. Measuring

In practice, another crucial choice is the measurement system. The efficiency of the calibration method is a function of the accuracy of the observations (measurements) itself [3,6,50,51]. A number of different measurement systems have been used for robot calibration and/or validation. Generally speaking, the measurement systems used to calibrate a robot can be classified into two groups: *complete pose measurement* and *partial pose measurement*. A complete pose measurement of the tool pose would consist of three position coordinates and three orientation angles (6D). This type of measurement method yields the maximum information for a given configuration. Examples of kinematic calibration techniques that make use of complete pose measurement include those described in [6,10,51–57]. Partial measurements of the tool pose (that is, less than six measured values per observation ranging from 3D to 1D) can also be used to identify the robot's geometry. Methodologies that have employed partial measurement equipments to calibrate a robot can be found in [3,20,23,24,26,50,58–74].

What is paramount to note from the cited research efforts (type of measurements used in their methods and reported performance analyses) is that incomplete pose information in accordance with a specific data-collection scheme can be used to successfully calibrate a robot (yields satisfactory results for most industrial robotic applications). Also to note is that, in most cases, complete pose measuring devices are found to be relatively more expensive. For these reasons, it behooves us to develop a kinematic parameters identification solution that functions appropriately with incomplete pose information. Moreover, considering the variability among existing partial pose measuring devices, we believe that, in order for a solution to have practical relevance, it ought to be adaptable to the supply of various types of incomplete pose information. Hence, our overall kinematic calibration framework is composed of two methodologies: one that uses 3D position measurements (3DCAL) and another that requires radial distance measurements only (1DCAL). Note that neither method requires orientation measurements. In this work, we made use of the 3D and 1D CompuGauge [75] measurement systems to acquire the partial pose measurements of the calibration points.

1.3. Identifying parameters

For the third procedural calibration step, in our framework, we have formulated kinematic parameters identification process as a simplified optimization problem. In our 3DCAL and 1DCAL systems, we make use of the DH(-) and DH(-)(-) error models. Unlike the 3D calibration methodologies presented in [3,58] and the 1D calibration scheme proposed by [71], our approaches do not require the explicit knowledge of the position of a reference frame (neither the robot's base frame nor the whereabouts of the measurement equipment's reference frame). We therefore believe that our solutions are more flexible compared to that of [3,58,71]. In this study, the TR approach and the Levenberg–Marquardt (LM) algorithm [76–78] are implemented to minimize the objective functions of both systems (3DCAL and 1DCAL). Even though both (TR and LM) algorithms converged to the same numerical values for *all* cases of non-linear least square analyses, we found TR to be more efficient compared to LM and hence the former is favored and used to optimize over the cost functions of both systems (i.e., used to solve for the relevant error parameters of the DH(-) and DH(-)(-) error models of both systems).

1.4. Implementing compensation

For this calibration procedural step, we allow user interaction. It must be recalled that access to modify the parameters in some controllers is not obvious, and may not be possible for second and third parties. Hence, we allow the user to select which DH parameters estimate subject to our rules that need to be applied to successfully derive the DH(-) error model (i.e., in order to render the original DH convention based error model continuous and