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Exploiting additional actuators and sensors for nano-positioning robust motion control

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ABSTRACT

The ongoing need for miniaturization and an increase of throughput in IC-manufacturing is obstructed by performance limitations in motion control of nano-positioning wafer stages. These limitations are imposed by flexible dynamical behavior, associated with structural deformations of the nano-positioning stages. The aim of this research is to investigate limits on achievable performance in a conventional control configuration and to mitigate these limits through the use of additional actuators and sensors. To this end, a systematic framework for control design using additional actuators and sensors in the generalized plant configuration is presented, which leads to a well-posed $\mathcal{H}_\infty$-control optimization problem that extends conventional design approaches in a natural way and exploits physical insight to address structural deformations in weighting filter design. Through an experimental confrontation of the design framework with a prototype next-generation nano-positioning motion system, successful performance enhancement beyond the conventional limits is demonstrated.

1. Introduction

In the near future, the demand for high machine throughput of nano-positioning systems necessitates explicit control of flexible dynamical behavior. An important application domain where positioning with nanometer accuracy plays a central role is the lithography step in IC-manufacturing, see, e.g., [1]. Herein, a desired IC-pattern is etched into a photosensitive layer on a substrate, using a device known as a wafer scanner [2]. For this purpose, the substrate, a silicon wafer, is placed on top of a wafer stage that facilitates the positioning with respect to the light source, see Fig. 1. On the one hand, a nanometer positioning accuracy has to be achieved in view of the required feature size of current ICs. On the other hand, it is vital for market viability of wafer scanners to achieve a high machine throughput. Since a high throughput demands for large accelerations of the wafer stage, next-generation stages are designed to be lightweight, as is further motivated in [3]. However, lightweight stages tend to undergo structural deformations upon large accelerations, which obstruct the intended positioning accuracy. Therefore, it is essential to explicitly address the flexible dynamical behavior that induces structural deformations in control design.

Flexible dynamical behavior of lightweight positioning stages leads to limitations on the achievable motion performance. Fundamental performance limitations for feedback control are formulated in terms of sensitivity integrals, which depend on right-half plane poles and zeros of the system, [4,5]. Extensions of these classical results towards the generalized plant framework for model-based control are provided in, e.g., [6,7]. In turn, the generalized plant framework encompasses two degree-of-freedom control configurations, as for example used in inferential control to account for unmeasured performance variables [8]. Fundamental performance limitations for such two degree-of-freedom control are derived in [9].

Although fundamental performance limitations are well-understood, the standard formulation does not immediately indicate that performance limitations in motion control result from structural deformations. For example, flexible dynamical behavior does not necessarily induce right-half plane poles and zeros, to which bandwidth limitations have been associated, see [10, Section 5.7, 5.9]. Nevertheless, it is known from practical experience that the attainable bandwidths in motion control are dominantly restricted by flexible dynamical behavior, as is also observed in [11–13]. To formalize this limitation, it is essential to explicitly involve model

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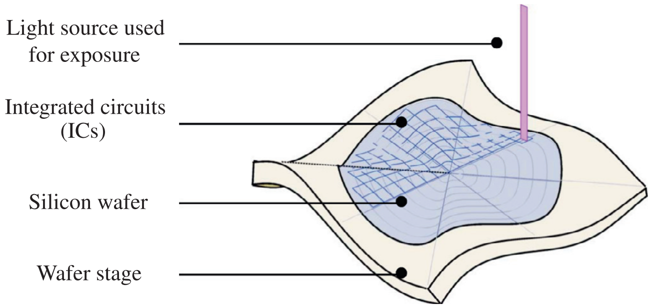

Fig. 1. Schematic illustration of flexible dynamics in a wafer stage.

uncertainty, see [14] and [10, Section 5.3.2]. This motivates a robust control perspective, in which performance-robustness trade-offs can be addressed systematically.

The goal of this paper is (i) to further investigate limitations on robust performance for a traditional control configuration, and (ii) to develop a systematic robust control design approach to go beyond these limits through active control of flexible dynamical behavior by means of additional actuators and sensors. Specifically, the main contributions are the following.

(C1) Using the generalized plant framework, it is supported that an extension of the conventional (rigid-body) control configuration with additional control inputs and outputs facilitates performance enhancements.
(C2) The classical performance-robustness trade-off is analyzed for the class of lightweight motion systems, revealing that flexible dynamical behavior limits the achievable performance.
(C3) Based on physical insight, it is revealed that through active control of flexible dynamical behavior, new freedom for improvement of motion performance beyond conventional limits is obtained.
(C4) A novel weighting filter design framework for $\mathcal{H}_\infty$ control design is proposed, that exploits the freedom provided by additional actuators and sensors in an automated robust performance optimization.
(C5) The design framework is applied to an industrial high-precision motion system.

Throughout, the system's inputs and outputs are assumed to be pre-selected, see Section 9.2 for further discussion.

This paper shows that active compensation of flexible dynamical behavior through control yields opportunities for enhancement of motion performance in terms of bandwidths. In fact, from a mechanical point of view, structural properties of the flexible motion system such as damping and stiffness are modified. In that aspect, the proposed framework is related to combined optimization of system and controller dynamics as considered in, e.g., [15–18]. The proposed framework extends existing approaches for robust performance optimization of systems with lightly damped modes in the controller cross-over region, see, e.g., [19–21]. These earlier results are mainly directed towards damping of flexible dynamics to prevent undesired vibrations. However, in motion control of nano-positioning devices, attenuation of structural deformations is merely a partial solution that enables an increase of motion control bandwidths to facilitate a high machine throughput and nanometer positioning accuracy.

The paper is organized as follows. In Section 2, the generalized plant framework is used to show that additional actuators and sensors potentially yield performance enhancement (C1). Then, in Section 3, performance limits for motion systems, associated with flexible dynamical behavior, are derived (C2). To address these limits in an extended control configuration, theoretical aspects of the generalized plant are addressed in Section 4. Subsequently, in Section 5, based on physical insight, an approach is proposed that exploits the additional actuators and sensors to counteract undesired deformations on the system (C3). In Section 6, this design approach is formalized in a loop-shaping framework for weighting filter design in $\mathcal{H}_\infty$ control (C4). Subsequently, this framework is confronted with an industrial high-precision positioning device in Section 8, where performance enhancement beyond conventional limitations is successfully shown (C5). Conclusions are drawn in Section 9.

Notation. *Matrices are tacitly assumed to be partitioned in accordance with signal dimensions. A unified theory is developed that applies to both continuous-time and discrete-time systems.*

2. Problem formulation and basic concept

2.1. Experimental setup

The experimental setup consider in this paper is a prototype lightweight wafer stage depicted in Fig. 2. The purpose of this device is to position a wafer, on top of which ICs are to be produced, with respect to a light source, see again Fig. 1. To increase productivity, the IC manufacturing industry is currently moving towards the use of wafers with a diameter of 450 mm. Therefore, the wafer stage shown in Fig. 2 has dimensions 600 × 600× 60 mm, such that it can actually hold a 450 mm wafer. At the same time, the system has been designed to be lightweight, as it weighs 13.5 kg only. Although lightweight system design is important to enable very fast accelerations of the wafer stage in production machines, it also makes active control of structural deformations indispensable.

2.2. Problem formulation

The first goal of this paper is to systematically analyze performance limitations that are induced by flexible dynamical behavior. This is relevant in traditional control configurations, in which the rigid-body motion degrees-of-freedom (DOFs) of the wafer stage are controlled.

The second goal of this paper is to go beyond the limits of a traditional control configuration by explicitly accounting for flexible dynamical behavior in control design. In particular, to counteract undesired structural deformations of the wafer stage, control using a large number of actuators and sensors is investigated. Therefore, the system has been designed such that there are abundant opportunities for actuator placement. In particular, Lorentz-actuators can be easily mounted at 81 distinct locations underneath the stage, see Fig. 3. With respect to sensors, linear encoders with nanometer resolution are available for position measurements at all four corners of the stage. Indeed, the use of additional control

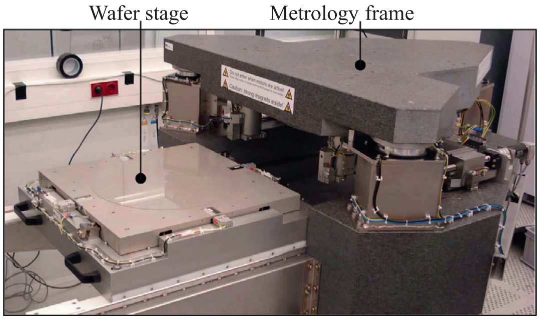

Fig. 2. A prototype lightweight wafer stage, enabling high accelerations.