Motion Control, Precision Mechatronics, and Robotics in Advanced Manufacturing

Xu Chen

Assistant Professor

Department of Mechanical Engineering

University of Conneticut

www.engr.uconn.edu/~xchen

www.xchen.lab.uconn.edu

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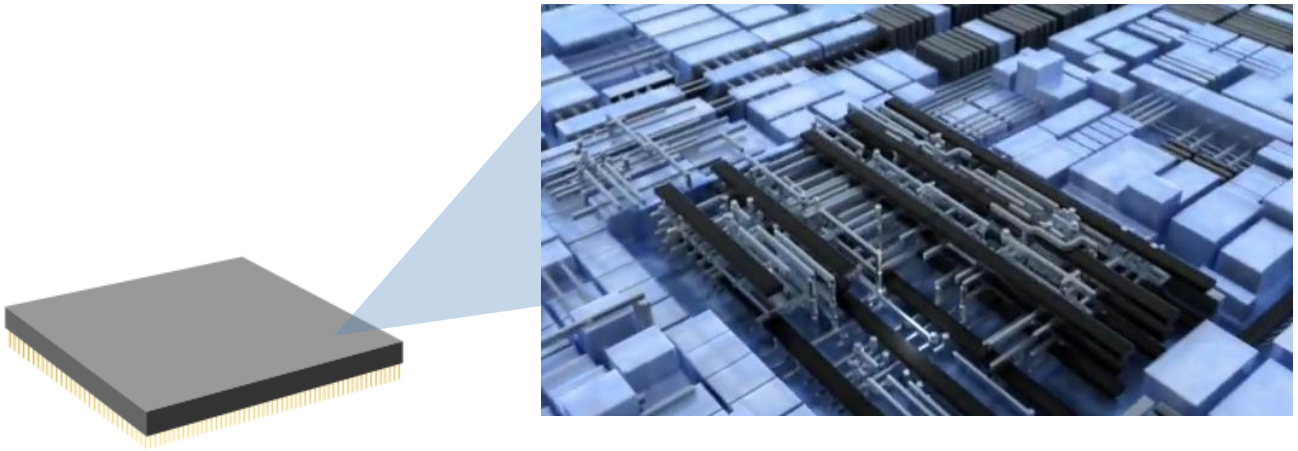
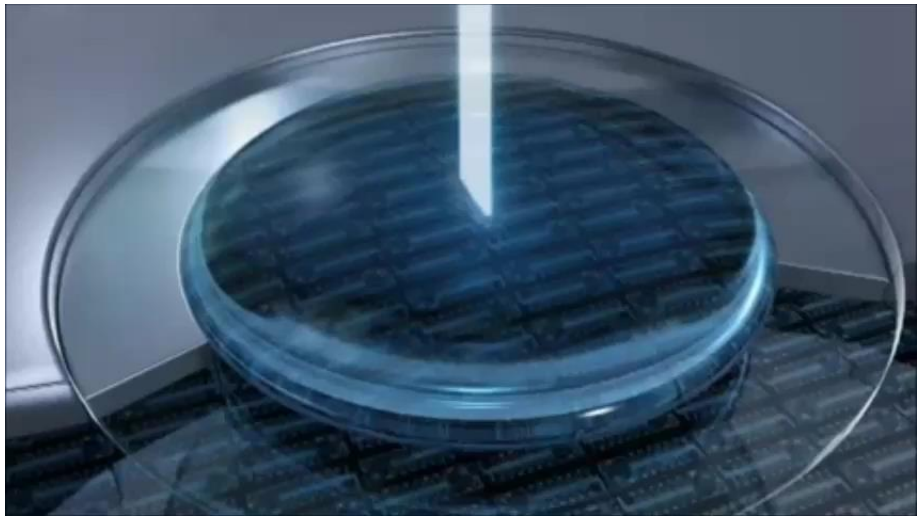
Outline

- Examples
  - Advanced semiconductor manufacturing
  - Nm-scale precision systems
- Theory
  - All-stabilizing Control
  - Adaptive Control
- Outlooks

Introduction: Semiconductor Manufacturing

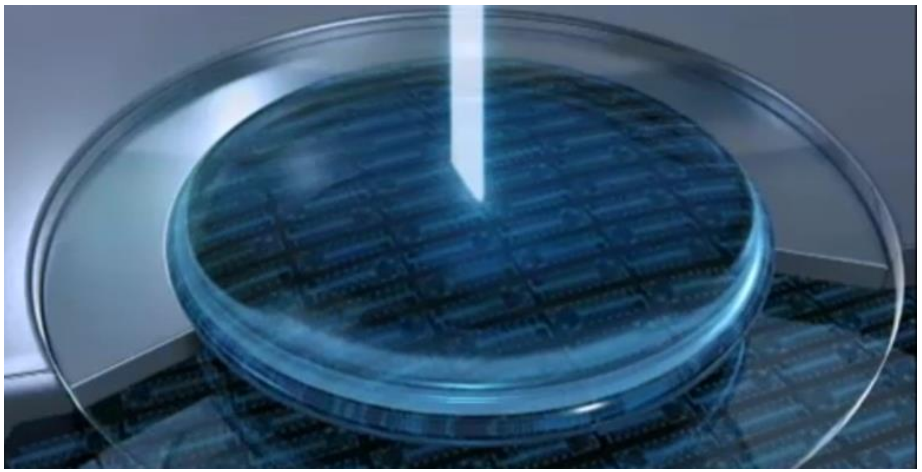


Billions of transistors are “built” into chips at the size of a finger nail, via photolithography.



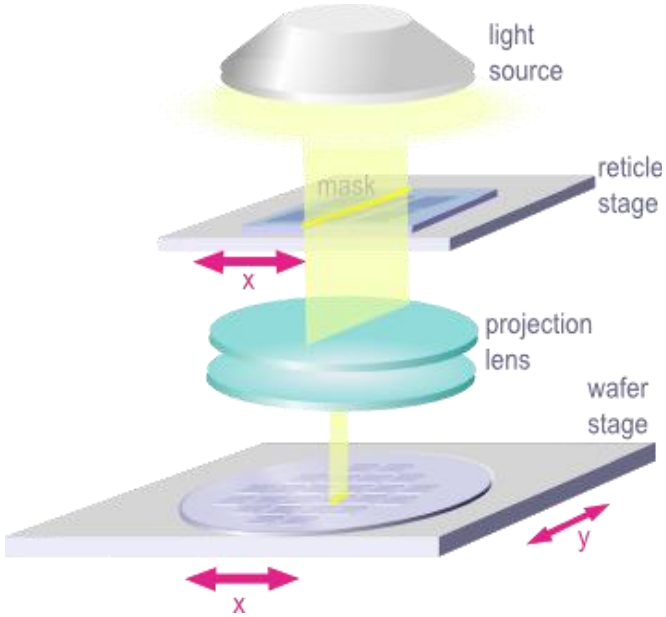
Courtesy of ASML

The Control Problem



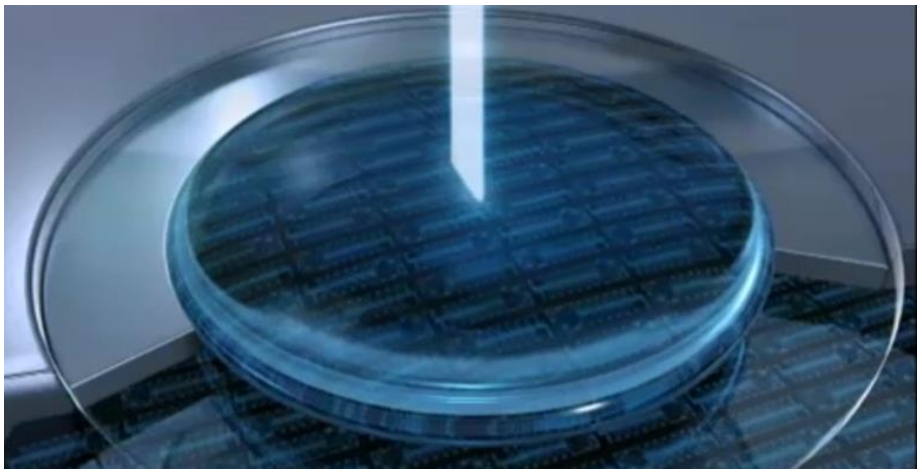
Courtesy of ASML

Photolithography



nm-scale precision manufacturing

The Control Problem



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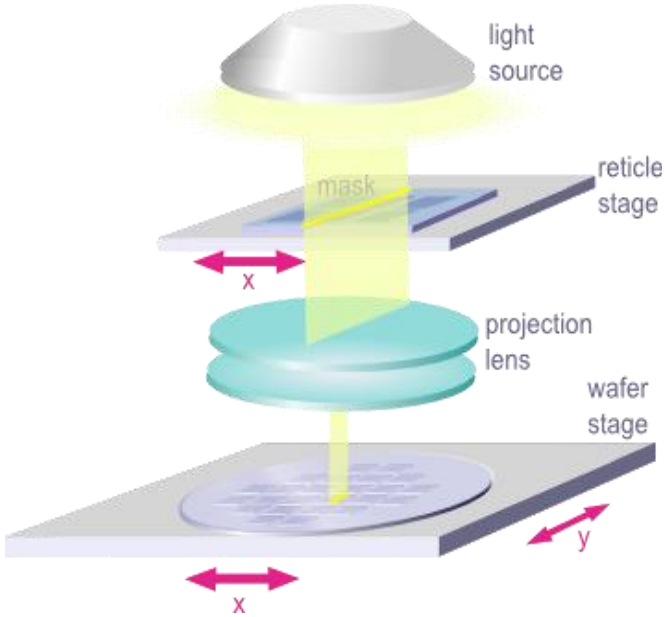
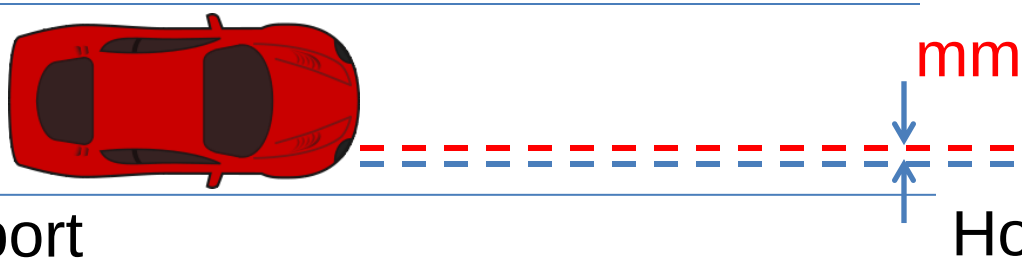
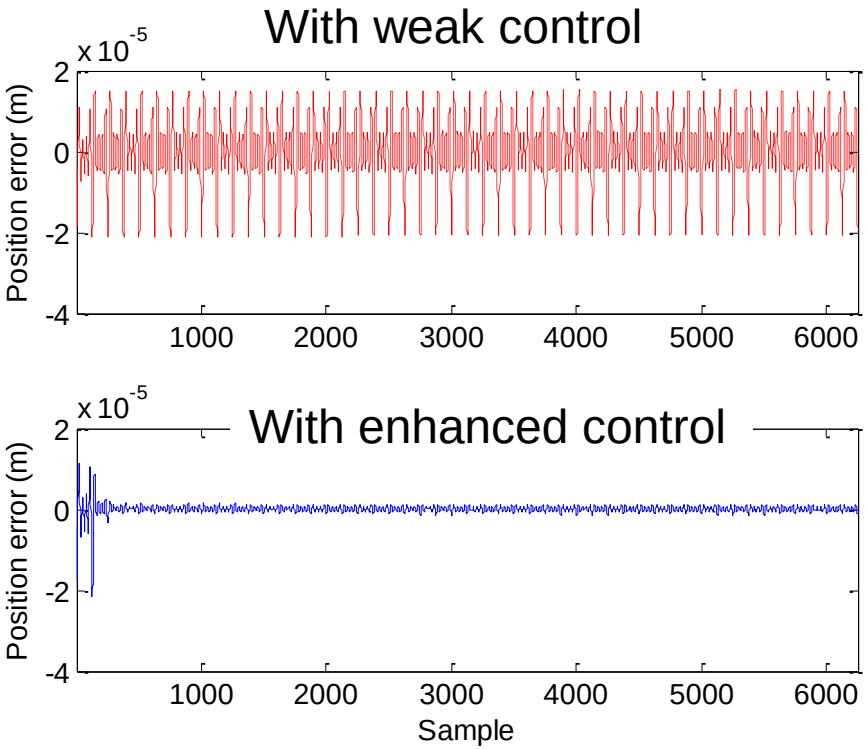
Photolithography

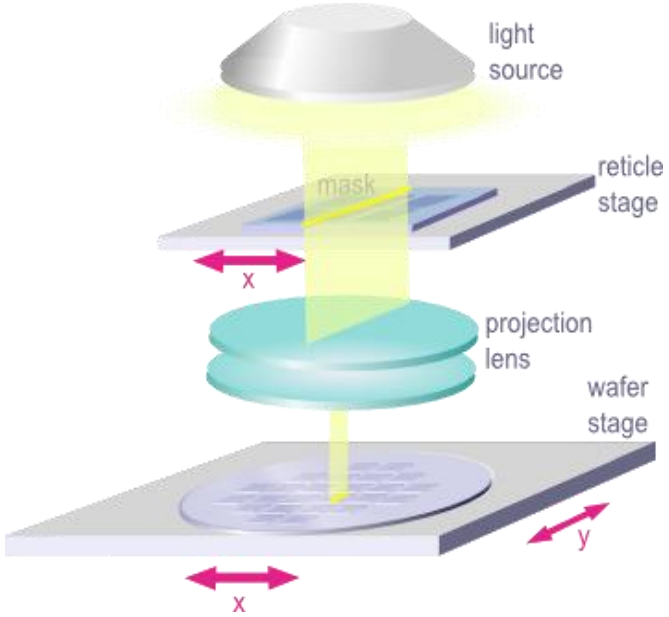


Analogous to driving:



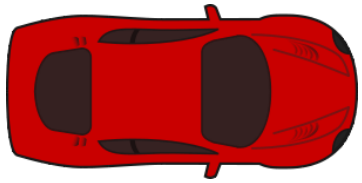
Role of Systems and Control Engineering





* Experiments done on a wafer-scanner testbed at UC Berkeley

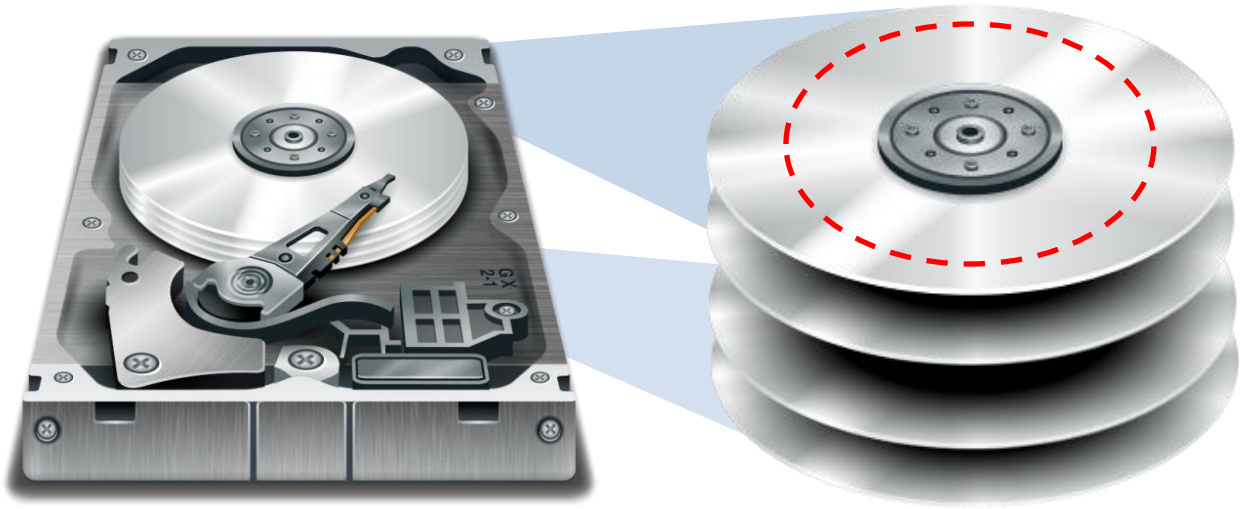
Role of Systems and Control Engineering



Hardware	Precision Mechatronics
Task Arrangement	System Automation, Supervisory Control
Dedicated Control	Vibration Suppression, Trajectory Tracking, Temperature Control, etc

More Details: Sources of Errors

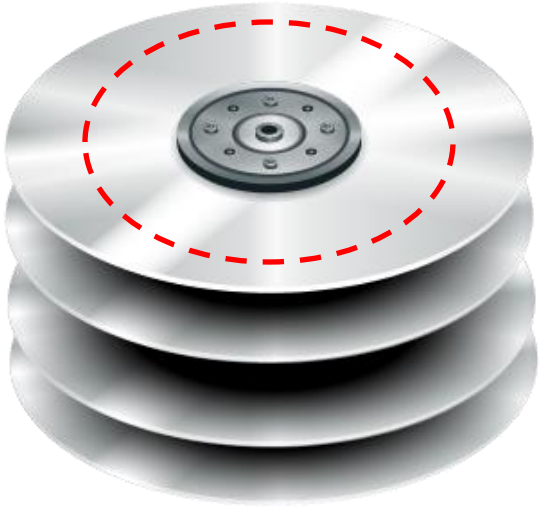
Sub-10nm position-error tolerance for data read and write

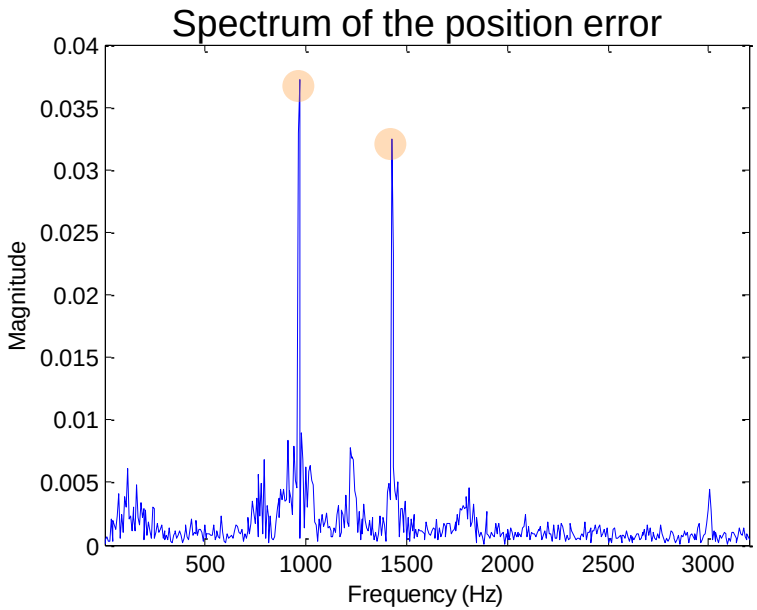


>900,000 tracks per inch

~ ten thousand tracks on a human hair..

Structured Errors from Hardware Imperfection





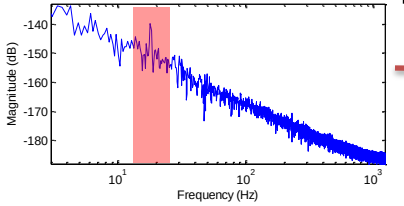
Complicated vibration sources:

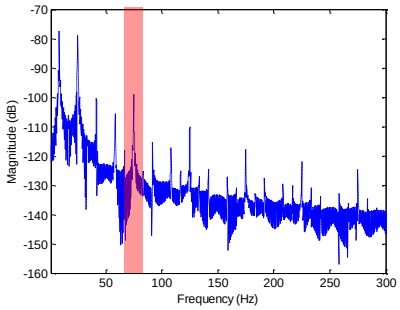
- Complex air dynamics
- Product-dependent characteristics

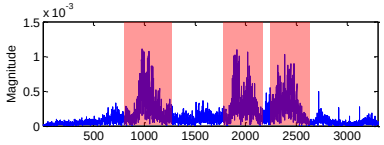
These complications are also common in general precision manufacturing.

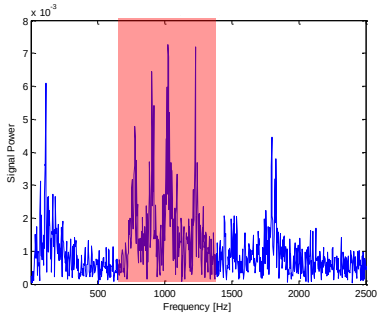
Overview of Error Sources

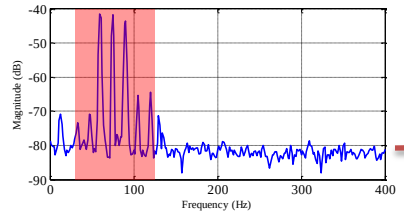
Error spectra











- **Hardware imperfection**
- **Task arrangements**
- **Operation environment**

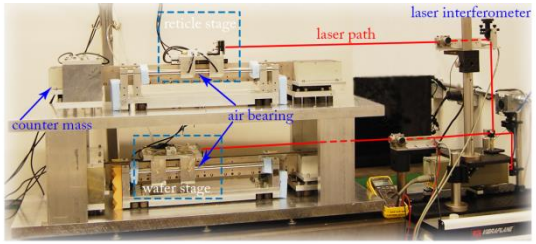
Structured Errors

Challenges to manufacturing:

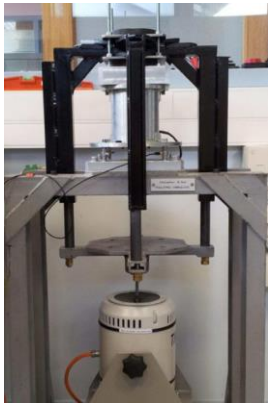
- **Precision and speed**
- **Robustness and intelligence**
- **Flexibility: setup time, etc**

Systems

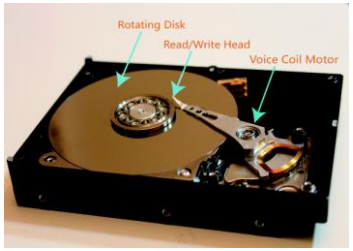
Wafer scanner



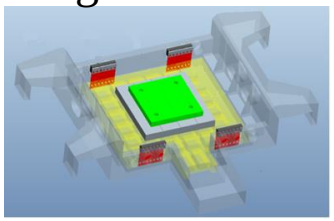
Active suspension



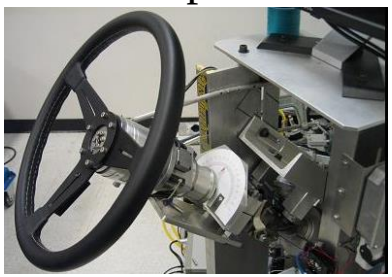
HDD



Diffraction Grating Ruling Machine



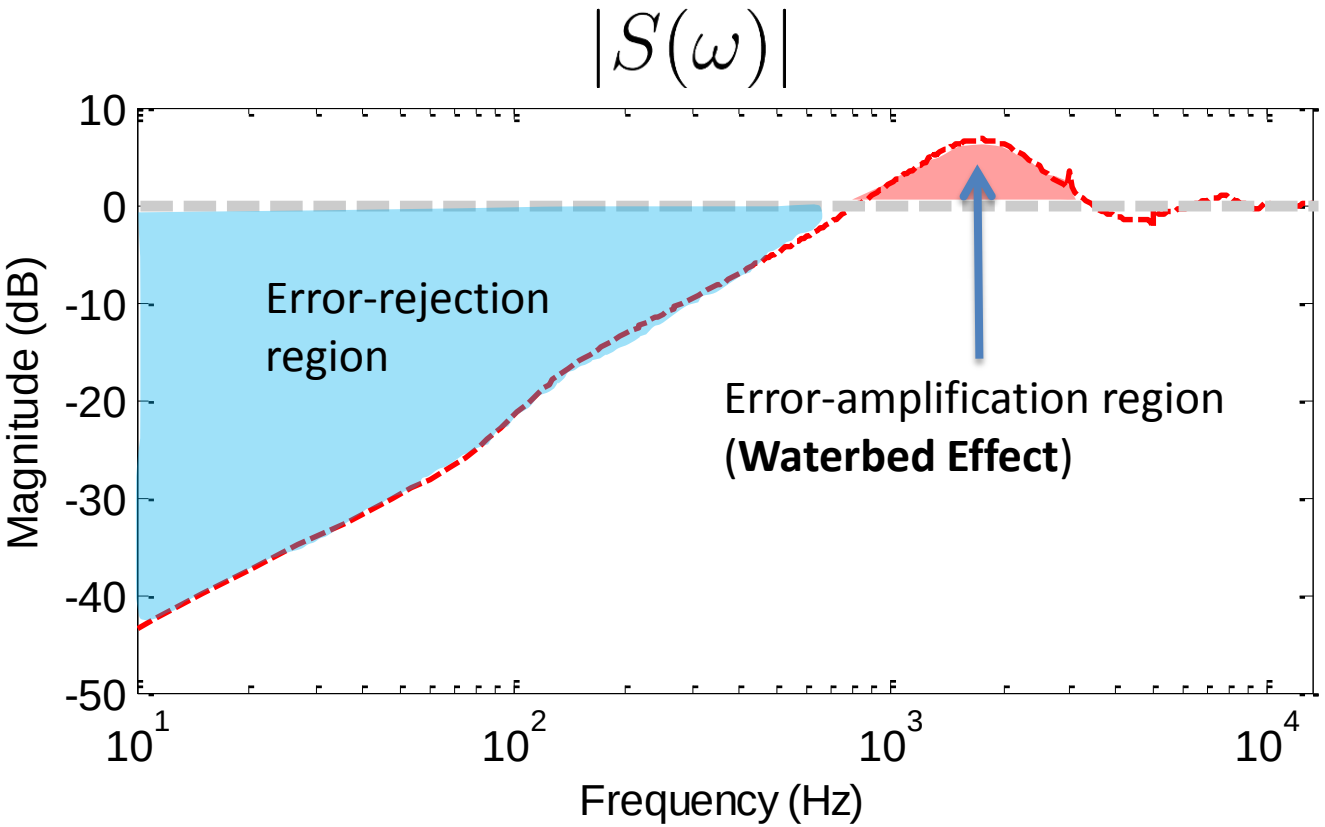
Electrical power steering

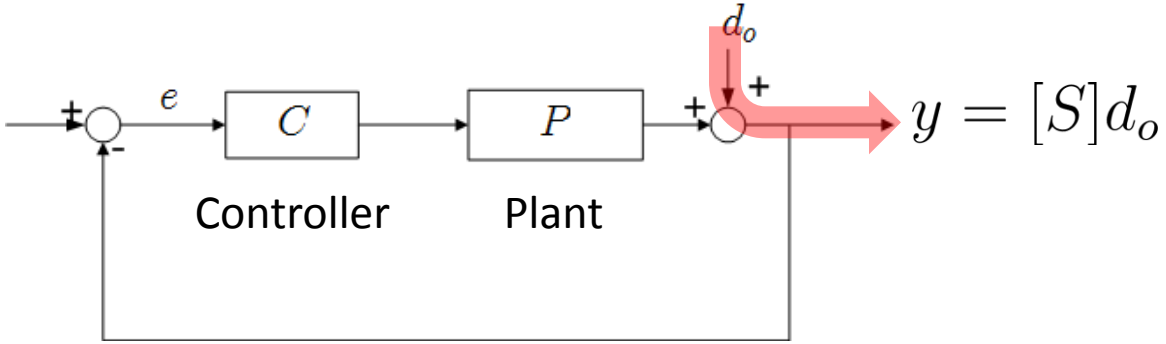


Outline

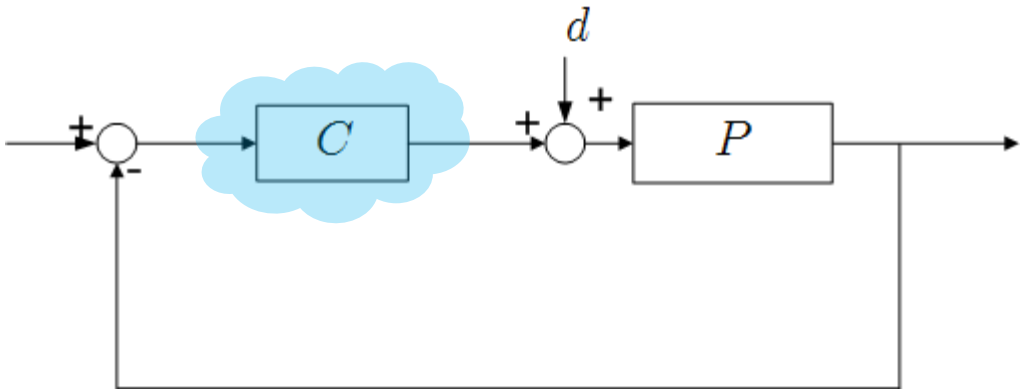
- Examples
  - Advanced semiconductor manufacturing
  - Nm-scale precision systems
- **Theory**
  - All-stabilizing Control
  - System Identification and Adaptation
- Outlooks

The Sensitivity Function $S=1/(1+PC)$





Standard All-stabilizing Parameterization



Theorem:

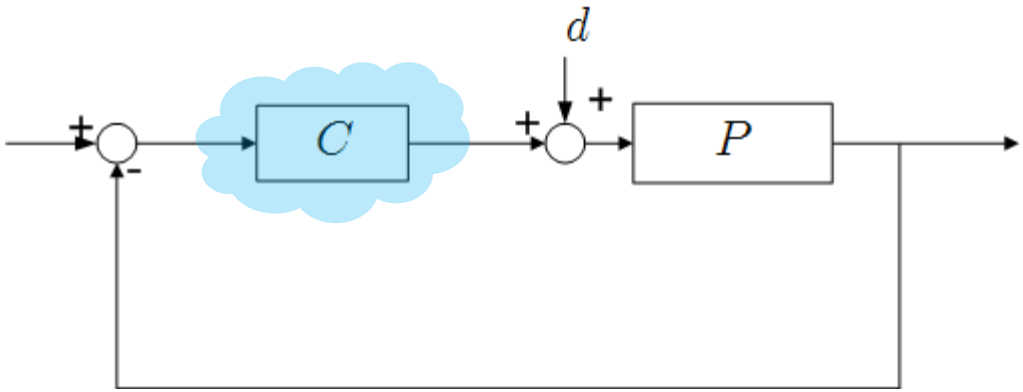
- Coprime factorizations: $P = N/D$, $C = X/Y$, $NX+DY = 1$
- **Any** stabilizing controller can be formed as:

$$C_{all} = \frac{X + DQ}{Y - NQ}, \quad Q \in \mathbf{S}.$$

- **S**:={stable, proper, and rational transfer functions}

Much simplified design on *Q*

Standard All-stabilizing Parameterization



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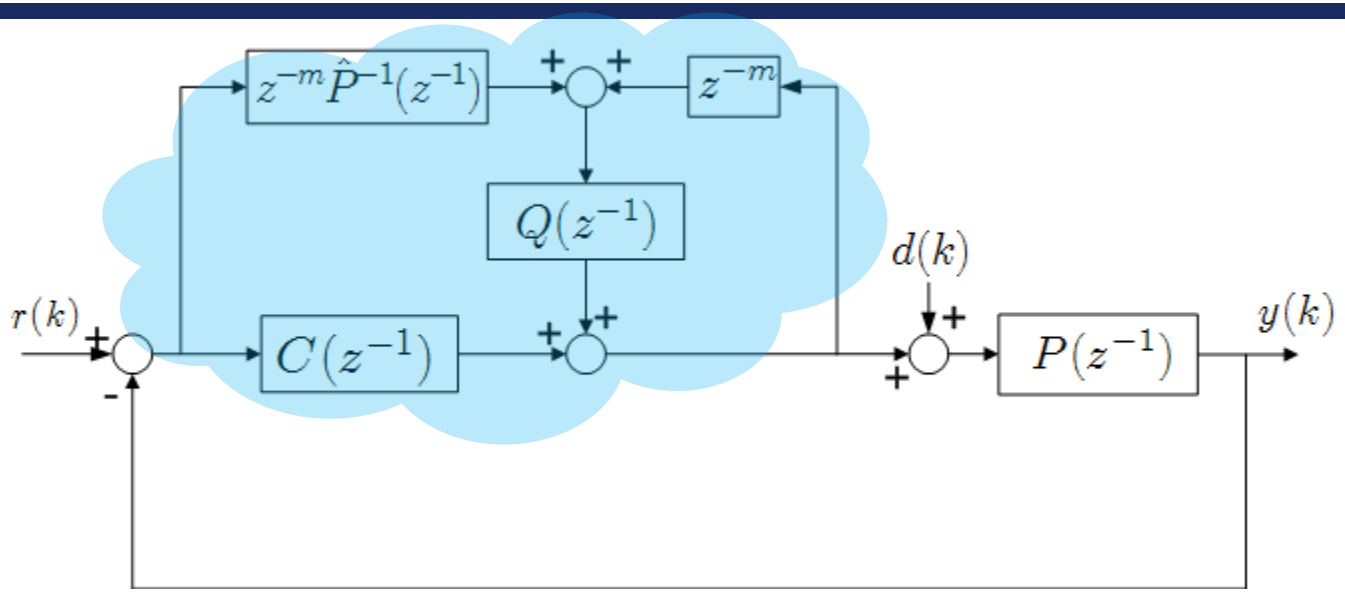
Challenge: general Q design for different applications

Inverse-based All-stabilizing Parameterization



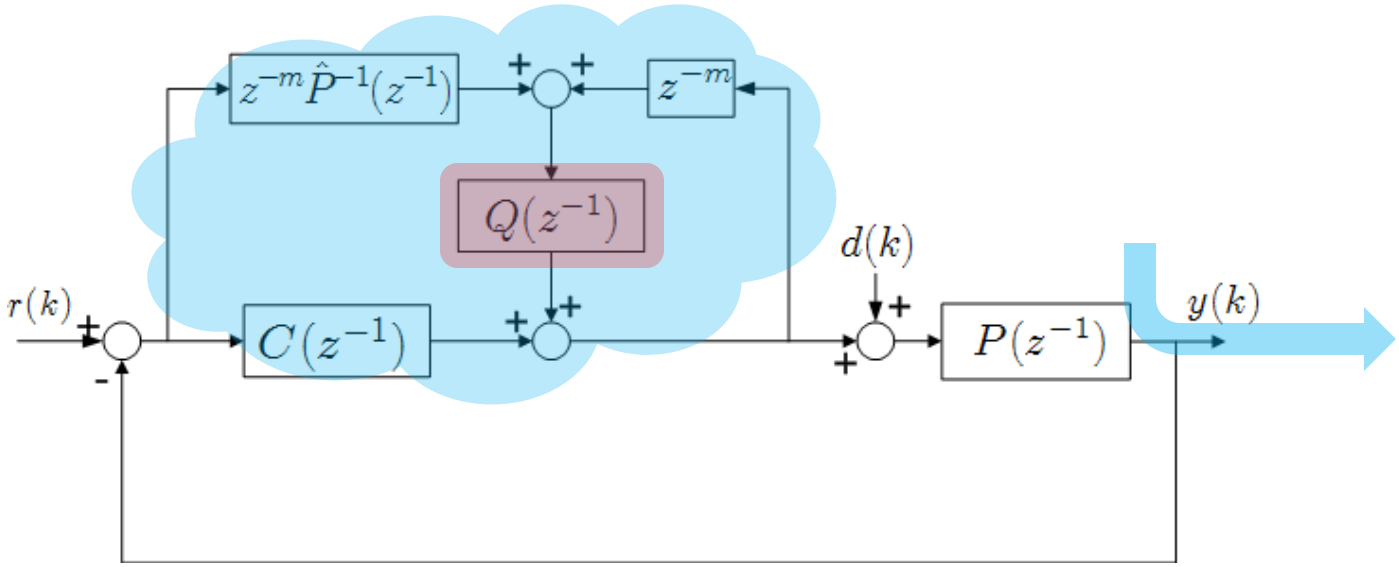
- "Coprime" factorizations: $P(z^{-1}) \approx \frac{z^{-m}}{z^{-m}\hat{P}^{-1}(z^{-1})} \quad C(z^{-1}) = \frac{C(z^{-1})}{1}$
- The following parameterization is always **stabilizing**:

$$C_{all}\left(z^{-1}\right) = \frac{C\left(z^{-1}\right) + z^{-m}P^{-1}\left(z^{-1}\right)Q\left(z^{-1}\right)}{1 - z^{-m}Q\left(z^{-1}\right)}, \; Q(z^{-1}) \in \mathbf{S}$$

X. Chen, "Adaptive Local Loop Shaping and Inverse-based Youla-Kucera Parameterization with Application to Precision Control," *UC Berkeley*, Ph.D. Dissertation, 2013.

X. Chen and M. Tomizuka, "Control Methodologies for Precision Positioning Systems," in *Proceedings of 2013 American Control Conference, Washington, DC,* Jun. 17-19, 2013, pp. 3710-3717. ***Tutorial Paper**

Mathematical Benefits of Inverse Parameterization



New sensitivity function:

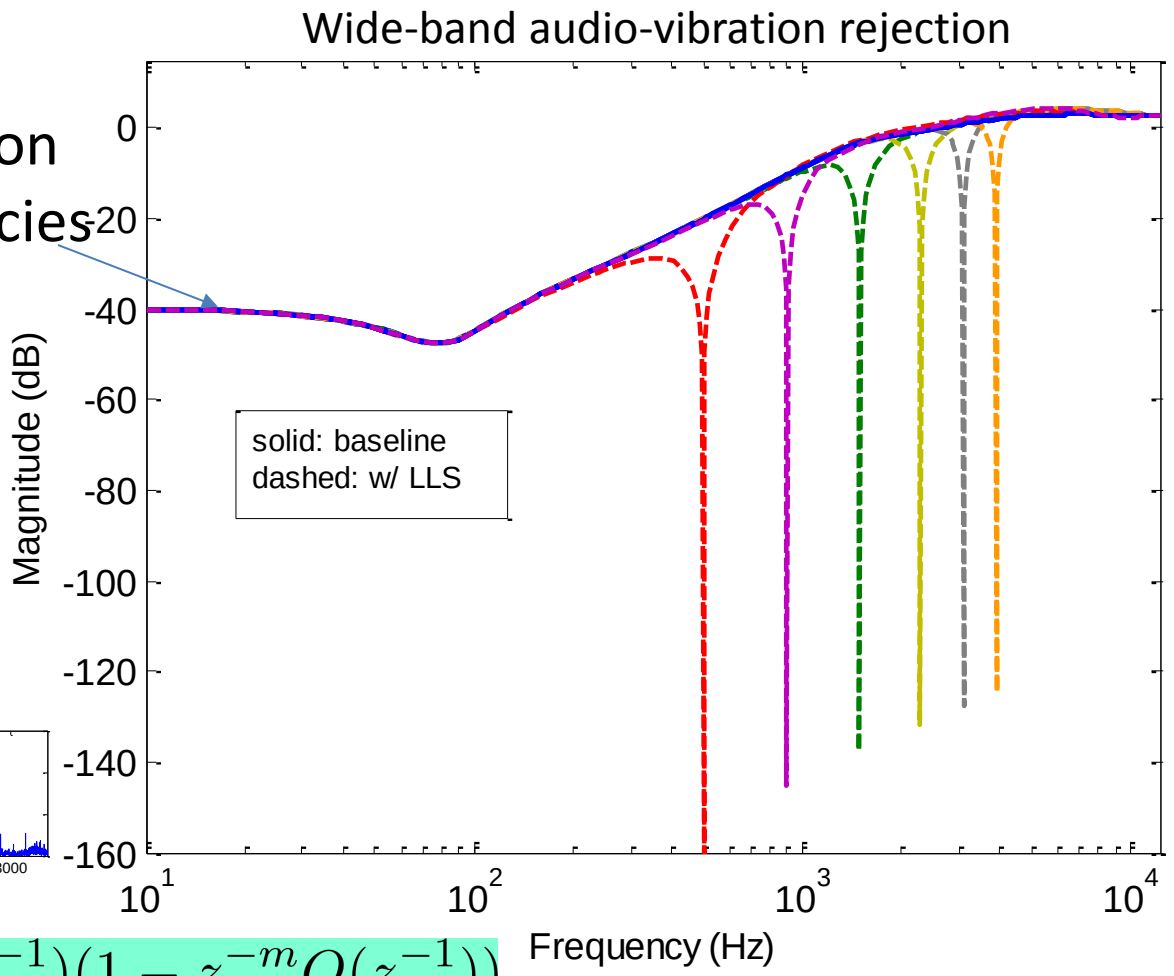
Affine Q parameterization (Simplicity)

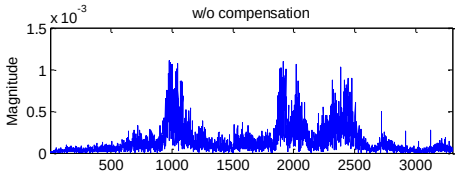
$$S(z^{-1}) \approx S_o(z^{-1})(1 - z^{-m}Q(z^{-1}))$$

"Plant-independent" Q design (Flexibility)

Achieved Loop Shapes

Small amplification
at other frequencies



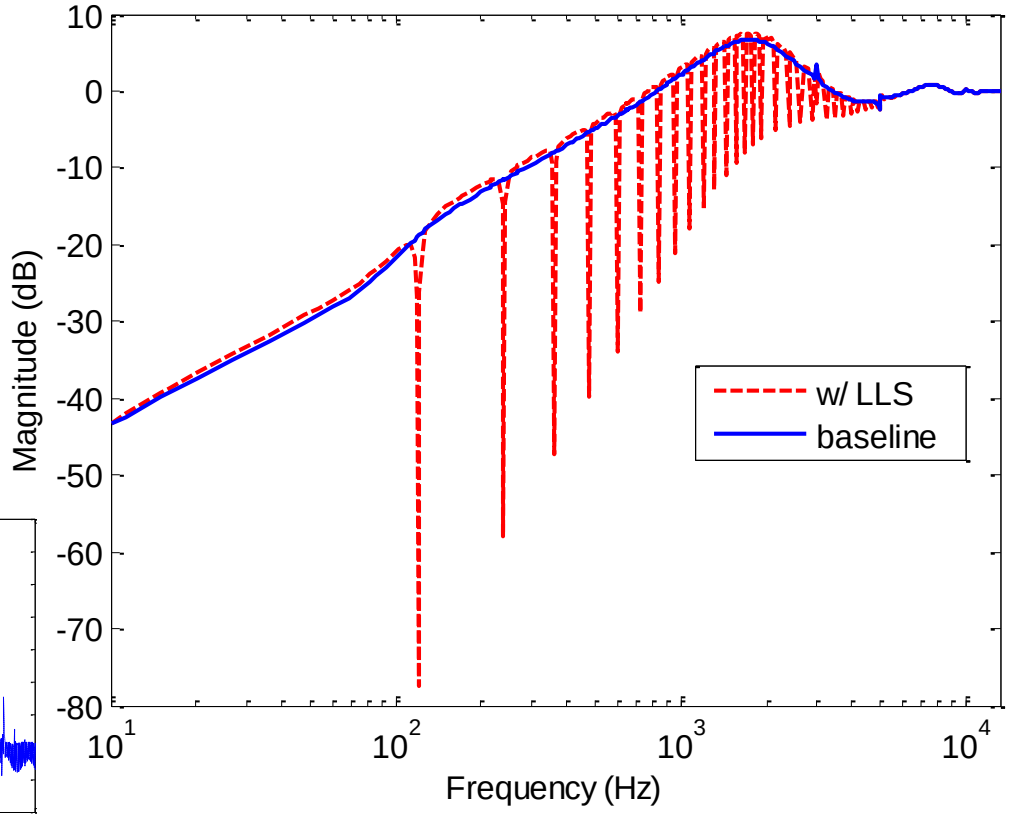


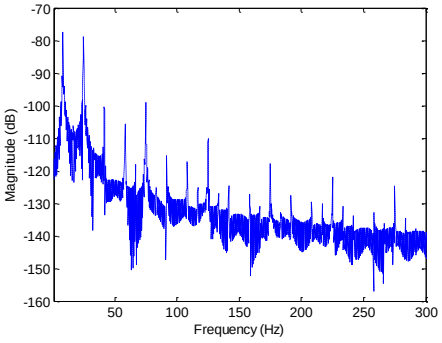
$$S(z^{-1}) \approx S_o(z^{-1})(1 - z^{-m}Q(z^{-1}))$$

$$Q(z^{-1}) = \frac{(\alpha^2 - 1 - a^2(\alpha - 1)) - (\alpha - 1)az^{-1}}{1 + a\alpha z^{-1} + \alpha^2 z^{-2}} \qquad a = -2\cos(2\pi\Omega T_s)$$

Achieved Loop Shapes

Enhanced repetitive control for harmonic cancellation





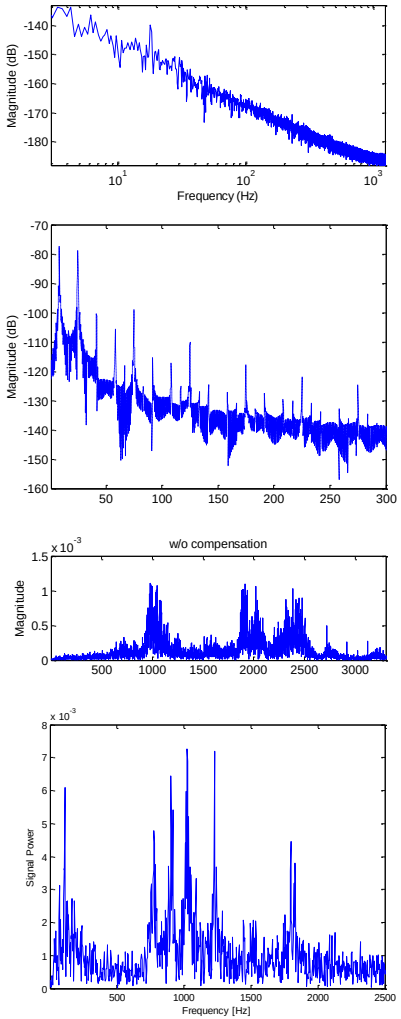
$$Q\left(z^{-1}\right) = \frac{\left(1-\alpha^N\right) z^{-(N-m-n_q)}}{1-\alpha^N z^{-N}} z^{-n_q} q\left(z, z^{-1}\right)$$

X. Chen and M. Tomizuka, "New Repetitive Control with Improved Steady-state Performance and Accelerated Transient," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 3, doi:10.1109/TCST.2013.2253102.

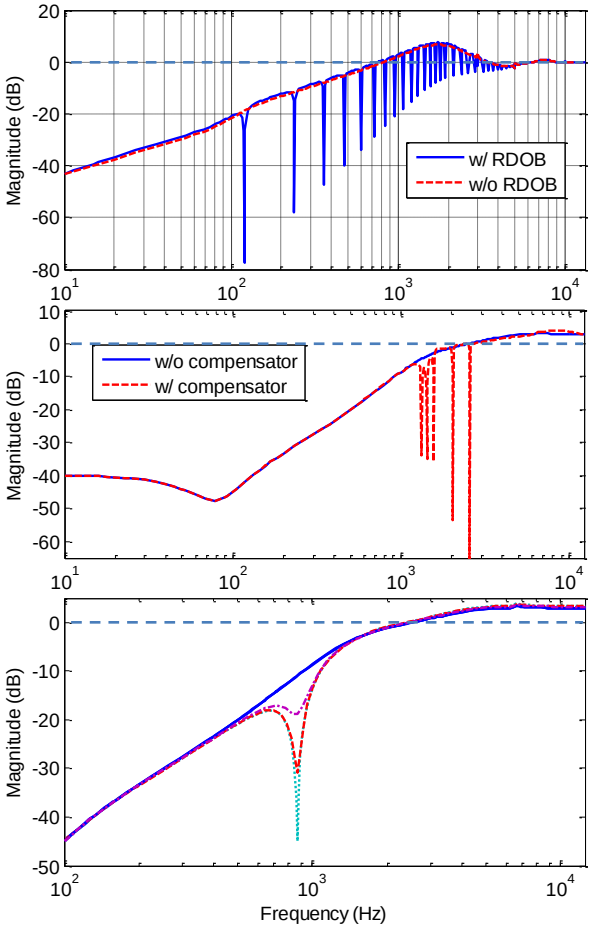
X. Chen and M. Tomizuka, "An Enhanced Repetitive Control Algorithm using the Structure of a Disturbance Observer," in *Proceedings of 2012 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Taiwan, Jul. 11-14, 2012, pp. 490-495.

Achieved Loop Shapes

Error spectra



Local loop shaping



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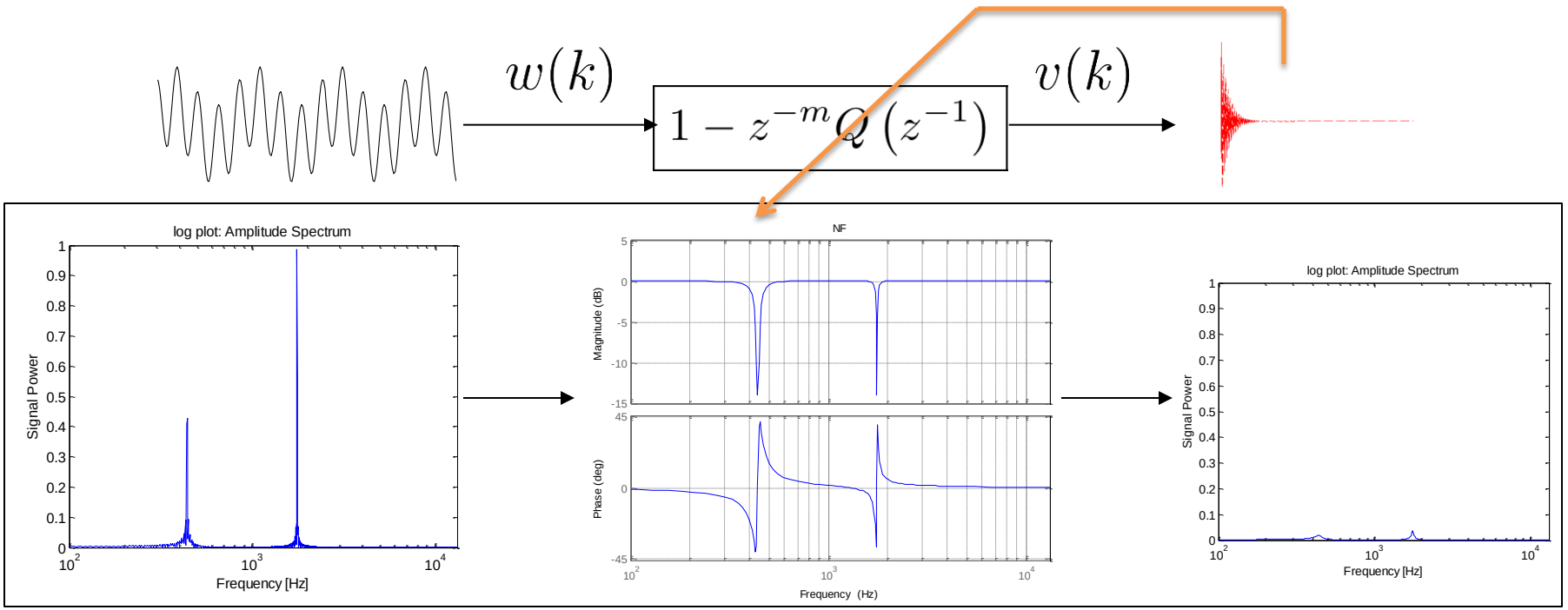
  - All-stabilizing Control
  - **Adaptive Control**
- Outlooks

Adaptive Control for System Intelligence

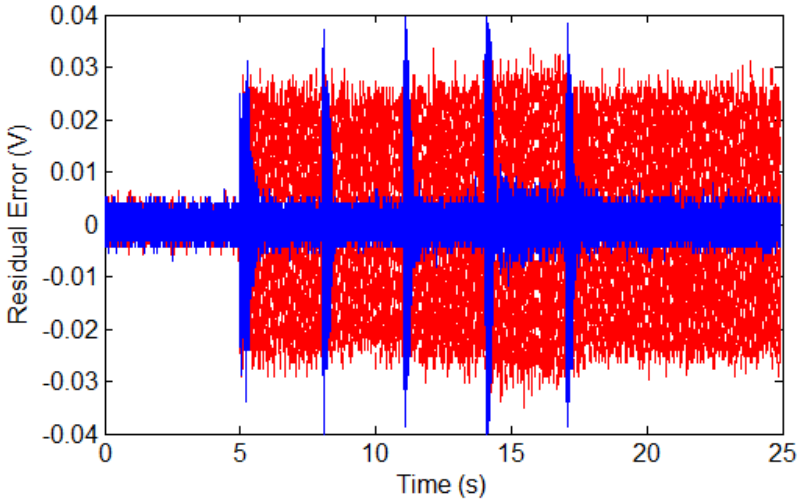
Parameter Adaptation Algorithm (PAA):



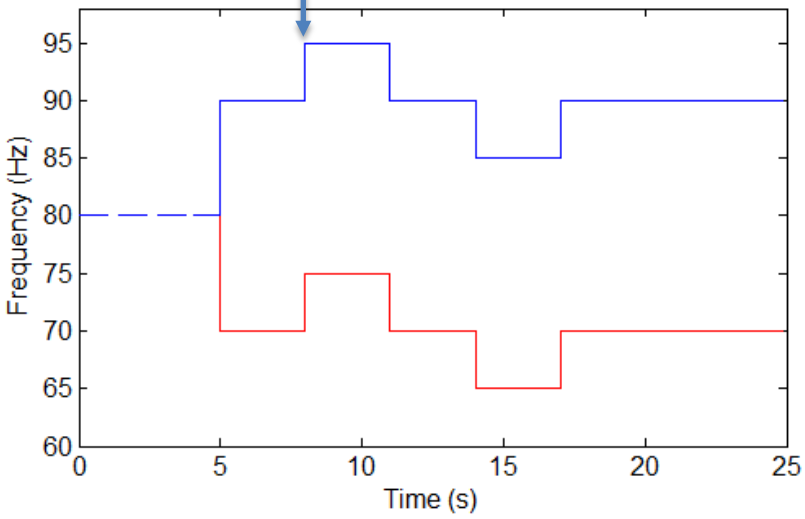
- Different choices for adaptation:
  - Equation-error methods: simple, guaranteed convergence in the noise-free case
  - Output-error methods: good performance in noisy environments

Example on An Active Suspension

Experimental results
Red: w/o adaptive compensation
Blue: w/ adaptive compensation



Vibration frequency jumps

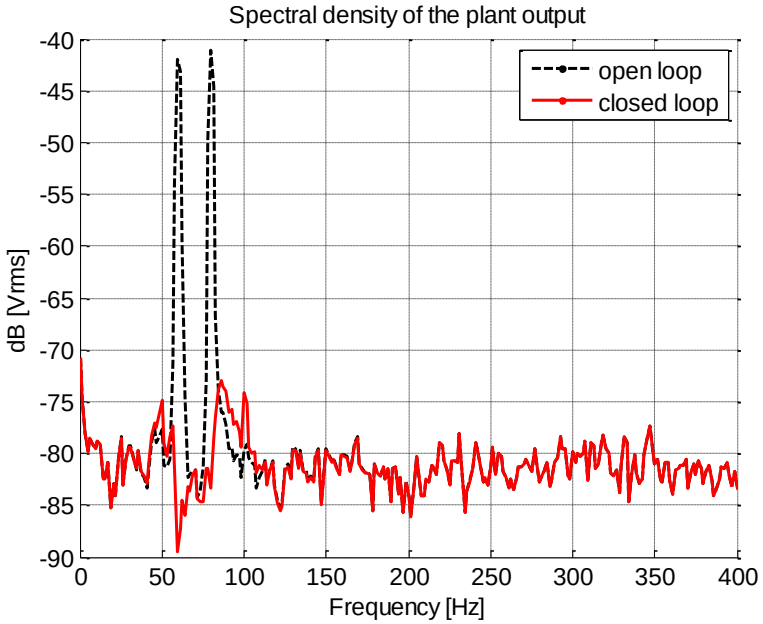


X. Chen and M. Tomizuka, "Selective Model Inversion and Adaptive Disturbance Observer for Time-varying Vibration Rejection on an Active-Suspension Benchmark," *European Journal of Control*, vol. 19, no. 4, pp. 300-312, Jul. 2013.

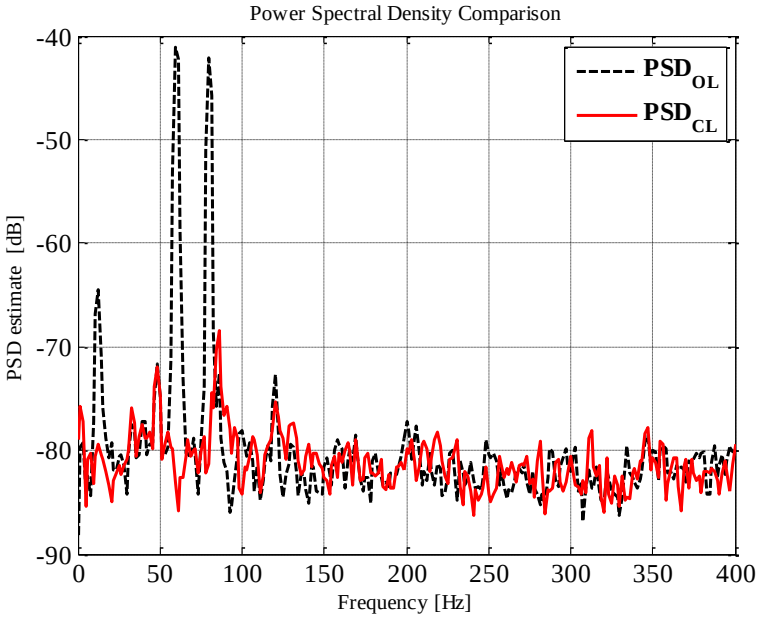
X. Chen and M. Tomizuka, "Adaptive Model Inversion For Rejection of Time-varying Vibrations On A Benchmark Problem," in *Proceedings of The European Control Conference 2013*, Zurich, Switzerland, Jul. 17-19, 2013, pp. 2897-2903.

Example on An Active Suspension

Simulation

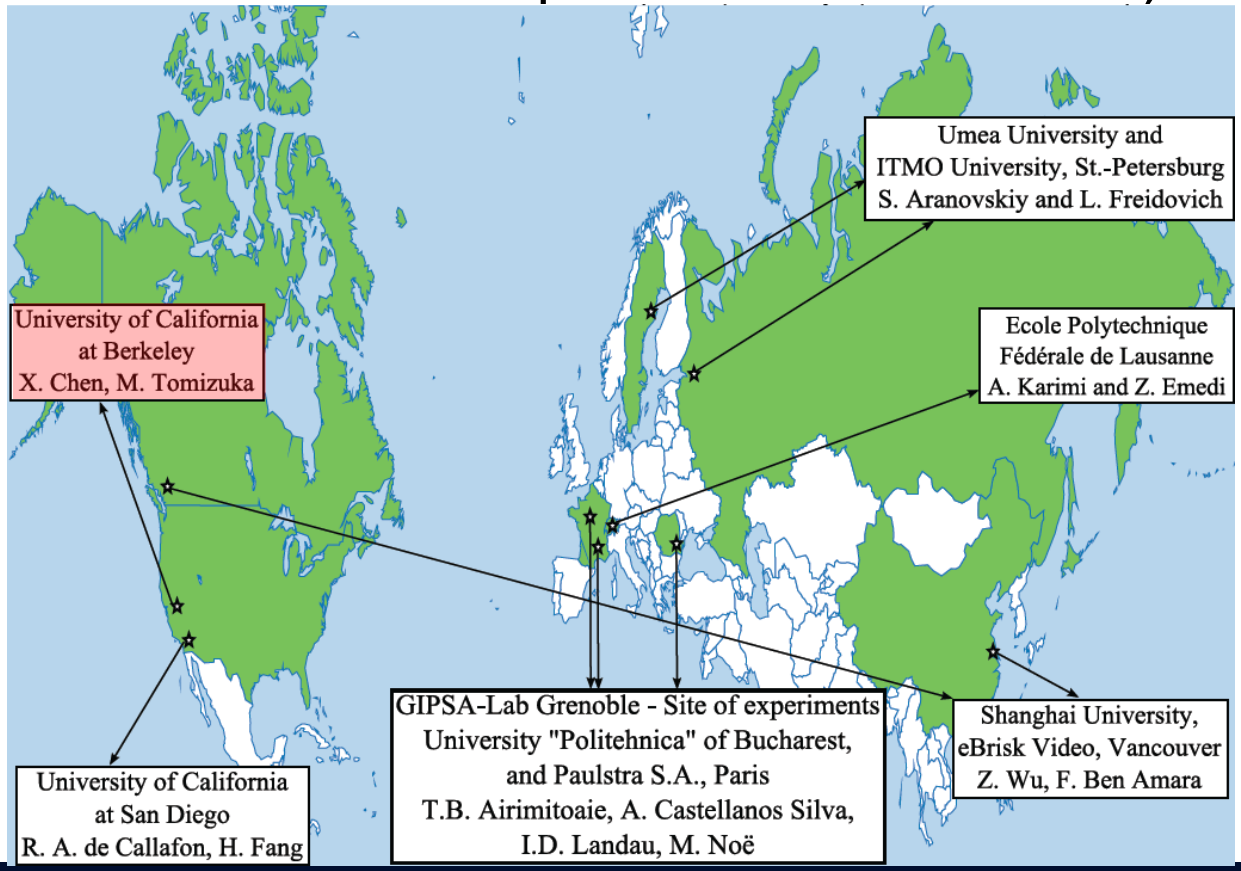


Experiments

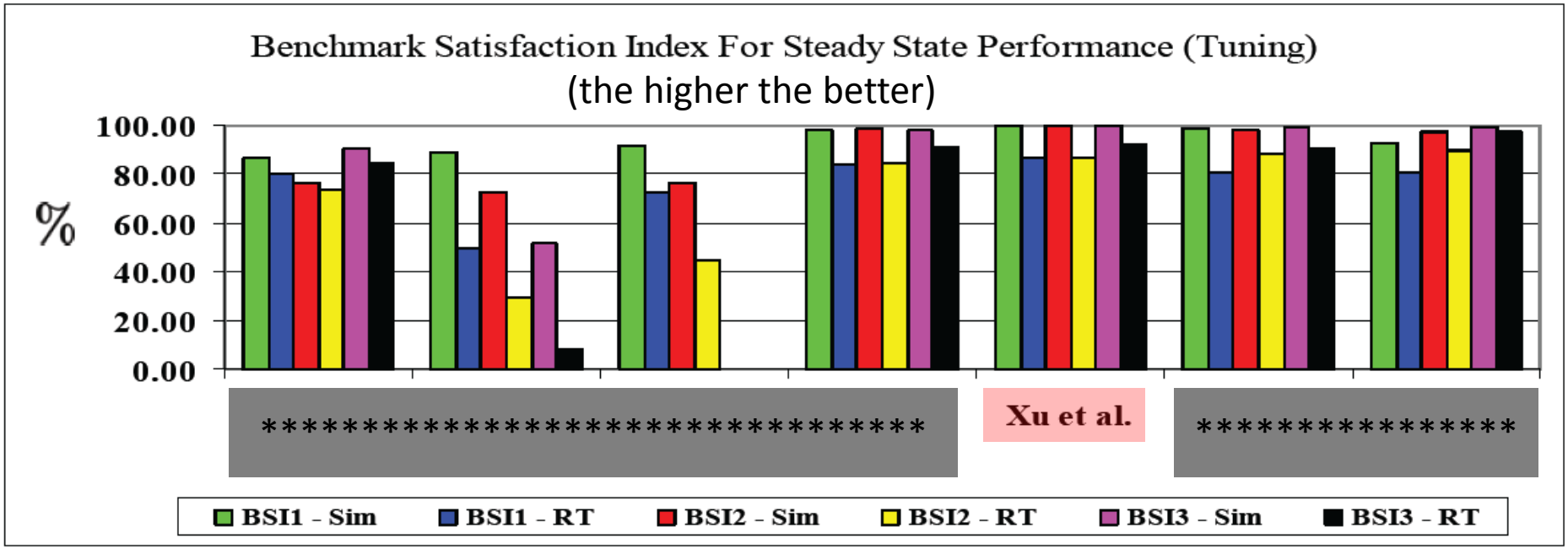


More Details

- Benchmark on Adaptive Regulation
  - Special Session in 2013 European Control Conference
  - Special Session in European Journal of Control, July 2013



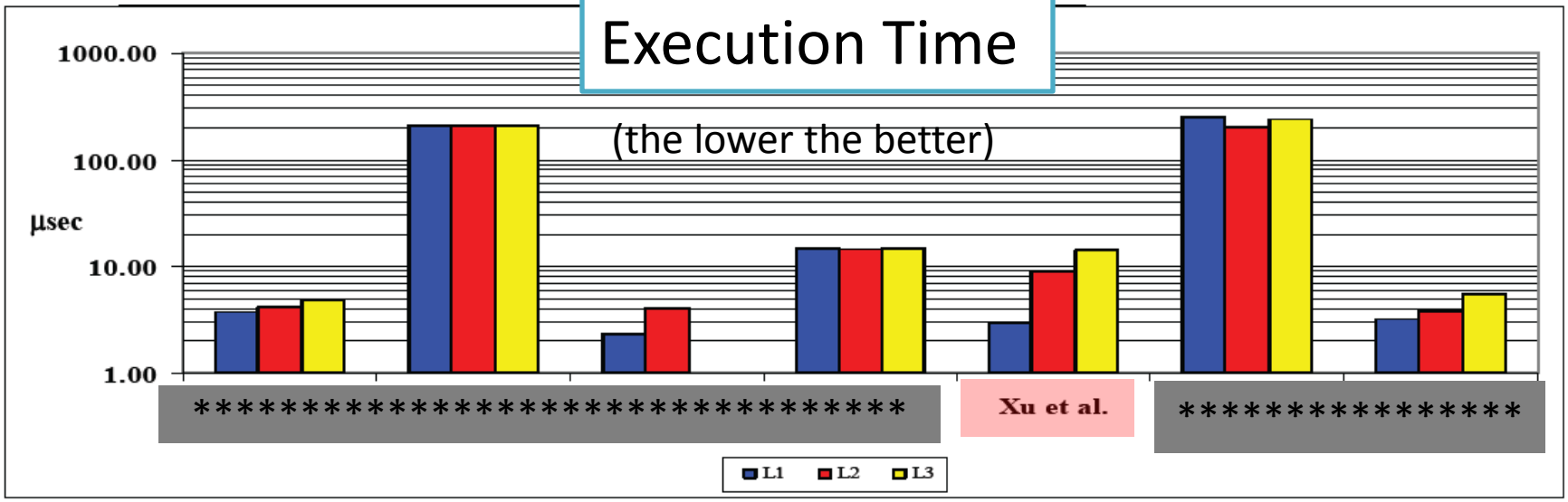
Benchmark Performance Comparison

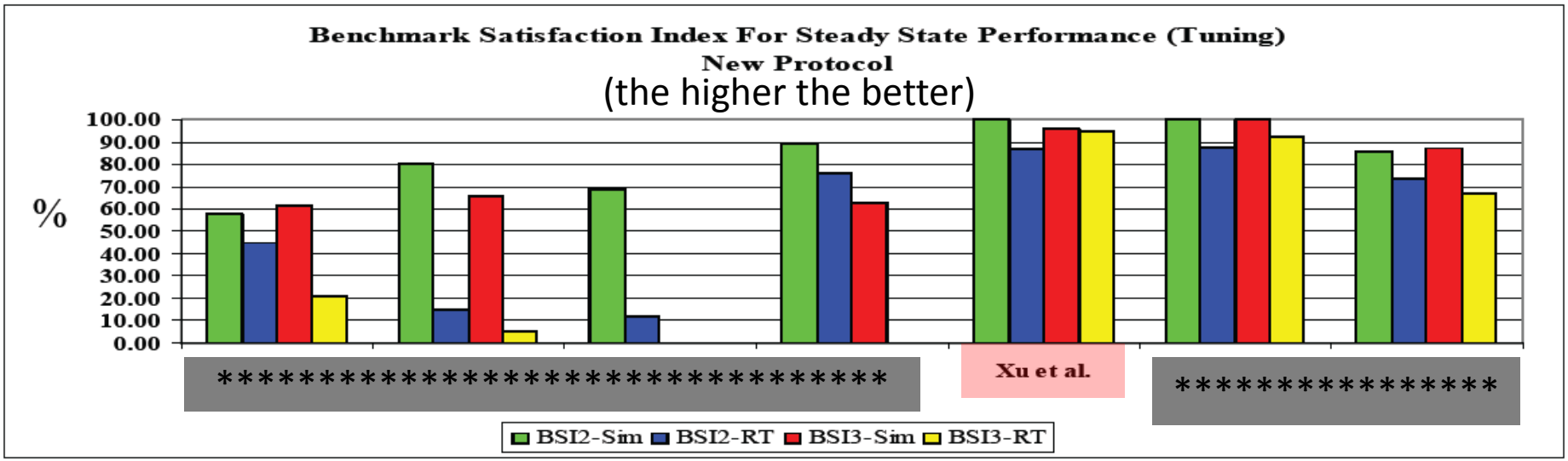


I.D. Landau et al, "An Active Vibration Control System as a Benchmark on Adaptive Regulation," *Proc. 2013 European Control Conf. (ECC)*, July 17-19, 2013, Zürich, Switzerland, pp. 2873-2878.

I. Landau, et al, Benchmark on adaptive regulation—rejection of unknown/time-varying multiple narrow band disturbances, *European Journal of Control*, Volume 19, Issue 4, July 2013, Pages 237-252.

Execution Time





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  - Adaptive Control
- **Outlooks**

Outlook: Intelligent and Adaptive Systems

- Make machines more “human-like”
- Developing rapidly
  - iRobot
  - Nest Thermostat
  - HVAC
  - …
- Lots of challenges in large-scale complex systems

Acknowledgement

- Sponsors:

- Acknowledgement:
  - Ph.D. Advisor at UC Berkeley: Masayoshi Tomizuka
  - UC Berkeley Colleagues: Roberto Horowitz, Andrew Packard
  - Ioan Landau and his Grenoble team (France): benchmark
  - Atsushi Oshima, Hironori Ogawa (NSK, Japan): human-machine interaction