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Identification of the manipulator stiffness model parameters in industrial environment

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ABSTRACT

The paper addresses a problem of robotic manipulator calibration in real industrial environment. The main contributions are in the area of the elastostatic parameter identification. In contrast to other works the considered approach takes into account the elastic properties of both links and joints. Particular attention is paid to the practical identifiability of the model parameters, which completely differs from the theoretical one that relies on the rank of the observation matrix only, without taking into account essential differences in the model parameter magnitudes and the measurement noise impact. This problem is relatively new in robotics and essentially differs from that arising in geometrical calibration. To solve the problem, physical algebraic and statistical model reduction methods are proposed. They are based on the stiffness matrix sparseness taking into account the physical properties of the manipulator elements, structure of the observation matrix and also on the heuristic selection of the practically non-identifiable parameters that employ numerical analyses of the parameter estimates. The advantages of the developed approach are illustrated by an application example that deals with the elastostatic calibration of an industrial robot in a real industrial environment.

1. Introduction

Industrial robots are gradually finding their niche in manufacturing, replacing less universal and more expensive CNC-machines. Application area of robots is constantly growing, they begin to be used not only for the assembly and pick-and-place operations, but also for machining operations. The latter requires special attention to the accuracy of the model, which is used to control the manipulator movements. Furthermore, for this process, the robot is usually subject to essential external loading caused by the machining forces that may lead to non-negligible deflections of the end-effector [1] and accordingly degrade the quality of the final product. This issue becomes extremely important in the aerospace industry, where the accuracy requirements are very high but the materials are hard to process. In this case, the manipulator stiffness modelling and corresponding error compensation technique are the key points [2–5], where in addition to an accurate geometric model a sophisticated elastostatic one is required.

In practice, the robot positioning accuracy can be improved by means of either on-line or off-line error compensation techniques [6–8]. It is clear that both approaches should rely on the accurate model, which is able to describe the end-effector deviations due to manufacturing tolerances and the external loading. Usually main geometric errors (such as offsets and link lengths) can be efficiently compensated by modifying internal parameters of the robot controller [9,10]. In contrast, the compliance errors (as well as some

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Nomenclature

$\mathbf{A}(\mathbf{q}, \mathbf{w}\|\boldsymbol{\pi})$	observation matrix defining the mapping between the unknown compliances $\boldsymbol{\pi}$ and the end-effector displacements $\Delta\mathbf{t}$ under the loading $\mathbf{w}$ for the manipulator configuration $\mathbf{q}$
$\mathbf{C}_\theta$	compliance matrix in the joint space
C_{ij}	the (i.j)th term of the compliance matrix
$\mathrm{cov}(\hat{\boldsymbol{\pi}})$	covariance matrix of the parameter estimates $\hat{\boldsymbol{\pi}}$
$\mathbf{g}(.)$	the vector function describing the geometric model
$\mathbf{J}_\theta$	Jacobians matrix with respect to the virtual joint variables $\boldsymbol{\theta}$
$\mathbf{K}_\theta$	stiffness matrix in the joint space
$\mathbf{K}_C$	stiffness matrix in the Cartesian space
$\mathbf{M}$	the binary matrix describing the mapping from the original to the reduced parameter space
s_i	diagonal elements of the matrix $\mathbf{S}$ (singular values)
$\mathbf{t}$	the vector of the end-effector position and orientation
$\Delta\mathbf{t}$	the vector of end-effector deflections
$\mathbf{T}$	homogenous transformation matrix
$\mathbf{q}$	the vector of the actuated joint coordinates
$\mathbf{U}, \mathbf{S}, \mathbf{V}$	orthogonal, diagonal and orthogonal matrices obtained after SVD-decomposition
$\mathbf{w}$	the external wrench applied to the end-effector
$\boldsymbol{\varepsilon}_j$	the vector of measurement errors
$\boldsymbol{\eta}$	the matrix of weighting coefficients
$\boldsymbol{\theta}$	the vector of virtual joint coordinates
ν_i	parameter-to-noise ratio
$\boldsymbol{\pi}$	the vector of the compliance matrix parameters to be identified
$\boldsymbol{\Sigma}^2$	matrix describing the statistical properties of the measurement errors
σ_{ij}	the (i.j)th term of the covariance matrix
$\boldsymbol{\tau}_\theta$	the vector of the torques in the virtual joints

geometric errors) have to be compensated via modifications of the controller inputs. A relevant on-line compensation strategy requires an external measurement system that continuously provides the end-effector coordinates, which are compared with the computed ones (obtained from direct geometric model of the robot controller) and the differences are used for adjusting the input trajectory [11,12]. The most essential advantage of such an approach is its ability to compensate the errors caused by all sources of robot inaccuracy. However, suitable measurement systems are quite expensive and often cannot ensure tracking the reference point in a whole robot workspace. Moreover, behaviour of some technological processes hampers the end-effector observability (cutting chip in milling, for instance) and may damage the measurement equipment. In such a case, an off-line error compensation technique looks more reasonable; it is aimed at adjusting the target trajectory in accordance with the errors to be compensated and the geometric model used in the robot controller [7,13]. It is evident that the efficiency of the latter approach is quite sensitive to the model completeness and the accuracy of its parameters.

To achieve a desired degree of accuracy, the manipulator model should be calibrated for each particular robot [14,15]. In modern robotics, there exist a number of techniques that allow the user to identify geometric and elastostatic parameters of either serial or parallel manipulators. In general, a classical calibration procedure contains four basic steps: modelling, measurement, identification and implementation [16]. The first step is aimed at *developing a model*, which is accurate enough and also suitable for the identification (i.e. without redundant parameters that can cause numerical problems). Relevant techniques are usually based on different parameterization methods of robot geometry that produce obviously complete (but redundant) models that are subject to further reduction. In the early works of Hollerbach [17], Veitschegger and Wu [18], the Denavit–Hartenberg (D–H) parameterization was used, which describes the link-to-link transformations via 4 geometric parameters only that does not guarantee the model completeness in general case. Later, Hollerbach et al. [19] and Hayati et al. [20,21] modified the D–H approach by utilizing 5 parameters to describe these transformations. Further developments led to models with 6 parameters per transformation, as they have been used by Stone [22] and Whitney et al. [23]. Any of these parameterizations can be used for geometric modelling. However to be suitable for calibration, the number of the parameters should be non-redundant. In practice, the maximum number of the identifiable geometric parameters is evaluated using so-called POE (Product Of Exponentials) formula [24,25]. In particular, Ruibo et al. [26] used POE formula for kinematic parameter identification of SCARA and PUMA robots. In [27] POE has been used for the calibration of an industrial serial robot Fanuc M-710iC/50.

In the manipulator stiffness modelling, there are three main approaches: the Finite Element Analysis (FEA), the Matrix Structural Analysis (MSA), and the Virtual Joint Method (VJM). The most accurate one is the FEA-based technique [28], which considers the manipulator components with their true shape and dimensions. However, this method is usually applied at the final design stage because of the high computational expenses [29]. The MSA method [30] incorporates the main ideas of the FEA, but operates with rather large elements — 3D flexible beams. This obviously leads to the reduction of the computational efforts, but does not eliminate the disadvantages of FEA. And finally, the VJM method [31–34], is based on the extension of