Inferential Motion Control: Identification and Robust Control Framework for Positioning an Unmeasurable Point of Interest

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Abstract—Performance requirements in precision motion systems, including those used in IC manufacturing and printing systems, are ever increasing. For instance, internal deformations cannot be neglected anymore. As a result, measured signals at sensor locations cannot be used directly to evaluate performance at the point of interest. The aim of this paper is to develop an inferential motion control framework that explicitly distinguishes between performance variables and measured variables. In the proposed framework, a dynamic model is used to infer the performance variables from the measured variables. As the inferred performance variables depend on the model quality, an identification for robust inferential control approach is pursued that tightly captures the uncertainty. Experimental results on a prototype motion system reveal that ignoring internal deformations using traditional motion control design approaches can lead to disastrous performance at the point of interest. In addition, it is shown that the proposed inferential motion control framework leads to high performance at the unmeasurable point of interest.

I. INTRODUCTION

Increasing performance in precision motion systems necessitates distinguishing between performance and measured variables. Herein, measured variables refer to the sensor signals that are accessible by the feedback controller. The performance variables are the signals that are directly related to the system’s performance but are not directly accessible to the controller. These variables are not identical in inferential motion control problems, as the following examples reveal.

A first example arises in the production of integrated circuits (ICs), see Fig. 1. Here, a silicon disc is exposed in a photolithographic process. This wafer, which is a silicon disc, must be repeatedly positioned in all six motion degrees-of-freedom (DOFs) by the wafer stage using accurate sensors. Since the accuracy demands are tightening to the nanometer scale, the assumption that the system can be represented as a rigid-body, e.g., as in [1], is no longer valid. Hence, the internal deformations in between the point-of-exposure (performance variable) and the sensor position (measured variable) have to be explicitly taken into account, as is also argued in [2].

A second example is encountered in printer systems [3]. Here, the medium positioning drive positions the paper with respect to the carriage that contains the printheads. The measured variable is the motor position $y$, whereas the performance is clearly defined at the position where the carriage is located ($z$). Due to internal deformations in the medium positioning drive, high accuracy in terms of $y$ does not necessarily imply good printing performance. Due to increasing performance requirements, this effect is of vital importance in next-generation printing systems.

The main contribution of this paper is the development of a framework for identification and robust inferential control and its application to a prototype motion system, including the following steps:

1. controller structures for inferential motion control are derived;
The outline of this paper is as follows. In the next section, S5 a robust controller is designed and experimentally implemented, revealing the necessity of the presented inferential control framework in next-generation motion systems.

The following selection is made to show possible hazards in the inferential control situation and a solution. The goal is to control the translation of the center of the beam, i.e., at sensor location $s_2$, hence

$$z_p = s_2, \quad (1)$$

where $s_2$ is unavailable for the feedback controller. Regarding the measured variable, the center of the beam is determined by averaging the outer sensors $s_1$ and $s_3$, i.e.,

$$y_p = \frac{1}{2} \left[ \frac{1}{2} \right] \begin{bmatrix} s_1 \\ s_3 \end{bmatrix}, \quad (2)$$

which in fact corresponds to a sensor transformation based on static geometric relations as is indicated in Fig. 3. Consequently, a discrepancy between the measured variable $y_p$ and performance variable $z_p$ may exist due to internal deformations of the beam. Only the outer actuators are used for control, i.e.,

$$a_1 = a_3 = u_p, \quad a_2 = 0. \quad (2)$$

Comparing (1) and (2) reveals that $u_p$ and $y_p$ are collocated. The resulting system is given by

$$\begin{bmatrix} z_p \\ y_p \end{bmatrix} = \begin{bmatrix} P_z \\ P_y \end{bmatrix} u_p = P u_p, \quad (3)$$

where $z_p$ denotes the performance variable, $y_p$ is the measured variable, and $u_p$ is the manipulated input. The resulting control problem above has closely resembles the examples in Sec. I and is investigated further in this paper.

II. PROTOTYPE SETUP AND PROBLEM FORMULATION

A. Experimental setup

The high precision prototype motion system in Fig. 2 has been developed for evaluating control strategies in next-generation motion systems that exhibit dominant flexible behavior [2], [21]. The movable steel beam has dimensions $500 \times 20 \times 2$ mm. Four out of six motion DOFs have been fixed by means of leaf springs. Thus, the system can move $x$ and $\varphi$ direction indicated in Fig. 3. The inputs consist of 3 current-driven voice-coil actuators, whereas the outputs are 3 contactless fiberoptic sensors with a resolution of approximately $1 \mu m$, controlled using a PowerDAQ rapid prototyping with sampling frequency $f_s = 1 \ [kHz]$.

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where $z_p$ denotes the performance variable, $y_p$ is the measured variable, and $u_p$ is the manipulated input. The resulting control problem above has closely resembles the examples in Sec. I and is investigated further in this paper.

B. Nonparametric identification

To obtain insight for in the prototype motion system, frequency response function estimates of $P_{z,o}$ and $P_{y,o}$ for a certain frequency grid $\omega_i \in \Omega^{id}$ are obtained using the approach in [22] and [2, Appendix A], see Fig. 4. The nonparametric models in Fig. 4 lead to the following observations.

1) At 4 Hz and 10 Hz, two resonance phenomena are present. These correspond to the rigid-body modes of the flexible beam system. This conclusion is supported by the fact that $P_{z,o}$ and $P_{y,o}$, see (3), have an identical frequency response function at these frequencies, hence the beam does not internally deform at these frequencies.

2) $P_{y,o}$ has a $-2$ slope up to 300 Hz where the anti-resonance phenomena are directly followed by resonance phenomena. Typically, such behavior is obtained for mechanical systems with collocated actuator and sensor pairs [23]. Note that the delay is caused by the digital computer implementation and aliasing interaction phenomena appear beyond 300 Hz [24].
Assumption 1. During identification, both $z_{p}$ and $y_{p}$ are measured, whereas the controller only has access to $y_{p}$ during normal operation of the system. Assumption 1 is required to obtain the part of the model that corresponds to the performance variable $z_{p}$, since it cannot be measured in real-time and will thus be inferred using the model. This assumption is non-restrictive in many applications, including those in Fig. 1, and can also be relaxed by pursuing grey-box modeling.

The mathematical model of the true beam system in Fig. 2 is necessarily an approximation, since any physical system is too complex to be represented exactly by means of a model. In the inferential control case, the model quality is especially crucial, since the quality of the inferred performance variables hinges on the model quality. Model uncertainty is taken into account to guarantee that the model-based controller performs well when implemented on the true system. As in standard robust control designs [4], the model set $\mathcal{P}(\hat{P}, \Delta)$ is built up from a nominal model $\hat{P}$ and model uncertainty $\Delta$, where it is assumed that

$$P_{o} \in \mathcal{P}(\hat{P}, \Delta).$$

(5)

Associated with the model set is a worst-case control criterion

$$\mathcal{J}_{WC}^{9}(P, C) = \sup_{P \in \mathcal{P}} \mathcal{J}^{9}(P, C),$$

(6)

hence using (5), the performance guarantee

$$\mathcal{J}^{9}(P_{o}, C) \leq \mathcal{J}_{WC}^{9}(P, C)$$

is obtained. This leads to the following robust control design.

Definition 2. Given the model set $\mathcal{P}(\hat{P}, \Delta)$, determine

$$C^{R9} = \arg \min_{C} \mathcal{J}_{WC}^{9}(P, C).$$

(7)

The resulting robust controller (7) highly depends on the shape of the model set $\mathcal{P}(\hat{P}, \Delta)$. For instance, if the model set is large in some sense, an unnecessarily conservative control design results. Hence, the model set should be tight to achieve high performance. In this paper, this is done by considering the dual problem to the robust control synthesis problem in Definition 2, leading to the following robust-control-relevant model set identification problem.

Definition 3. Given a controller $C^{exp}$ that is used during the identification experiment, determine

$$\mathcal{P}^{R9} = \arg \min_{P} \mathcal{J}_{WC}^{9}(P, C^{exp})$$

subject to $P_{o} \in \mathcal{P}$. (8)

Several remarks are appropriate. First, the identification setting associated with (8) depends on the experimental conditions which are specified in the next sections. Second, in [6] and [7], related approaches have been presented that are restricted to the case where the set of measured variables is equal to the set of performance variables. Third, $\mathcal{P}^{R9}$ in (8) depends on $C^{exp}$. For the considered application, the standard PID controller in Fig. 9 is used. The performance can be iteratively and monotonously improved by alternating between identifying a model set and synthesising a robust controller, as in [6] and [7]. Fourth, as already mentioned in Sec. I, the identification of a nominal model $\hat{P}$ and quantification of model uncertainty $\Delta$ will be dealt with separately. In Sec. VI, it will be shown that these independent steps jointly minimize the criterion in Definition 3.

III. CONTROLLER STRUCTURES FOR INFERENTIAL MOTION CONTROL

The inferential control problem imposes additional requirements on the controller structure that are not encountered in traditional control applications. Suitable controller structures for inferential motion control are presented in this section, constituting Step S1 in Sec. I.
In the inferential servo control situation, the control goal is to let performance variable \( p \) track a certain reference \( z_{\text{ref}} \), given measurements \( y_p \). Note that in the typical non-inferential control situation, where \( y_p = z_p \), this is equivalent to the minimization of \( z_{\text{ref}} - y_p \), in which case a suitable control structure is obtained by using the error signal \( z_{\text{ref}} - y_p \) as input to the controller, as a result the single DOF feedback controller in Fig. 5 (a) is obtained. Here, \( r_2 \) should be selected as \( z_{\text{ref}} \), whereas \( r_1 \) is an additional signal used in the further analysis.

However, the single DOF controller structure is inadequate in the inferential servo problem, since

1) in general \( \dim z_p \neq \dim y_p \), e.g., both \( s_1 \) and \( s_2 \) can be used as measured signals, in which case an error signal cannot be computed based on a difference between \( z_{\text{ref}} \) and \( y_p \); and

2) even in case \( \dim z_p = \dim y_p \), then minimization of \( z_{\text{ref}} - y_p \) does not imply that \( z_{\text{ref}} - z_p \) is minimized. For example, the scaling of \( y_p \) in (1) is arbitrary, hence minimization of \( z_{\text{ref}} - y_p \) is not sensible in general.

3) joint tracking and disturbance attenuation may not be achievable. In particular, assume that \( P,C \) contains a factor \( \frac{1}{s} \), i.e., an integrator. Then, application of a step in either \( r_1 \) or \( r_2 \) leads to \( \lim_{t \to \infty} y_p = 0 \). Next, it can be immediately verified that application of a step in \( r_1 \) leads to \( \lim_{t \to \infty} z_p = 0 \), whereas a step in \( r_2 \) leads to \( \lim_{t \to \infty} z_p = P_{12}(0) r_2 \).

The deficiencies of single DOF controller structures in view of the inferential control problem are further elaborated on and exemplified in [26, Sec. 3.3].

Extended controller structures that can deal with the inferential servo control problem are depicted in Fig. 5 (b) and Fig. 5 (c). In Fig. 5 (b), also referred as the indirect approach, controller \( C_2 \) transforms the reference \( z_{\text{ref}} \) for \( z_p \) to a reference \( C_2 z_{\text{ref}} \) for \( y_p \). Clearly, this can resolve a scaling difference in the \( z_p \) and \( y_p \) variables. In addition, it appropriately deals with the situation \( \dim z_p \neq \dim y_p \). Similarly, the situation in Fig. 5 (c) corresponds to the case where \( C_2 \) reconstructs the performance variable \( z_p \) from the measured variable \( y_p \).

Although the controller structures in Fig. 5 (b) and (c) and Fig. 5 (d) can deal with inferential servo control and are intuitive to comprehend, a more detailed analysis of these controller structures reveals that these cannot be used directly in conjunction with standard optimization-based control algorithms [4]. Therefore, the unifying controller structure \( C = \begin{bmatrix} C_1 & C_2 \end{bmatrix} \), see also Fig. 5 (d), is adopted in the framework in this paper, since it encompasses (a), (b), and (c), and it enables the use of standard controller synthesis algorithms.

IV. \( \mathcal{H}_\infty \)-OPTIMAL INFERENTIAL CONTROL FRAMEWORK

A. Towards a nine-block setup

In this section, the general setup is presented and weighting filters are selected, thereby constituting Step S2 of this paper. The design of \( \mathcal{H}_\infty \)-optimal robust motion controllers involves the specification of the control goal in terms of exogenous signals and associated weighting filters. As the inferential problem is a significant extension of traditional motion control problems, including [1], [11], several modifications are required. Two requirements are imposed. The exogenous signals should be selected such that i) internal stability is guaranteed, and ii) various control requirements, e.g., loop-shaping requirements, can be appropriately specified. This extends pre-existing design strategies, including [4], [12], [1], [11], to the proposed controller structure in Sec. III and the explicit distinction between \( z_p \) and \( y_p \).

A selection of these inputs and outputs is presented in Fig. 6. Regarding the general weighting filter selection, the exogenous signals can be given the following interpretation: \( r_1 \) represents disturbances at the system input that have to be attenuated, \( r_2 \) represents measurement noise that should not be tracked, and \( r_3 \) represents the reference signal. In addition, \( e_2 \) is the tracking error, \( y_p \) is the system output, and \( u_p \) is the system input. Here, \( y_p \) and \( u_p \) should also remain bounded in view of internal stability of the feedback loop. The closed-loop transfer function matrices are given by

\[
\tau = \overline{M}(P,C)w
\]

\[
\overline{M}(P,C) = \begin{bmatrix} r_2 & T_1 \end{bmatrix} (I + C_2 P) \begin{bmatrix} C_1 & C_2 \end{bmatrix} - \begin{bmatrix} T_1 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}
\]

\[
w = \begin{bmatrix} r_2 \\ r_1 \end{bmatrix}
\]

In (9), \( T_1 \in \mathcal{R} \mathcal{H}_\infty \) is a reference model, which ensures a sensible problem formulation. Due to the specific structure in \( \overline{M}(P,C) \), the problem is referred to as a nine-block problem. The reasons for the specific structure are threefold.

First, the condition \( \tau \in \mathcal{R} \mathcal{H}_\infty \) is equivalent to internal stability of the closed-loop system, which is a basic requirement for a satisfactory control system. Second, the specific formulation directly fits in the standard plant formulation, enabling the use of standard optimization algorithms. Let \( \tau \) be defined by \( \left[ \begin{array}{c} \tau \\ u \end{array} \right] = \overline{G}(P) \left[ \begin{array}{c} w \\ u \end{array} \right] \), hence \( \overline{M}(P,C) = \mathcal{F}_{11}(\overline{G}(P),C) \).

Third, the setup in Fig. 6 enables a general weighting filter selection. In particular, the setup in Fig. 6 generally has to be extended with weighting filters to pose a sensible control problem. Let

\[
W = \begin{bmatrix} W_{0} & 0 & 0 \\ 0 & W_{2} & 0 \\ 0 & 0 & W_{3} \end{bmatrix}, \quad V = \begin{bmatrix} v_{0} & v_{0} & 0 \\ 0 & v_{2} & 0 \\ 0 & 0 & v_{1} \end{bmatrix},
\]

be bistable weighting filters and define

\[
z = W\tau, \quad w = Vw \]

\[
M(P,C) = W\overline{M}(P,C)V, \quad J^{\text{opt}}(P,C) = \| M(P,C) \|_{\infty}.
\]

The control criterion in (12) is considered throughout. The selection of inferential weighting filters is presented next in Sec. IV-B.

B. Weighting filter selection

In this section, weighting filter selection is considered, which is required prior to the control-relevant parametric identification procedure in Sec. V. The presented framework and associated
control criterion enable a large freedom in the selection of the control goal. In this paper, the focus is on loop-shaping feedback control and the weighting filters are designed such that these achieve similar control properties as in the design of single DOF feedback controllers, see [11] and [1]. Alternative signal-based approaches are pursued in [4].

The following steps lead to the design of the weighting filters. Throughout, the matrix \( M(P, C) \) is partitioned according to the signals in (10), i.e.,

\[
M(P, C) = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}. \tag{13}
\]

I) The weighting filters \( W_y, W_u, V_1, V_2 \) are designed using standard loop-shaping techniques as in [12], [11], and [1]. In particular, \( W_1 \) and \( W_2 \) are used to specify the desired loop-shape \( W_2 PW_1 \) and are absorbed into the system to enable controller roll-off and integral action. Note that

\[
W_y = W_2, \quad W_u = W_1^{-1}, \quad V_2 = W_2^{-1}, \quad V_1 = W_1.
\]

As loop-shaping requires knowledge of the system, the non-parametric estimate in Fig. 4 is employed for designing the weighting functions, see Fig. 7. This is in sharp contrast to pre-existing approaches, including [12].

II) \( W_e \) allows for additional scaling. Due to the fact that \( z_p \) and \( y_p \) are defined in the same unit and have approximately the same scaling, see (1) and Fig. 4, no additional scaling of the \( M_{12} \) and \( M_{13} \) blocks is required.

III) A suitable reference model \( T_f \) is selected. To enforce similar feedback properties for the two DOF controller as for the four-block problem, which is used in the traditional situation, including [12], [11], and the single DOF controller, a reference model \( T_f \) is chosen to have a low-pass characteristic with a bandwidth that corresponds to the desired closed-loop bandwidth in Step I. In addition, a sufficiently high roll-off rate is selected to avoid a nonproper optimal \( C_1 \).

IV) Next, weighting filters \( W_e = \beta_1, \quad V_3 = \beta_2 \) are defined, where \( \beta_1, \beta_2 \in \mathbb{R} \). These constants are set to \( \beta_1 = \beta_2 = 1.25 \) to emphasize the importance of the block \( M_{11} \) in (13).

By the specific selection of weighting filters, all blocks are (indirectly) scaled. The lower-right block in (13) represents the standard feedback controller part, whereas the upper-left block directly affects the inferential servo part, which can be relatively weighted using \( \beta_1 \) and \( \beta_2 \) as in [27].

V. PARAMETRIC SYSTEM IDENTIFICATION

The inferential controller will (implicitly) incorporate a model to predict the performance variables from the measured variables through the use of a model. Indeed, optimal controllers are typically observer-based [28], where the identified model is directly used. In this section, a new approach to identify a suitable model for (robust) inferential control is presented and applied to the prototype motion system, constituting Step S3.

A. Control-Relevant Identification

As is motivated in Sec. II-C, a control-relevant nominal model is estimated by virtue of Definition 3. However, control-relevant identification techniques, including the procedures in [13] and [7] are restricted to single DOF controller structures and to the situation where the set of performance variables equals the set of measured variables. Therefore, control-relevant identification techniques are extended appropriately, and the inferential-control-relevant identification criterion

\[
\|M(P_o, C^{\text{exp}}) - M(\hat{P}, C^{\text{exp}})\|_\infty \tag{14}
\]

is considered, which is to be minimized over \( \hat{P} \). Here, \( M(P_o, C^{\text{exp}}) \) is the closed-loop transfer function matrix defined in (11), where \( M \) in fact has already been identified to obtain the results in Fig. 4. In particular, since the system operates in closed-loop with \( C^{\text{exp}} \) implemented, \( M(P_o, C^{\text{exp}}) \) is identified for a certain frequency grid \( \omega_i \in \Omega^{\text{id}} \) using the approach in [22] and [2, Appendix A]. By appropriate manipulation of \( M(P_o, C^{\text{exp}}) \), frequency response function estimates of \( P_z, o \) and \( P_y, o \) have been obtained for \( \omega_i \in \Omega^{\text{id}} \), see Fig. 4.  

Note that details on the derivation of (14) are provided in [29]. In Sec. VI, it will be shown that the criterion in (14) indeed is useful to determine a robust-control-relevant model set \( P^{\text{RCR}} \) in view of Definition 3.

B. Control-Relevant Coprime Factor Identification

To appropriately extend the identified nominal model \( \hat{P} \) of the beam system with a perturbation model that represents model uncertainty, the internal structure of the model \( \hat{P} \) should be carefully specified. To anticipate on the model uncertainty structure in Sec. VI, the model is represented as a factorization

\[
\hat{P} = \begin{bmatrix} \hat{N}_z \\ \hat{N} \end{bmatrix} \hat{D}^{-1}, \tag{15}
\]

where \( \hat{N}_z \in \mathcal{RH}_{\infty} \) and \( \hat{N}, \hat{D} \) constitute a coprime factorization of \( \hat{P}_y \) over \( \mathcal{RH}_{\infty} \). Substitution of (15) into (14) reveals that the control-relevant identification criterion in (14) is invariant under a change of internal structure of the model \( P \). Following the developments in [29, Proposition 8], a particular coprime factorization results in a connection to the control-relevant
identification criterion in (14). In particular, this result states that (14) is equivalent to
\[
\| W \left( \begin{bmatrix} N_{z,o} \\ N_c \\ D_o \end{bmatrix} - \begin{bmatrix} \hat{N}_z \\ \hat{N}_c \\ \hat{D}_o \end{bmatrix} \right) \|_\infty,
\]
where
\[
\begin{bmatrix} \hat{N}_z \\ \hat{N}_c \\ \hat{D}_o \end{bmatrix} = \begin{bmatrix} P_x \\ P_y \end{bmatrix} (\hat{D}_c + \hat{N}_c v_2^{-1} P_y)^{-1}.
\]
and \{\hat{N}_c, \hat{D}_c\} is a left coprime factorization with co-inner numerator of \( \begin{bmatrix} C_1 V_3 \\ C_2 V_2 \end{bmatrix} \), \( \hat{N}_c = [\hat{N}_{c,3} \ \hat{N}_{c,2} \ \hat{N}_{c,1}] \).

C. Results

The criterion (16) can be minimized directly using the approach in [7]. The identified nonparametric factors \( N_{z,o}, N_z, \) and \( D_o \), are computed from the identified frequency response function \( M(P_o, C^{\exp}) \) for \( \omega_i \in \Omega_{31} \). Given these identified factors, the criterion in (16) is minimized over \( N_{z}, N_c, \) and \( D \).

The resulting nominal model \( \hat{P} \) in (15) is depicted in Fig. 8. Control-relevance can for instance be seen from the fact that the resonances within the controller bandwidth are accurately modeled, as well as the 180 Hz resonance that is known to endanger stability for typical control designs.

VI. MODEL UNCERTAINTY QUANTIFICATION

Inferential motion control depends on predictions of the performance variables through a model. This amplifies the need for addressing model uncertainty in a robust control design compared to traditional motion control [1], [6], [7].

In traditional motion control, the dual-Youla uncertainty structure has proved useful to minimize robust-control-relevant identification criteria of the form (8) where \( z_p = y_p \). In this paper, the recent extension of dual-Youla towards inferential control, as first presented in [29], is exploited.

In particular, the model uncertainty structure
\[
\left\{ P \mid \begin{bmatrix} \hat{N}_z + W_{c2}^{-1} \Delta z \\ \hat{N} + D_{c,22} \Delta o \end{bmatrix} (\hat{D} - \hat{N}_{c,2} \Delta o)^{-1}, \left\| \frac{\Delta o}{\Delta_o} \right\|_\infty \leq \gamma \right\}.
\]

is adopted, where \( \{N_{c,2}, D_{c,22}\} \) is any right coprime factorization of \( C^{\exp} \), see also Sec. V-A. The key point is that (17) guarantees that \( J^3_{WC}(P, C^{\exp}) \) in (8) remains bounded.

Next, using the specific factorization of \( \hat{P} \) that is identified in Sec. V in conjunction with a \( \{W_o, W_y\} \)-normalized right coprime factorization of \( C^{\exp} \), which can directly be computed using the state-space formulas in [7], the important result
\[
J^3_{WC}(P, C^{\exp}) \leq J^3(\hat{P}, C^{\exp}) + \sup_{\Delta \in \Delta} \| \Delta \|_\infty
\]

is obtained, see [29] for a proof. Clearly, the norm of \( \Delta \) directly affects the control criterion, leading to a transparent connection between nominal model identification, model uncertainty quantification, and robust control. The result (18) extends the result in [7] to the inferential situation, and constitutes Step S4.

To evaluate the model quality of \( \hat{P} \), the validation-based uncertainty modeling procedure as in [2] is applied to a large number of validation experiments. This leads to \( \sup_{\Delta \in \Delta} \| \Delta \|_\infty \leq 5.6 \).

The resulting model set (17) is formulated in an abstract coprime factor domain. To obtain insight in the open-loop model set \( P^{RRCR} \), it is visualized in Fig. 8. It appears that the model indeed is most accurate around the desired cross-over region at approximately 50 Hz and at the modeled resonance at approximately 180 Hz, see also Sec. V-C.

The performance of the model (set) can also be quantified in terms of the control criterion (6), see Table I. Clearly, (18) is satisfied, since \( J^3_{WC}(P^{RRCR}, C) = 201.38 \leq 196.82 + 5.6 \).

VII. ROBUST CONTROL DESIGN

Next, controller synthesis is performed for different situations. First, both the inferential situation, i.e., involving \( J^3 \), is considered, as well as the traditional non-inferential case, i.e.,
\[
J^3(P_y, C) = \left\| \begin{bmatrix} W_o & 0 \\ 0 & W_y \end{bmatrix} \begin{bmatrix} P_x \\ I + C P_y \end{bmatrix}^{-1} \begin{bmatrix} C \\ [V_2 \ 0] \end{bmatrix} \right\|_\infty
\]

where \( J^3_{WC} \) is defined analogous to (6). Second, both nominal controllers for \( \hat{P} \) and robust controllers for \( \hat{P} \) are computed using H\( \infty \)-optimization and skewed-\( \mu \) synthesis [2].

The resulting controllers are defined in Table I, including their computed performance. Bode diagrams of the controllers are shown in Fig. 9. Inspection reveals that the nominal controller achieves \( J^3(\hat{P}, C^{NPN9}) = 7.80 \), yet \( J^3_{WC}(P^{RRCR}, C^{NPN9}) = 70.54 \) is drastically higher. On the other hand, the robust controller achieves \( J^3(\hat{P}, C^{RPN4}) = 9.34 \) and \( J^3_{WC}(P^{RRCR}, C^{RPN4}) = 10.88 \). As \( J^3(\hat{P}, C^{RPN9}) \) is close to \( J^3(\hat{P}, C^{RPN4}) \) and \( J^3_{WC}(P^{RRCR}, C^{PNP9}) \) is close to \( J^3_{WC}(P^{RRCR}, C^{RPN4}) \), the controller is indeed robust control relevant.

Next, the controllers are implemented on both the model and the experimental setup. Only the results of \( C^{\text{exp}}, C^{\text{RPN4}}, \) and \( C^{\text{RPN9}} \) are shown. The implementation on the nominal
model is depicted in Fig. 10. Considering \( y_p \), it is observed that \( C^{\exp} \) has the slowest response. Clearly, the nominal four-block controller \( C^{RP4} \) significantly improves the response in terms of the measured variable \( y_p \). However, when considering the performance variable \( z_p \) in Fig. 10, it is observed that \( C^{RP4} \) deteriorates the true system performance compared to the initial \( C^{\exp} \). The key point is that the response \( z_p \) is not measured during normal operation. Hence, the control designer typically does not realize from measured data \( p y \) in the control loop that \( C^{RP4} \) in fact is performing poorly. In contrast, \( C^{RP9} \) leads to a very satisfactory response in terms of \( z_p \).

Furthermore, Fig. 10 reveals that \( C^{RP9} \) has a small oscillation in the \( y_p \) response at 0.07 s, see Fig. 10 (right). In Fig. 10 (left), the reason for this oscillation becomes clear: the trajectories of \( z_p \) and \( y_p \) are inherently related due to the use of only a single actuator \( u_p \), see (2), and the small oscillation is incorporated to deliver a good response in \( z_p \). Similar control inputs have been proposed in overhead cranes [30]. Concluding, the optimal inferential controller \( C^{RP9} \) is able to enhance the system performance, i.e., the response in terms of \( z_p \).

Finally, it is noted that these results on the nominal models are directly confirmed by inspecting Bode plots of

\[
[z_p] = \left[ \frac{P_z}{P_y} \right] (I + C_2 P_y)^{-1} C_1 r_3,
\]
details of which are omitted due to space limitations.

Next, the controllers have been implemented on the experimental beam setup and the responses have been measured, see Fig. 11 for responses in the \( z_p \) and \( y_p \) variables. The simulation results reliably predict the experimental results, which confirms that the model is control-relevant. Thus, \( C^{RP9} \) enhances the performance of the experimental beam system. In contrast, \( C^{RP4} \) deteriorates the system performance.

To further analyze the poor inferential performance corresponding to the controller \( C^{RP4} \), observe from Fig. 11 that the highly oscillatory behavior in the \( z_p \) variable contains a dominant frequency component that coincides with the resonance phenomenon in Fig. 4 at approximately 32 Hz. When comparing the response of the \( z_p \) and \( y_p \) variables, see Fig. 12, it is observed that the two variables are approximately in counter-phase. This confirms that the deformation shown in Fig. 3 causes the oscillatory response. Again, it is emphasized that the measured signal \( y_p \) does not provide any indication that the performance variable \( z_p \) is highly oscillatory.

VIII. CONCLUSIONS

The results presented in this paper enable the next step in precision motion control by explicitly taking the distinction between performance variables and measured variables into account. This step is necessary as internal deformations cannot be neglected in view of the required accuracy in future motion systems. The presented framework connects system identification and robust control design, as a model-based approach is essential for the inferential motion control problem.

The experimental results confirm the necessity of the proposed framework. A common robust \( H_\infty \)-loop-shaping controller \( C^{RP4} \) is shown to significantly enhance the response of measured variables. However, this deteriorates the actual

![Fig. 9. Bode diagram of controller: optimal robust nine-block inferential controller \( C^{RP9} \) (black solid), optimal robust four-block controller \( C^{RP4} \) (gray solid), and initial controller \( C^{exp} \) (black dashed).](image)

![Fig. 10. Step responses using nominal model: optimal robust nine-block inferential controller \( C^{RP9} \) (black solid), optimal robust four-block controller \( C^{RP4} \) (gray solid), and initial controller \( C^{exp} \) (black dashed).](image)

![Fig. 11. Experimental step responses: optimal robust nine-block inferential controller \( C^{RP9} \) (black solid), optimal robust four-block controller \( C^{RP4} \) (gray solid), and initial controller \( C^{exp} \) (black dashed).](image)

![Fig. 12. Experimental step responses using optimal robust four-block controller \( C^{RP4} \): The performance variable \( z_p \) (black solid) is oscillating in counter-phase with respect to the measured variable \( y_p \) (gray solid).](image)
performance variables. This is a potentially dangerous situation in high-precision systems, since the poor performance cannot be directly detected from the measured signals.

The proposed inferential motion framework effectively deals with the distinction between measured and performance variables. The key step is to use model knowledge to infer the performance variables from the measured variables.

This paper focuses on inferential feedback control, which is achieved through a reference model. This can be further enforced by a two-stage approach [31], structured controller optimisation, or designing a separate observer in the control structure of Fig. 5 (c) as is done in [32]. In addition, the present paper focusses on $H_\infty$-based control design, since model uncertainty is of key importance in motion control systems and the uncertainty in the model to predict the $z_p$ variable has been explicitly addressed.

The results can be directly generalised. For instance, direct extensions along the lines of [33], [34] are immediate, whereas implications towards ILC are recently investigated in [35]. Furthermore, the results in this paper might shed new light on ongoing challenges in motion systems, see [36], [37], [38], [2] for an overview. Current research focuses on the use of overactuation [21] to enhance inferential performance, addressing position dependent effects induced by position varying measurement of the mode shapes, and recently progress has been made on inferential control for thermal aspects in lithographic applications.

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