Article Identifier
DOI: 10.22032/dbt.58700
URN: urn:nbn:de:gbv:ilm1-2023isc-121:7

60^{th} ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 4 – 8 September 2023
URN: urn:nbn:de:gbv:ilm1-2023isc:1

ROBUST ADAPTIVE TRACKING CONTROL FOR HIGHLY DYNAMIC NANOPRECISION MOTION SYSTEMS

Alex S. Huaman[†], *Johann Reger*[‡]

[†] IMMS Institut für Mikroelektronik- und Mechatronik- Systeme gemeinnützige GmbH (IMMS GmbH), 98693 Ilmenau, Germany
[‡] Control Engineering Group, Technische Universität Ilmenau, 98693 Ilmenau, Germany

ABSTRACT

This abstract focuses on the design and real-time implementation of advanced control strategies for motion systems with highly dynamic nanopositioning capabilities [1]. The key exemplar is the lifting and actuating unit (LAU), which integrates a pneumatic actuator for weight force compensation and a parallel electromagnetic drive to produce precision motion forces. Initial investigations cover the modeling and parametric identification of the overactuated nature of a single LAU [2]. This lifting module, integrated into a test bench, renders a 1D vertical motion system aimed to perform subnanometer positioning tasks while minimizing heat emission. To this end, we propose a control allocation strategy to assign (zero-mean) high-dynamic forces to the electromagnetic channel, producing a very low heat emission while the performance is fulfilled using an LQ-type controller plus an L_1 adaptive augmentation [3]. This investigation closes with RMS positioning errors less than 0.25 nm and electrical currents less than 0.30 mA. Further investigations involve a 3D tilt-and-lift vertical motion system integrating three LAUs, each placed in each corner of a triangular payload. The key challenge of this configuration is to cope with the high cross-couplings between the degrees of freedom (DOF), i.e., vertical and rotational motion. The core of the decoupling task is the nominal LQG-type controller comprising disturbance-rejection-based observers aimed to fully compensate cross-couplings, while the L_1 adaptive augmentation recovers the nominal performance in the presence of parametric uncertainties w.r.t. the input gain [4]. Given that the heat emission problem is fully solved for a single LAU (see [2] and [3]), we then focus on the performance and robustness of the 3D closed-loop system. Since full-state information of the cross-couplings is not simple to reconstruct, we adopt the output-feedback control architecture for the nominal controller and L_1 adaptive augmentation [4]. The effectiveness of the proposed control strategy is verified via real-time experimentation rendering vertical RMS positioning errors of less than 0.25 nm and RMS rotational errors of less than 0.04 µrad while satisfying the heat emission constraint.

The investigations conclude by exploring the outstanding performance/robustness trade-off of the L_1 adaptive control theory for a nanometer planar positioning system with a travel range of ø200 mm (i.e., NPPS200) and the subsequent integration with the 3D vertical motion system, thereby transitioning to a full 6D system (i.e., NPPS200-6D) with 25 mm vertical stroke. Within this framework, the complexity of the controller design is higher because of the number of DOF, cross-couplings, external disturbances, and parametric perturbations. We completed our investigations through experimental validation with planar and vertical RMS positioning errors of less than 0.80 nm and RMS rotational errors of less than 0.05 µrad, as shown in Figure 1.

Index Terms – Nanopositioning and nanomeasuring machines, motion control systems, adaptive control, decoupling problem, disturbance rejection, overactuated systems

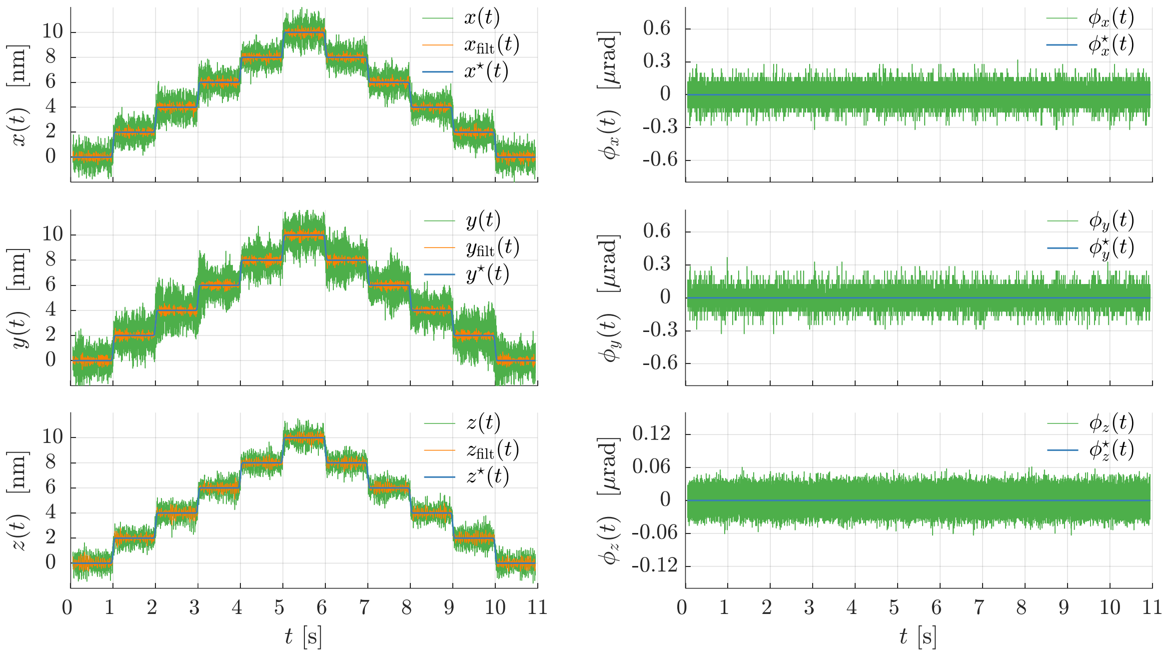

Figure 1: Raw data of $x(t)$, $y(t)$, $z(t)$, $\phi_x(t)$, $\phi_y(t)$, $\phi_z(t)$. Time series for 2 nm planar and vertical motion (steps) in closed-loop operation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG) in the framework of the Research Training Group “Tip- and Laser-Based 3D-Nanofabrication in Extended Macroscopic Working Areas” (GRK 2182) at the Technische Universität Ilmenau, Germany.

REFERENCES

[1] A.S. Huaman, M. Katzschmann, S. Hesse, C. Schäffel, C. Weise, D. Dontsov, E. Manske, and J. Reger, “Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control,” 2021 IEEE International Conference on Mechatronics (ICM), Kashiwa, Japan, pp. 1-6, 2021.

[2] A.S. Huaman, and J. Reger, “Robust Tracking Control with L_1 Adaptive Augmentation for a Long-Stroke Vertical Nanopositioning System: Part I,” 2022 IEEE Conference on Control Technology and Applications (CCTA), Trieste, Italy, pp. 614-620, 2022.

[3] A.S. Huaman, and J. Reger, “Robust Tracking Control with L_1 Adaptive Augmentation for a Long-Stroke Vertical Nanopositioning System: Part II,” 2022 IEEE Conference on Control Technology and Applications (CCTA), Trieste, Italy, pp. 621-627, 2022.

[4] A.S. Huaman, and J. Reger, “Robust Adaptive Tracking Control of a 3D Vertical Motion System for Nanometer Precision Applications,” IFAC World Congress 2023, Yokohama, Japan, 2023, accepted.

CONTACTS

M.Sc. A.S. Huaman	email: alex.huaman@imms.de
Prof. Dr.-Ing. J. Reger	email: johann.reger@tu-ilmenau.de