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An Overview of Robot Calibration

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Abstract: Calibration plays an increasingly important role in enhancing robots positing accuracy. The research gives an overview of the existing work on robot calibration and points out the utility of calibration in areas such as the production, implementation and operation of robots. Modeling, measuremet, identification and compensation issues in robot calibration are discussed.

Key words: Kinematic calibration, modeling, parameter identification

INTRODUCTION

Calibration is used to enhance robot positioning accuracy, through software rather than changing the mechanical structure or design of the robot itself. As, robots similar to other mechanical devices can be affected by slight changes or drifts caused by wear of parts, dimensional drifts, tolerances and components replacement, calibration can minimize the risk of having to change application programs due to slight changes or drifts caused by the above mentioned factors in the robot system. This is useful in applications that may involve a rather large number of task points.

At most general level, calibration can be classified into two types. Model-based parametric calibration and Model non-parametric calibration. Most work on Model-based parametric calibration has concentrated on kinematic-Model-based calibration or kinematic calibration as called in this work.

The goal of this paper is to provide an overview of robot calibration, identify some of the related research issues and to point out the utility of robot calibration.

To aid this, robot calibration is classified into two types. In each type, the sequential steps, modeling, measurement, identification and compensation are addressed and relevant researches are reviewed.

Robot calibration: Robot calibration is a process by which robot positioning accuracy can be improved by modifying the robot positioning software instead of changing or altering the design of the robot or its control system. To fulfill this, the procedure involves developing a model whose parameters accurately represent the real robot. Next, specifically chosen features of the robot are accurately measured.This step is followed by identification procedure to compute those parameter values, which when input in the robot model accurately reflect the measurements made.

Nowadays robot calibration plays an increasingly important role in robot production as well as in robot implementation and operation within computer-integrated manufacturing or assembly systems. The production, implementation and operation of robots are all areas where robot calibration results can lead to significant accuracy improvement and/or cost-saving as explained below:

Implementing off-line planned and simulated robot tasks: Robot calibration makes possible the implementation of off-line designed computer integrated systems. Large time-saving is possible and costly mistakes can be avoided when the robot task can be planned and simulated off-line. For a control system to successfully execute an off-line program generated in the planning and simulation system, the dimensions of the real robot and the work cell must be very similar to those of the models used for program design. If not, their differences in dimensions will show up as robot positioning errors when the program is executed at the shop-floor.

Improving control and simulation of robot motion: Another important utility of robot calibration, is the calibration for improvement in motion control and simulation. Namely, values of robot mass characteristics-also referred to as inertial parameters. Precise identification of these parameter values is important for accurate control and simulation of the robot motion. Also friction and structural stiffness play important roles in this area.

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Evaluating robot production: Robot accuracy is largely dependent on how closely the robot can be manufactured to its specifications at a minimum tolerance. The important specifications are the precise geometric arrangement of a robot joint axes and transmission mechanisms used to actuate each joint. Measurement of these specifications is essential to evaluate the quality of production and to check how closely these specifications are being met. However after assembly, many of these specifications can not be easily measured. Calibration on the other hand is a tool that provides a practical and effective means of implicit parameter measurement.,

Monitoring robot components wear: Once a robot is operating in a flexible manufacturing system, component wear-and-tear or repair can determintally affect positioning accuracy. A periodic re-calibration can be performed to determine if repairs are needed and/or if programs need adjusting.

This communication addresses each of the general type of calibration individually. At each class the steps forming the calibration process viz. modeling, measurement, identification and compensation are discussed and current research in that area is highlighted.

Kinematic model-based calibration: Most works carried on model-based parametric calibration have concentrated on kinematic model-based calibration or simply kinematic calibration[1-7]. Kinematic calibration is also called level-2 calibration[8]. In kinematic model-based calibration, geometric factors are applied to identify the model parameters. Despite this, few papers have taken non-geometrical factors into account[9,10]. Some claim that all non-geometrical errors are responsible for about 10% of the total error, so they restrict their analysis to geometrical errors to simplify their equations Jean *et al.*[11] while Whitney *et al.*[9] reported that non-geometric errors are as significant as geometric errors in affecting robot accuracy for a general robot (PUMA 560). It is difficult to judge which method is better since the relative contribution of geometric and non-geometric errors to robot accuracy vary from one robot to another.

Generally kinematic model-based calibration is considered as a global calibration method that improves robots accuracy across the whole volume of robot space. Kinematic calibration consists of four sequential steps:

- Modeling
- Measurement
- Identification
- Compensation or Correction

The steps are described below:

Modeling: A kinematic model is a mathematical description of the geometry and motion of a robot. A number of different approaches exist for developing the kinematic model of a robot manipulator. The most popular method, has been established by Denavit and Hartenberg[12]. The method based on homogeneous transformation matrices. The procedure consists of establishing coordinate systems on each joint axis. Each coordinate system is then related to the next through a specific set of coefficients in the homogeneous transformation matrices. Later, many researchers pointed out the model singularity problem inherent in D-H representation. Hayati[1] proposed a modification to D-H modeling by incorporating an extra rotation parameter for parallel revolute axes. Ibara and Perreira[13] utilized the D-H procedure and modified each transformation matrix with a differential screw matrix for small misalignment.

Many alternative kinematic models have been proposed to perform robot calibration. For example the S-model[14] which uses six parameters for each link. The Zero-reference model[15] which does not use a common normal as a link parameter, to avoid model singularity. However, D-H representation dominates the kinematic models used in most existing robot controllers.

Measurement: The measurement phase involves workspace sensing of positions of the end effector or tool of the robot. The actual measured positions of the robot end effector are then compared with the positions predicted by the theoretic model to obtain the workspace inaccuracy data.

Generally, six parameters are necessary (But, not necessarily sufficient) to completely specify the position of a rigid body[8]. The sufficiency requirements depend on the exact nature of the six conditions used to specify the position of the body. Measurement is the most difficult and time-consuming phase of robot calibration. The measurement procedure must exhibit the individual parameters of the model in some way and the measurement system must be accurate enough to measure the affects of these parameters. A good model is useless without a measurement procedure and a system to match.

Different measurement methods and different measuring devices have been used for robot calibration. These include the use of acoustic sensors[14] visual sensors[6,16] co-ordinate measuring machines[17] and visual and automatic theodolites[18]. The measuring techniques and measuring devices accompany them, vary considerably in their accuracy, ease of use and cost, but they all share the following drawbacks:

- Trained personnel are required to operate the measuring devices properly
- Data collection is fatiguing, time-consuming and difficult to automate.
- The measuring techniques are mainly designed for robot calibration in laboratory environment except very few of them.
- The set-up and measurement procedures require a lot of human intervention, which make them unsuitable for robot on-site calibration in an industrial environment.

It is a proven fact that, in robot calibration, is not necessary to make complete measurement of the end-effector position. Instead, several equivalent incompletely specified position measurements will also be enough. The idea was addressed by so many researchers. Tang and Mooring[19] utilized a mechanical fixture to obtain partial information of a robot end-effector location, while Veitchegger and Wu[20] calibrated a PUMA robot based on the use of the similar plate fixture with a set of precisely positioned holes.

The introduction of partial pose measurement scheme to robot calibration with its low cost and elimination of large external measuring devices makes it demanding for on-site application. However, the measuring process is carried manually and requires intensive human interventions.

Identification: Parameter identification involves numerical methods. The methods must be reliable enough so that a solution can be reached while maintaining a reasonable level of confidence in the resulting identified parameter values. The identification of the parameters in a robot kinematic model is a problem that has been addressed by a number of researchers[3,9,13,21] using a variety of models and identification methods.

In this phase, kinematic parameter errors are identified, by minimizing the collected work-space inaccuracy in the least mean square sense.

It is known that the kinematic identification is a standard non-linear or linear least square optimization procedure. When linear least square algorithms applied, they require less computation time to converge, but suffer from numerical problems of ill-conditioning of the identification Jacobian. To overcome this problem, minimization techniques such as Levenberg-Marquardt algorithm have been used[22,23]. To investigate the relationship between calibration accuracy and measurement noise, Mooring *et al.*[7] applied Kalman filtering techniques. A more advanced parameter estimation technique known as a maximum likelihood estimator was used by Renders *et al.*[24] in kinematic identification.

Recently, researchers have addressed some theortical issues to improve kinematic identification strength and efficiency. Such issues include: the condition number of the identification Jacobian by Khalil *et al.*[25] to determine optimum calibration configurations, an observability index by Born and Meng[26] to find the optimal measurement configurations for robot calibration. The optimal measurement configurations determined by the later, mean that the measurement points should spread the whole workspace as widely as possible. The observation is useful for robots in laboratory environment where they can be controlled to move to arbitrary configurations but not for robots in an industrial environment where the movement is usually constrained[27].

Compensation: This is the final and decisive step in robot kinematic calibration, which is the implementation of the new model in the position control software of the robot. Sometimes referred to as the correction step. Due to the difficulty in modifying the kinematic parameters in the robot controller directly, joint compensations are made to the encoder readings of the robot obtained by solving the inverse kinematics of the calibrated robot.

Since the inverse kinematics of the calibrated robot, generally not solvable analytically, numerical algorithms such as the Newton-Raphson approach are usually applied to solve the model to find the joint corrections needed to compensate for Cartesian errors[28,29]. With the Newton-Raphson algorithm, on-line compensation is problem due to the computation expense and the algorithm breaks down in the vicinity of robot singular configurations, because the approach is based on the iterative inversion of the compensation Jacobian. Veitschegger and Wu[30] presented the differential transformation compensation method in which two nominal inverse problems are solved for one task point compensation.

Non-kinematic calibration: In kinematic calibration, the model is formed under the assumptions that the links of the robot are perfectly rigid, the joints would allow no undesired motion their axes and the robot is not under dynamic control. If the assumptions are not valid, or the robot is under dynamic control, then non-kinematic calibration must be considered. Non-kinematic calibration is also called level-3 calibration[8]. Apart from the geometrical errors, robots are affected by other error sources present in their structures. These are called non-geometrical error sources. Among these error sources that have the most significant effect on robot accuracy, are joint flexibility, link flexibility, gear transimission error, backlash in gear transmission and temperature effect.

From the above error sources it can be said, in non-kinematic calibration, a number of effects exist which may be modeled. To include such factors, the model used in the position control software of the robot must be modified. On the other hand, if the robot is under dynamic control, then factors such as translational and angular velocity and acceleration of the end effector must be considered in the functional relationship. Of course, this will complicate the functional relationship equation, even if the links of the robot assumed to be perfectly rigid and the joints are frictionless.

Due to the difficulties and complication of level-3 calibration, very few researchers attempted this area. Here, are some of the efforts that have been done in this field. Jean *et al.*[11] and Becquet[31] reported that flexibility in joints and in links is responsible for 8-10% of the position and orientation errors of the end effector. Link flexibility is than joint flexibility error-below 5%[31]. Judd and Knasinski[10] proposed a gearing error model combining the effects of gear transmission errors with six extra parameters for each joint.

Backlash is one of the most difficult error sources to identify. In addition to that its contribution to the global error is from 0.5-1.0%. Despite this fact[11] built a maximum likelihood estimator, taking into account possible backlash in transmission units, measuring device limits and manufacturing tolerances.

Temperature of course, expands the robot mechanical structure. Its effect depends on the metal coefficient of expansion. But fortunately, the error due to temperature is responsible for only 0.1% of the total error.

The dynamic problem was addressed by Neuman and Khosla[22] who describe a technique for the determination of the dynamic parameters of a rigid-link robot having a known kinematic structure. Kok and Shah[33] presented a dynamic analysis of a 3 DOF in-parallel actuated manipulator. The analysis provides the solution to predict the forces required to actuate the links so that the manipulator follows a predetermined trajectory. In addition it provides a basis for future theoretical research to develop the control scheme and for experimental research to estimate the inertia parameters.

In this communication, we have reviewed the existing work related to calibration, which enhance robots positioning accuracy. We also pointed out the areas where robot calibration can lead to significant accuracy improvement and/or cost saving opportunities. We described two classes of calibration together with the sequential steps needed for each one and explained that kinematic model based calibration is a global calibration method, intensively investigated and widely spread compared to non-kinematic calibration.

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