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Compensating quasi-static disturbances for inferential control: an observer-based approach applied to a wafer stage

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Increasing demands on positioning accuracy and throughput in high-tech motion systems leads to a situation where structural deformations are no longer negligible and need to be compensated for. This, in combination with a practical inability to measure directly at the position where performance is required, creates an inferential control problem where standard single degree-of-freedom (DOF) controllers are incapable of obtaining the required performance. The aim of this paper is twofold; to show that the single DOF controller structure is indeed inadequate and propose a method that is capable of dealing with complicated inferential control problems. The proposed method extends the single DOF controller structure with an augmented observer in an intuitive fashion. Finally, the method is applied to a lightweight motion system showing that it is capable of dealing with structural deformations in an inferential control problem.

Keywords: Advanced motion control, Inferential control, Observer-based control, Two degree-of-freedom control, disturbance-observer

1. Introduction

In high-precision motion systems it is often not possible to directly measure at the location where performance is required. Therefore, these unmeasured performance variables need to be inferred from non-collocated sensor measurements. If flexible dynamic behavior is negligible, then a rigid-body approximation can be used to compute the desired variable by means of a static transformation [4]. However, due to increasing positioning accuracy in next-generations motion systems, structural deformations which are possibly induced by unknown disturbances as shown in Fig. 1, need to be explicit compensated for. This leads to a complicated inferential control problem.

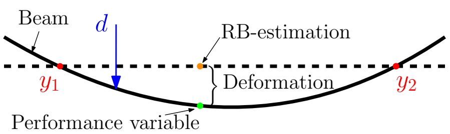

Fig. 1. Beam example, with disturbance d and sensors y_1 and y_2 leading to an inferential control problem.

Although recently substantial progress has been made on the topic of inferential control [1] [2] [3], exogenous (quasi-static) disturbances cannot be handled. The aim of this paper is to (i) indicate why the conventional controller structure is not suitable for inferential control (section 2); (ii) propose an observer-based method that is capable of addressing structural deformations for inferential control (section 3); (iii) validate the method on a light-weight motion system (section 4).

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2. Problem definition

The conventional single degree-of-freedom (DOF) controller structure is depicted in Fig. 2, where the plant P is given by

$$\begin{bmatrix} z_p \\ y_p \end{bmatrix} = \begin{bmatrix} P_{zd} & P_{zu} \\ P_{yd} & P_{yu} \end{bmatrix} \begin{bmatrix} d \\ u \end{bmatrix} \quad (1)$$

in which y_p are measured signal(s), z_p unmeasured performance signal(s), d disturbance(s) and u the control input(s). The control goal is defined as; *minimize the positioning error* $e_z(t) = r_z(t) - z_p(t)$ *given a reference* $r_z(t)$ *and in the presence of an unknown disturbance* $d(t)$.

To set up the framework, assume for the moment that the performance variable is directly measured and deformations are negligible, as in conventional control, i.e., $z_p = y_p$. Then, the positioning error is given by $e_z = e_y = r_z - y_p$, and can be written as,

$$e_y = S_o \begin{bmatrix} I & -P_{yd} \end{bmatrix} \begin{bmatrix} r_z \\ d \end{bmatrix}, \quad (2)$$

where $S_o = (I - P_{yu}K)^{-1}$ is the output Sensitivity. Note that the positioning error e_y is split up in reference-induced and disturbance-induced errors. Both are simultaneously minimized by minimizing the (output) Sensitivity function, which is achieved by high-gain feedback.

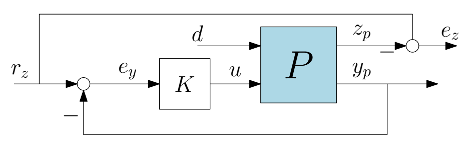

Fig. 2. Conventional single DOF controller structure.

Now consider the case where deformations are not negligible, i.e., assume that $y_p \neq z_p$. The positioning error is then expressed as,

$$e_z = \begin{bmatrix} S_z & -T_{zd} \end{bmatrix} \begin{bmatrix} r_z \\ d \end{bmatrix} \qquad (3)$$

in which $S_z = I - P_{zu}KS_o$ and $T_{zd} = P_{zd} - P_{zu}KS_oP_{yd}$. Hence if $y_p \neq z_p$, then (3) is not minimized by minimizing S_o, i.e., by high-gain feedback. This is clarified by means of the following example.

Example 1 *Suppose that the goal is to obtain zero steady state tracking error with* $y_p \neq z_p$, *i.e.,* $\lim_{t\to\infty} e_z(t) = 0$. *Furthermore,* $r(t)$ *and* $d(t)$ *are step signals, i.e.,* $r(t) = r_0 \cdot 1(t)$ *and* $d(t) = d_0 \cdot 1(t)$, *and all transfer functions are SISO. Using the Final Value Theorem and Laplace transforms of the inputs, this can equivalently be written as*

$$\lim_{s\to 0} s \cdot e_z(s) = S_z(0)r_0 - T_{zd}(0)d_0 = 0. \qquad (4)$$

The error is split up in (a) reference induced errors and (b) disturbance induced errors. Part (a) can be set to zero with a specific controller K_r. *The same holds for part (b), with controller* K_d.

$$K_r = \frac{1}{P_{zu} - P_{yu}}, \; K_d = \frac{-P_{zd}}{P_{zd}P_{yu} - P_{zu}P_{yd}}. \qquad (5)$$

Note that K_d *and* K_r *are completely determined by plant dynamics and* $K_d \neq K_r$. *Therefore, it is not possible to find one controller that attenuates both (a) and (b) simultaneously.*

For a detailed analyses see [3]. From this example it can be concluded that there does not generally exist a single DOF controller that is capable of attenuating both disturbance-induced and reference-induced errors simultaneously, implying that additional design freedom is required.

3. Two degree-of-freedom controller structure

Example 1 confirms that additional controller design freedom is essential if the performance variable is not measured. This is provided in 2-DOF controller structures, of which several types are encountered in literature [5] [2]. More details about these structures can be found in [2]. In this work the observer-based controller architecture in Fig. 3 is explored. This structure allows to split the control problem in (1) an

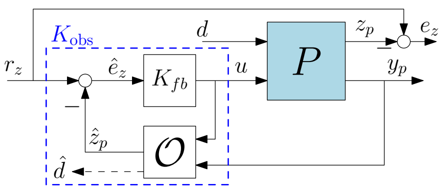

Fig. 3. Observer-based 2-DOF controller structure.

estimation problem and (2) feedback controller design an in intuitive fashion which simplifies 2-DOF controller design. First an augmented-observer ($\mathcal{O}$) creates an accurate estimate $\hat{z}_p$ of the performance variable [1], secondly a feedback controller (K_{fb}) is designed. Using this observer-based controller structure, the controller K_{fb} is fed with an estimate of the performance variable, i.e., $e_{\hat{z}}$, which is similar to the conventional case, where K is fed with e_y. Therefore, the role of K_{fb} is similar to K meaning that the high-gain feedback design principles are once again applicable using this controller architecture, which facilitates controller design. Note that for stability analysis the observer must be taken into account.

4. Experimental results and conclusions

In this section, the observer-based method as proposed in Section 3, and the conventional control method are applied to the light-weight motion system depicted in Fig. 4. The goal

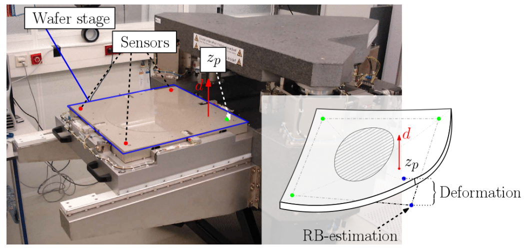

Fig. 4. Prototype wafer stage and schematic representation of the deformation.

of the experiment is to control the unmeasured performance variable (z_p), while an unknown quasi-static disturbance d acts on the system and a reference signal r_z is present. An $\mathcal{H}_\infty$-optimal approach is used to synthesize the feedback controllers for both cases, and the method in [1] is used to obtain the augmented observer. A static disturbance is applied to the system and the resulting positioning error $e_z = r_z - z_p$ is depicted in Fig. 5. The results show that the proposed observer-

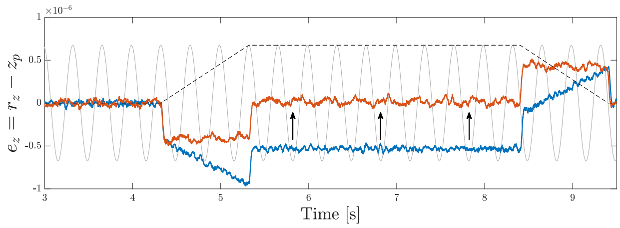

Fig. 5. Positioning error e_z obtained with conventional controller (blue) and inferential controller (red), reference (gray) and disturbance (dashed gray).

based method eliminates the (quasi-) static positioning error resulting from the structural deformation. While the conventional controller is incapable of dealing with this deformation. It is concluded that the proposed method is capable of estimating and attenuating the structural deformations in an intuitive fashion, resulting in a major performance increase.

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