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Increasing the Accuracy for a Piezo-Actuated Micro Manipulator for Industrial Robots using Model-Based Nonlinear Control

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Abstract: We consider the problem of modeling and control of the nonlinear dynamics of a micro manipulator, utilized for machining operations in combination with industrial robots. Position control of the micro manipulator is a challenging problem because of the actuation principle, which is based on piezo-actuators with inherent nonlinear behavior. The major nonlinearities in the manipulator are identified and explicitly modeled in this paper. Different model structures are outlined and subsequent identification experiments are performed and evaluated. The obtained models form the basis for a combined feedforward and feedback control scheme for accurate position control. Experimental results obtained with the developed control scheme are presented and discussed. We show that the accuracy of the controller is increased significantly with the proposed scheme, compared to a linear controller.

1. INTRODUCTION

As a result of the increased demand on cost-efficiency and flexibility in the manufacturing industry, industrial robots have emerged during the past decade as an appealing alternative to the dedicated machine-tools for performing high-accuracy machining operations, such as milling and grinding. Because of the significant process forces required during machining operations, joint flexibilities in combination with lack of measurements on the arm side of the robot, limit the achievable accuracy (Zhang et al., 2005). Consequently, deviations from the nominal path may occur during the machining operation.

To overcome the limitations of industrial robots when performing machining operations, a piezo-actuated micro manipulator has previously been developed (Puzik et al., 2009). The purpose of the developed micro manipulator is to compensate for path deviations, which the robot per se is unable to compensate for. The micro manipulator achieves this by stiff actuation, realized by piezo-actuators, combined with a mechanical design such that the bandwidth of the micro manipulator is significantly higher than that of the industrial robot. Following the concepts introduced by Sharon et al. (Sharon et al., 1993), the terms micro manipulator and macro manipulator will be used for the compensation mechanism and the robot, respectively.

We presented a prototype control scheme without explicit modeling of the nonlinear behavior of the piezo-actuators in (Olofsson et al., 2011), and a subsequent experimental evaluation in (Sörmno et al., 2012). However, since the piezo-actuators in the micro manipulator are inherently nonlinear in their input-output dynamics, the performance of the control scheme, and hence the machining performance, can be increased by modeling the nonlinear dynamics and utilizing the models for feedforward control in the control scheme.

The main contribution of this paper is the development and application of a model-based control scheme for the nonlinear dynamics of the micro manipulator, as well as an analysis of the proposed feedforward controller based on describing functions. Furthermore, an experimental verification showing a significantly higher accuracy of the position control with the proposed control scheme, compared to a linear controller based on feedback, is presented.

This paper is organized as follows. In Sec. 2, the design of the micro manipulator is briefly reviewed. The theory for the nonlinear models of the piezo-actuators is given in Sec. 3, whereas the identified models and the control scheme for the nonlinear dynamics of the micro manipulator are presented in Sec. 4. Experimental results are provided in Sec. 5, and finally conclusions and aspects on future work are given in Sec. 6.

2. BACKGROUND

This section briefly reviews the mechanical design of the developed micro manipulator, which is displayed in Fig. 1. It is to be noted that the machining spindle is attached to the micro manipulator—i.e., the robot is holding the workpiece—in the proposed experimental setup.

2.1 Mechanical design

The design of the micro manipulator is such that compensation is possible in a three-dimensional Cartesian coordinate system with axes x, y, and z, as shown in Fig. 1. Each axis is actuated by a piezo-actuator. Further, flexure elements between the actuators and the end-effector increase the compensation range of the micro manipulator. The gear ratio is approximately five in

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2.2 Nonlinear phenomena in the micro manipulator

During the initial dynamic characterization of the micro manipulator, it was noted that the nonlinear effects in the piezo-actuators are significantly influencing the positioning accuracy. The most apparent nonlinear dynamics were hysteresis and creep effects. The characteristics of the former phenomenon are shown in Fig. 2. The creep effect has been quantified for the different axes to approximately 0.02 μm/s.

Consequently, modeling of the nonlinear hysteresis effect is necessary in order to achieve accurate position control of the micro manipulator. Since the creep phenomenon exhibits significantly slower dynamics than the hysteresis, this effect can be handled without explicit modeling. Instead, feedback from the strain gauge sensors on the actuators is utilized. In particular, integral feedback from the control error is considered.

3. THEORY

Several approaches to modeling the hysteresis effect have been discussed in the literature. Three main categories of hysteresis models can be identified; approaches based on the Preisach model (Ge and Jouaneh, 1996; Lei et al., 2011), the Prandtl-Ishlinskii model (Al Janaideh et al., 2009; Krejci and Kuhnenn, 2001; Sun and Yang, 2009) and neural networks (Hastie et al., 2008; Xu, 1993).

3.1 Prandtl-Ishlinskii model

The Prandtl-Ishlinskii model is based on the play operator \( G_r[·] \) depicted in Fig. 3. Following (Brokate and Sprekels, 1996), a continuous function \( v(t) \in C[0, T] \), piecewise monotone in each of the subintervals

\[
[t_i, t_{i+1}], \quad 0 = t_0 < t_1 < \ldots < t_N = T
\]

is assumed as input. Hence, the play operator \( G_r[·] \) can in each subinterval \( [t_i, t_{i+1}] \), \( i = 0, \ldots, N-1 \), be written as

\[
G_r[v](t) = \max(v(t) - r, \min(v(t) + r, G_r[v](t_i))) ,
\]

with the initial value

\[
G_r[v](0) = \max(v(0) - r, \min(v(0) + r, 0))
\]

Utilizing the definition of the play operator in (2), the Prandtl-Ishlinskii operator \( H[v](t) \) can be written as a superposition of play operators according to (Brokate and Sprekels, 1996)

\[
H_1[v](t) = \alpha v(t) + \int_0^R \rho(r) G_r[v](t) \, dr
\]

where \( \rho(r) \) is a positive density function and \( \alpha \) is a constant parameter.

The generalized Prandtl-Ishlinskii operator (Al Janaideh et al., 2009), is an extension of the standard Prandtl-Ishlinskii model (4) in that the input \( v(t) \) is shaped with a continuous and strictly increasing function \( \varphi(·) \). The generalized Prandtl-Ishlinskii operator can be written as (Al Janaideh et al., 2009)

\[
H_2[v](t) = \alpha(\varphi \circ v)(t) + \int_0^R \rho(r) G_r[\varphi \circ v](t) \, dr
\]

To the purpose of implementation, a finite-dimensional Prandtl-Ishlinskii operator is established by discretization of the integral. This results in the finite-dimensional Prandtl-Ishlinskii operator

\[
y_k = \alpha \varphi(v_k) + \sum_{i=1}^n \rho(r_i) G_{r_i} [\varphi(v_k)]
\]

where \( Y = \{y_k\} \) and \( V = \{v_k\} \) are considered as discrete time-series and \( G_{r_i}[·] \) denotes the discretized play operator.

3.2 Inverse model based on Prandtl-Ishlinskii operator

The advantage of using the Prandtl-Ishlinskii operator for modeling of the hysteresis is that the analytic inverse of the
4. RESULTS

Hysteresis models were identified based on experimental input-output data. Since it is desirable that the model represents the hysteresis for different frequencies of the input signal, an excitation signal containing frequencies in the range of interest was chosen. Accordingly, the input signal

\[ v(t) = v_0 + \sum_{i=1}^{n} a_i \sin(\omega_i t) \]  

where \( v_0 \) is an offset and \( a_i \) and \( \omega_i, i = 1, \ldots, n \), are the amplitudes and frequencies of the sinusoids, was applied to the micro manipulator.

4.1 Models based on Prandtl-Ishlinskii operator

The model parameters were identified using nonlinear optimization. Introduce the notation \( p \) for the set of parameters to be identified. To the purpose of parameter identification, the following quadratic cost function is considered

\[ J(p) = \sum_{i=1}^{N} (y_k - y_k^{(m)})^2 \]  

where \( y_1, \ldots, y_N \) is the identification data and \( y_k^{(m)}, \ldots, y_k^{(m)} \) is the corresponding model output. With the threshold values \( r_i \) parametrized in the parameter \( \beta \) according to \( r_i = \beta i \) with \( \beta > 0 \), and the density function \( \rho(r) = \gamma \exp(-\delta r) \) with \( \gamma, \delta > 0 \), several different models with \( n \) play operators were identified. In particular, the choice of the shaping function \( \phi(\cdot) \) is of importance in order to obtain good correspondence between experimental data and the model. The following shaping functions common in the literature were considered

\[ \phi_1(v) = c_1 v + c_2 \]  

\[ \phi_2(v) = c_3 \tanh(c_4 v + c_5) + c_6 \]  

where \( c_i, i = 1, \ldots, 6 \), are model parameters to be identified. The selection criterion for the shaping function was the final cost \( J(p^*) \), where \( p^* \) is the vector of optimal parameter values.

The output from the identified model of the hysteresis nonlinearity in the \( x \)-axis of the micro manipulator, with the shaping function \( \phi_2(v) \) in Eq. (16) and \( n = 6 \), is compared to the measurements from the experimental setup in Fig. 5. It is to be noted that the model exhibits a good fit to the experimental data and that the input-output relation for the input signal of choice is satisfactory. The corresponding models for the \( y \)- and \( z \)-axes are similar, and are therefore not presented here.

4.2 Models based on recurrent neural network

Hysteresis models based on the recurrent neural network were trained using the cost function in Eq. (14) and with stochastic initialization of the model parameters \( \{b_{m1}^{(1)}, b_{m2}^{(2)}, w_{m1}^{(1)}, w_{m2}^{(2)} \} \), based on a normal distribution. A model for the \( x \)-axis nonlinearity with \( M = 25 \) neurons was found to result in similar performance as the previous Prandtl-Ishlinskii model. The model details are omitted here because of the limited space. Further, a neural network was trained for the inverse of the nonlinearity, which can be utilized to the purpose of feedforward control.

4.3 Scheme for position control

The control scheme depicted in Fig. 6 is proposed. In this scheme, each of the Cartesian axes of the micro manipulator is...
controller, the reader is referred to (Olofsson et al., 2011) and the states in the model of the linear dynamics are estimated using a Kalman filter. For further details regarding this controller, the reader is referred to (Olofsson et al., 2011).

4.4 Inner control scheme for piezo-actuators

Based on the inverse of the previously identified models of the hysteresis nonlinearity in the micro manipulator, a combined feedforward and feedback control scheme is proposed. A feedforward controller alone is not sufficient, since unmodeled dynamics and parameter variations will degrade the performance significantly. Consequently, feedback from the strain gauge sensors attached to the piezo-actuators is necessary.

The feedforward controller is based on the inverse of the hysteresis nonlinearity in the micro manipulator. The inverse model is established for each Cartesian axis as described in Sec. 3; either from the model based on the Prandtl-Ishlinskii operator or training a neural network for the inverse function directly.

The feedback controller is chosen as a PID controller, whose control law is given by

\[ u(t) = K \left[ e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right] \]  

where \( u(t) \) is the control signal, \( e(t) \) the control error, and \( K, T_i, \) and \( T_d \) are controller parameters. The D-part is essential, since it contributes with phase advance in the system. Furthermore, the D-part is lowpass-filtered in order to avoid amplification of high-frequency noise and the I-part is accompanied by an anti-windup scheme. The parameters of the PID controller should be chosen such that the gain is maximized, without causing instability of the closed-loop system, in order to reduce the effects of the nonlinearities in the piezo-actuators.

4.5 Outer control loop for micro manipulator position

With the inner piezo-actuator control loops closed, the linear dynamics of the micro manipulator is identified using subspace-based identification methods (Johansson, 1993). The position is controlled by a model-based linear-quadratic Gaussian (LQG) optimal controller (Åström and Wittenmark, 1997), where the states in the model of the linear dynamics are estimated using a Kalman filter. For further details regarding this controller, the reader is referred to (Olofsson et al., 2011).

4.6 Describing function analysis of the feedforward controller

In order to analyze the properties of the feedforward control based on the Prandtl-Ishlinskii operator, describing function analysis, see, e.g., (Slotine and Li, 1991), is utilized. The describing function analysis is based on a Fourier series expansion of the output from the nonlinear model, with a sinusoidal input. Even though this is an approximate analysis in the frequency domain, it gives valuable information about the global behavior of the feedforward controller. The analysis can further be motivated by considering the fact that the linear dynamics of the micro manipulator is of lowpass character.

Consider the finite-dimensional inverse Prandtl-Ishlinskii model in (7). Further, assume continuous-time input and output. With the input \( y(t) = y_0 + A \sin(\omega t) \), the first terms in the Fourier series expansion of the output are given by

\[ v_0 = \frac{1}{2\pi} \int_0^{2\pi} f(y(t)) d(\omega t) \]

(18)

\[ a_1 = \frac{1}{\pi} \int_0^{2\pi} f(y(t)) \sin(\omega t) d(\omega t) \]

(19)

\[ b_1 = \frac{1}{\pi} \int_0^{2\pi} f(y(t)) \cos(\omega t) d(\omega t) \]

(20)

where \( f(\cdot) \) is the inverse hysteresis model mapping. The describing function \( N(A) \) is defined based on the \( a_1 \) and \( b_1 \) coefficients as

\[ N(A) = \frac{a_1 + ib_1}{A} \]

(21)

Introduce \( \theta_i = \pi - \arcsin(1 - (2\tilde{\tau})/A) \) and

\[ \Gamma_i = \left\{ \begin{array}{cc} 1, & \text{if } A > \tilde{\tau}_i \\ 0, & \text{otherwise} \end{array} \right. \]

(22)

Assume that the shaping function \( \varphi(v) = 1 \) and \( y_0 = 0 \). It is straightforward to verify that \( v_0 = 0 \). The \( a_1 \) coefficient can, after simplification, be written as

\[ \frac{a_1}{A} = \frac{1}{\alpha} + \frac{1}{\pi} \sum_{i=1}^{n} \tilde{\rho}(\tilde{r}_i) \Gamma_i \left\{ \frac{3\pi}{2} + \frac{1}{2} \sin(2\theta_i) + 2 \left( \frac{2\tilde{r}_i}{A} - 1 \right) \cos(\theta_i) - \theta_i \right\} \]

(23)

A similar calculation for the \( b_1 \) coefficient gives

\[ \frac{b_1}{A} = \frac{1}{\pi} \sum_{i=1}^{n} \tilde{\rho}(\tilde{r}_i) \Gamma_i \left\{ -\frac{3}{2} + \frac{1}{2} \cos(2\theta_i) + 2 \left( 1 - \frac{2\tilde{r}_i}{A} \right) \sin(\theta_i) \right\} \]

(24)

Hence, the quantity \( |N(A)| = \sqrt{a_1^2 + b_1^2}/A \) can be utilized as a measure of the amplitude-dependent gain.

The analysis can be extended to the case when \( \varphi(\cdot) \) is a different function than the unity mapping and \( y_0 \neq 0 \). However, if the complexity of the shaping function is increased, calculation of the required integrals has to be performed using numerical quadrature. The describing function analysis is performed for the model presented in Fig. 5 with the shaping function \( \varphi_2(v) \) in Eq. (16), whereby the offset and gain shown in Fig. 7 are obtained. In this analysis, the offset in the input signal has been chosen to \( y_0 = 70 \), which is in the middle of the working range of the piezo-actuators in the micro manipulator.

It is to be noted that no singularities are visible in the describing function within the amplitude range of interest, which is defined...
5. EXPERIMENTAL RESULTS

To the purpose of experimental verification, the feedforward controller based on the Prandtl-Ishlinskii operator, was implemented and tested on the experimental setup.

5.1 Experimental setup

The micro manipulator was interfaced via a dSPACE DS1103 system, where the sensor signals were read and the actuator signals were written. The control scheme was implemented in MATLAB Simulink, and then translated to C-code and compiled. The controller was installed in the dSPACE system and executed at a sampling frequency of 10 kHz.

5.2 Experimental verification of control scheme

The $x$-axis of the micro manipulator was chosen for evaluation of the proposed control scheme for the piezo-actuators. The results for the other axes are similar, and are therefore not presented here. The reference signals were of the format

$$v(t) = v_0 + A \sin(2\pi ft)$$  \hspace{1cm} (25)
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