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Modeling and Identification of an Industrial Robot for Machining Applications

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Abstract
Industrial robots represent a promising, cost-saving and flexible alternative for machining applications. Due to the kinematics of a vertical articulated robot the system behavior is quite different compared to a conventional machine tool. This article describes the modeling of the robot structure and the identification of its parameters with focus on the analysis of the system's stiffness and its behavior during the milling process. Therefore a method for the calculation of the Cartesian stiffness based on the polar stiffness and the use of the Jacobian matrix is introduced. Based on the results of the identification and the experimental validation the machining performance of the robot is evaluated and conclusions are drawn.

Keywords:
Robot, Machining, Structure model

1 INTRODUCTION

The fields of application for industrial robots developed from the classical handling, assembly and welding tasks to a wide range of production applications, e.g. quality control and machining. Especially in new fields where high process loads are affecting the accuracy of the robot a lot of research work is currently done, e.g. robot shaping, friction stir welding, folding and cutting. This article describes a method of robot modeling and parameter identifying to analyze its properties and accuracy. The method described focuses on processes that induce bigger loads into the robot structure. The method is applicable for all of the above mentioned machining applications. However, the research was done especially for cutting operations. The following examinations were conducted particularly for vertical articulated robots which have a significant distribution in the manufacturing industry.

1.1 Fields of Application

The major fields of cutting applications for industrial robots are prototyping, cleaning and pre-machining of cast parts as well as end-machining of middle tolerance parts. In the field of prototyping the resulting process forces and the demand on accuracy are feasible for the machining with standard industrial robots. There the challenge lies in the realization of user friendly programming methods. However, this is not the focus of this article. For the cleaning and pre-machining of the gating system and riser from cast parts out of aluminum and iron many machining processes are still conducted manually due to a missing economic machine tool concept. For these operations in a noisy, dusty and unhealthy environment automation with robots is highly desirable. The machining of bigger, complex and free formed work pieces is realized with huge and expensive five axes machine tools because there is no alternative machine tool concept that fulfils the multi-axes machinability of larger parts. For the machining and pre-machining application research and development of essential components of the robot has been made.

1.2 Research Approaches

Quite a lot of research has been done to analyze the robot structure and to increase the accuracy. The major fields of interest can be subdivided into kinematic, control, programming and process development. Most of the kinematic examinations concern system calibration. Due to manufacturing and assembly tolerances as well as temperature influences the deviation between real structure and model is analyzed and the model is adapted to the real performance [1, 2]. Furthermore, the major components such as structure, bearings and gears were examined. Many publications and research identify the gears as main responsibility for the system compliance. Dependent on the type and robot size the gear compliance ranges from 50% to 75% of the overall compliance [3, 4]. The robot control and resulting effects on the accuracy were examined in the wide field of robotics. Many enhancements that were realized can be drawn into the field of robot machining. Much effort was made by force control [5]. The aim was to move the robot by the information of contact forces. This idea was also transformed in the field of robot deburring and milling [6, 7]. Based on the knowledge of the system stiffness and the contact force the resulted path deviation was readjusted. The problem especially for deburring was the correct force signal analysis and differentiation between residual material and work piece material. The other problem was the control speed of the force feedback and process intervention. In the research project Advocut another method for accuracy improvement by control approach was developed at the Institute of Production Management, Technology and Machine Tools (PTW), Darmstadt University of Technology [8]. Rotational position sensors were integrated at the driven site of the gears for the compensation of the positional inaccuracies. The integration ensures a direct measurement of the actual shaft position. The positioning error provoked by the compliance of the gear can be measured and controlled. The shortcoming of this method was also the control speed when integrating this concept in standardized robot control architectures. The Advocut project was also focused on process development. By the help of High Speed Cutting (HSC) the process forces can be reduced so that the load on the structure can be minimized. Moreover, process stability investigations for the milling process have been made. Another investigation in machining stability with industrial robots was made by Zhang and Pan [9, 10]. Both investigations [8, 9, 10] emphasize the significant differences between the milling on a conventional machine tool and a vertical

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articulated robot. To understand the robot's performance an analytically based stiffness model with regard to the special needs for machining applications will be introduced in the following chapter.

2 ANALYTICALLY BASED STIFFNESS MODEL

The investigations at PTW were made with a five axes vertical articulated robot (RV130HSC from Reis Robotics). Unlike a standardized industrial robot with six axes, the fork head was modified in the way that axis number six was removed. A high speed motor spindle was directly integrated into axis number five (Figure 2).

2.1 Modeling of the Robot Structure

As mentioned above the compliance of the gears is the major problem for the deviation of the tool center point (TCP). To overcome and analyze this problem, a model that takes the gear's stiffness of each axis into consideration was established.

The considered manipulator consists of a series of links connected by revolute joints. With the direct kinematics one can calculate the position and orientation of the end effector as a function of the joint variables q_i. The position and orientation of an arbitrary frame K_i (attached at link i) with respect to a reference frame K_{i-1} are described by the position vector $\boldsymbol{p}_{i-1,i}^{(i-1)}$ of the origin and the unit vectors $\boldsymbol{x}_i^{(i-1)}$, $\boldsymbol{y}_i^{(i-1)}$, $\boldsymbol{z}_i^{(i-1)}$, where the upper index in brackets indicates the frame in which a certain vector is described. The calculation of the joint variable dependent homogeneous transformation matrices

$$ {}_{i-1}^{\ i}\boldsymbol{T}(q_i) = \begin{pmatrix} \boldsymbol{x}_i^{(i-1)} & \boldsymbol{y}_i^{(i-1)} & \boldsymbol{z}_i^{(i-1)} & \boldsymbol{p}_{i-1,i}^{(i-1)} \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1} $$

is usually done by the well known Denavit-Hartenberg convention [11, 12]. To compute the position and orientation of an arbitrary frame K_i with respect to the base frame K_0 equation (2) can be used

$$ {}_0^i\boldsymbol{T}(\boldsymbol{q}) = \prod_{k=1}^{i} {}_{k-1}^{\ k}\boldsymbol{T}(q_k) = \begin{pmatrix} \boldsymbol{x}_i^{(0)} & \boldsymbol{y}_i^{(0)} & \boldsymbol{z}_i^{(0)} & \boldsymbol{p}_{0,i}^{(0)} \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{2} $$

For $i = n$ (n = number of joints) the tool frame $\boldsymbol{T}_\mathrm{T}(\boldsymbol{q}) = {}_0^n\boldsymbol{T}(\boldsymbol{q})$ can be calculated.

The mapping between static forces applied to the end effector and resulting torques at the joints is described by a matrix, termed Jacobian. The Jacobian has as many rows as there are degrees of freedom (normally 6) and the number of columns is equal to the number of joints n

$$ \boldsymbol{J}(\boldsymbol{q}) = (\boldsymbol{J}_1, \boldsymbol{J}_2, \ldots, \boldsymbol{J}_n), \tag{3} $$

with the column vectors

$$ \boldsymbol{J}_i = \begin{pmatrix} \boldsymbol{z}_{i-1}^{(0)} \times \left(\boldsymbol{p}_{0,n}^{(0)} - \boldsymbol{p}_{0,i}^{(0)}\right) \\ \boldsymbol{z}_{i-1}^{(0)} \end{pmatrix}. \tag{4} $$

To calculate the Cartesian compliance from the compliance of the gears the principle of virtual work is used which allows making certain statements about the static case. The work has to be the same in any set of generalized coordinates, e. g. the work in Cartesian terms dW_x has to be the same as the work in joint-space terms dW_q

$$ \mathrm{d}W_\mathrm{x} = \boldsymbol{F}^\mathrm{T}\mathrm{d}\boldsymbol{x} = \tau^\mathrm{T}\mathrm{d}\boldsymbol{q} = \mathrm{d}W_\mathrm{x}, \tag{5} $$

where $\boldsymbol{F}$ is the 6 x 1 Cartesian force-torque vector acting at the end effector, d$\boldsymbol{x}$ the 6 x 1 infinitesimal displacement of the end-effector (linear and angular displacement), τ the 6 x 1 vector of the torques at the joints and d$\boldsymbol{q}$ the 6 x 1 vector of infinitesimal joint displacements. With the definition of the Jacobian [11, 12]

$$ \mathrm{d}\boldsymbol{x} = \boldsymbol{J}(\boldsymbol{q})\mathrm{d}\boldsymbol{q}, \tag{6} $$

equation (5) can be rewritten as

$$ \boldsymbol{F}^\mathrm{T}\boldsymbol{J}(\boldsymbol{q})\mathrm{d}\boldsymbol{q} = \tau^\mathrm{T}\mathrm{d}\boldsymbol{q}, \tag{7} $$

which must hold for all d$\boldsymbol{q}$. Hence, after transposing both sides one gets

$$ \tau = \boldsymbol{J}(\boldsymbol{q})^\mathrm{T}\boldsymbol{F}. \tag{8} $$

The relationship between the static Cartesian force-torque vector and the displacement is given by

$$ \mathrm{d}\boldsymbol{x} = \boldsymbol{H}_\mathrm{x}(\boldsymbol{q})\boldsymbol{F}, \tag{9} $$

with the Cartesian compliance matrix $\boldsymbol{H}_\mathrm{x}(\boldsymbol{q})$, whereas the relationship between the static torque vector in joint-space and the angular displacement is denoted as

$$ \mathrm{d}\boldsymbol{q} = \boldsymbol{H}_\mathrm{q}\tau, \tag{10} $$

with the joint-space compliance matrix

$$ \boldsymbol{H}_\mathrm{q} = \mathrm{diag}\left(h_{\mathrm{q}1}, \ldots, h_{\mathrm{q}n}\right). \tag{11} $$

Substituting the Cartesian and angular displacements in equation (6) with equation (9) and (10) yields

$$ \boldsymbol{H}_\mathrm{x}(\boldsymbol{q})\boldsymbol{F} = \boldsymbol{J}(\boldsymbol{q})\boldsymbol{H}_\mathrm{q}\tau. \tag{12} $$

Substituting τ with equation (8) equals

$$ \boldsymbol{H}_\mathrm{x}(\boldsymbol{q}) = \boldsymbol{J}(\boldsymbol{q})\boldsymbol{H}_\mathrm{q}\boldsymbol{J}(\boldsymbol{q})^\mathrm{T}. \tag{13} $$

Equation (13) is a very interesting relationship, in that it allows converting the joint-space compliance $\boldsymbol{H}_\mathrm{q}$ into the Cartesian compliance $\boldsymbol{H}_\mathrm{x}(\boldsymbol{q})$ without calculating any inverse kinematic functions.

2.2 Parameter Identification

The compliance of the gears was identified by experiments. For the measurement of each axis the robot structure was not disassembled. To ensure the decoupling of the axes only one gear at a time was loaded. Therefore while measuring axis (i) all axes from the base to axis (i-1) were clamped. The experimental results were compared with the manufacturer and the data from the robot company. Table 1 shows the experimental identified compliance of the axes. In axes 3 and 5 the compliance is the compound of gear and belt compliance. The maximum difference between given information and experimental results were less than 25%. The reason for this mismatch can be traced back to wear mechanism and idealization of the gears' real behavior.

Axis-Number i	1	2	3	4	5
Compliance h_{qi} [rad/Nm]*10^{-7}	2.97	2.97	3.12	1.92	78.0

Table 1: Experimentally identified compliances