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Editorial

Introduction to the special issue on control of high-precision motion systems

Driven by increasing societal, economic, and technological pressures, high-precision motion systems must achieve ever increasing speed and accuracy requirements. Motion systems are used in many different application areas, including hard disk drives (HDDs) in consumer electronics, wafer steppers and scanners in nano-scale manufacturing machines, electron and atomic force microscopes for nano-scale imaging, and (nano-) printing devices. Despite the large differences in the application areas, these motion systems share a common aspect: control is essential for achieving the speed and accuracy requirements.

The main goal of this special issue is to bring together the control challenges encountered in different high-precision motion systems that are of current interest. These challenges include modelling of complex and high-dimensional dynamics, feedback and tracking control, feedforward and model inversion, position-dependent and time-dependent behavior of both system dynamics and disturbances, flexible system behavior and spatial performance, nonlinear dynamics and control, and repetitive versus non-repetitive disturbances.

Overall, 34 manuscripts have been received. All manuscripts have been thoroughly reviewed, and a total of 18 resulting papers have been accepted and included in this special issue. The papers are ordered according to the following aspects: (1) feedforward design and learning, (2) feedback design and flexible systems, (3) optimal control, (4) nonlinear systems, (5) disturbance analysis, observation, and control.

Feedforward design and learning. In Altin and Barton [1] a signal-based iterative learning control scheme based on $\mathcal{L}_1$ adaptive feedback is presented. The proposed scheme effectively deals with parametric uncertainties, and is demonstrated to achieve high performance in a simulation study on a motion system. An extension to filter-based feedforward control and input shaping is presented in Boeren et al. [3]. The authors show that the proposed extension enables high performance for point-to-point stage positioning while avoiding a full plant inversion and its related stability issues. In addition, a data-driven tuning procedure is proposed and implemented on an industrial motion system. Aspects of input shaping are also considered by Yang et al. [17] with a focus on high bandwidth tracking control. The authors successfully implemented their method on a piezoelectric stage, achieving a significant increase in tracking bandwidth. A paradigm shift from feedforward control for rigid-body positioning systems to flexible systems is presented by Ronde et al. [13]. The authors propose a spatial feedforward controller to address the position-dependent stage dynamics over an entire surface instead of only optimizing the performance at the sensor location, as is traditionally done in data-driven feedforward tuning algorithms.

Feedback design and flexible systems. In terms of feedback control, Salt and Tomizuka [14] demonstrate the effect of multi-rate control in hard disk drives (HDDs). The authors present a framework based on a lifting procedure, and experimentally compare the proposed approach with a classical single-rate controller implementation. Next, integral force feedback control and structured PI tracking control are compared by Teo et al. [15] on an objective lens positioner. In the context of atomic force microscopes (AFMs) and stage positioning, Karvinen and Moheimani [11] present a new Q control concept, which is based on the principles of modulation and demodulation. The authors successfully demonstrate the results on an experimental setup, revealing significant improvements in scan speed and image quality. Stage positioning is also the topic of Hoogendijk et al. [8] who present a loop-shaping notch filter design procedure for flexible motion systems, so-called spatial notching. The authors effectively take into account the multivariable aspect of deformations in a manual design procedure and illustrate the results on a flexible beam setup. Through a passive approach, Verbaan et al. [16] present a tuned-mass-damper design that achieves broad-band damping for these generally lightly-damped flexible systems. This work is done in the context of improved wafer scanning and next-generation wafer stage design.

Optimal control. To overcome traditional performance limitations imposed by flexible dynamics, Van Herpen et al. [7] propose a framework to exploit extra sensors and actuators for precision motion control. To deal with the increasing system complexity, a systematic optimal control framework is proposed that in a robust manner accounts for model errors. Returning to the field of HDDs, Chamanbaz et al. [4] present the design of a probabilistic robust track-following controller. The probabilistic framework provides a computationally tractable solution for such robust control design problems. The presented framework is experimentally applied to a commercial HDD, thereby providing robust performance in the presence of model uncertainties. Finally, an optimal data-driven nonlinear control design procedure for linear motion systems is proposed by Hunnekens et al. [10]. The authors show that an optimised piecewise linear controller leads to improved performance using techniques from machine-in-the-loop optimization. The results are demonstrated on the wafer stage systems of a state-of-the-art lithography machine.

Nonlinear systems. To avoid reticle slip in lithography systems, nonlinear effects in piezoelectric devices are inventively dealt with

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by Amin-Shahidi and Trumper [2]. In the presented mechatronic design of a reticle assist device, self-sensing contact detection and charge control with hybrid hysteresis compensation form two aspects that avoid the need of sensors and that support the open-loop control design approach. Piezoelectric properties are also addressed in Khoury Moussa et al. [5] who discuss the modelling and control of a microactuator with proprioceptive sensing capabilities. Topology optimization using observability-based criteria, modal observation of the flexible structure, and the optimal integration of piezoelectric actuation and sensor capabilities form the core aspects of this work. Nonlinear aspects in the form of hysteretic behavior are analyzed and effectively compensated using the Prandtl-Ishlinskii static hysteresis model. The effects of friction are addressed in Yoon and Trumper [18], especially regarding identification, modelling, and compensation. The friction parameters needed for the feedforward model are identified with the so-called Dahl resonance method that is performed in the frequency domain. Model-based feedforward control is effectively demonstrated on an experimental setup including an Aerotech servomotor, encoder, and motor driver.

Disturbance analysis, observation, and control. Disturbance modelling and control in high-acceleration motion control systems with permanent magnet linear synchronous motors are addressed by Liu et al. [12] who design a disturbance observer for this purpose. In terms of time-domain identification, a relay feedback test is discussed to determine the parameters of the model to be identified. Hoogerkamp et al. [9] present an observer design to counter the effects of dynamic links like hoses for coolant and wires for electrical signals associated with stages for lithography machines. By rewriting the observer structure into an internal model control problem, they show that the design boils down to designing an observer that is sufficiently robust to modelling error. The control of nanopositioning systems in general heavily relies on the ability to measure with sufficient resolution. This aspect is addressed in the work of Fleming [6] where the foremost noise sources in a nanopositioning motion system are identified. The paper also describes a voltage technique in which only one recording and filtering operation is needed to predict closed-loop resolution. The paper provides the valuable and practical means for measuring and predicting resolution in the context of high-precision motion system.

We believe that the special issue provides a clear overview of many aspects of the control challenges in precision motion systems. We hope that academic and industrial readers in both the control community and the broader area of mechatronic design will appreciate the selection of papers and benefit from the contributions.

References

[1] Altin B, Barton K. Robust iterative learning for high-precision motion control through $\mathcal{L}_1$ adaptive feedback 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.04.007.

[2] Amin-Shahidi D, Trumper DL. Design and control of a piezoelectric driven reticle assist device for prevention of reticle slip in lithography systems 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.03.001.

[3] Boeren F, Bruijnen D, Van Dijk N, Oomen T. Joint input shaping and feedforward for point-to-point motion: automated tuning for an industrial nanopositioning system 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.03.005.

[4] Chamanbaz M, Keikha E, Venkataramanan V, Al Mamun A, Wang Q-G. Design of a probabilistic robust track-following controller for hard disk drive servo systems 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.02.007.

[5] El Khoury Moussa R, Grossard M, Boukallel M, Hubert A, Chaillet N. Modeling and control of a piezoelectric microactuator with proprioceptive sensing capabilities 2014. http://dx.doi.org/10.1016/j.mechatronics.2013.12.002.

[6] Fleming AJ. Measuring and predicting resolution in nanopositioning systems 2014. http://dx.doi.org/10.1016/j.mechatronics.2013.10.003.

[7] Van Herpen R, Oomen T. Exploiting additional actuators and sensors for nano-positioning robust motion control 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.03.008.

[8] Hoogendijk R, Heertjes MF, Van de Molengraft MJG, Steinbuch M. Directional notch filters for motion control of flexible structures 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.01.011.

[9] Hoogerkamp M, Waiboer RR, Van Dijk J, Aarts RGKM. Attenuation of disturbances introduced by dynamic links in precision motion systems using model-based observers 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.04.006.

[10] Hunnekens BGB, Heertjes MF, Van de Wouw N, Nijmeijer H. Performance optimization of piecewise affine variable-gain controllers for linear motion systems 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.02.011.

[11] Karvinen KS, Moheimani SOR. Modulated-demodulated control: Q control of an AFM microcantilever 2014. http://dx.doi.org/10.1016/j.mechatronics.2013.11.011.

[12] Liu C, Wu J, Liu J, Xiong Z. High acceleration motion control based on a time-domain identification method and the disturbance observer 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.01.001.

[13] Ronde MJC, Leenknegt GAL, Van de Molengraft MJG, Steinbuch M. Data-based spatial feedforward for over-actuated motion systems 2014. submitted for publication.

[14] Salt J, Tomizuka M. Hard disk drive control by model based dual-rate controller – computation saving by interlacing 2014. http://dx.doi.org/10.1016/j.mechatronics.2013.12.003.

[15] Teo YR, Russell D, Aphale SS, Fleming AJ. Optimal integral force feedback and structured PI tracking control: application for objective lens positioner 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.04.004.

[16] Verbaan CAM, Rosielle PCJN, Steinbuch M. Broadband damping of non-rigid-body resonances of planar positioning stages by tuned mass dampers 2014. http://dx.doi.org/10.1016/j.mechatronics.2013.12.013.

[17] Yang M-J, Gu G-Y, Zhu L-M. High-bandwidth tracking control of piezo-actuated nanopositioning stages using closed-loop input shaper 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.02.014.

[18] Yoon JY, Trumper DL. Friction modeling, identification, and compensation based on friction hysteresis and Dahl resonance 2014. http://dx.doi.org/10.1016/j.mechatronics.2014.02.006.

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