The Power of Controls

A Working List of Demos

Xu Chen

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Associate Professor

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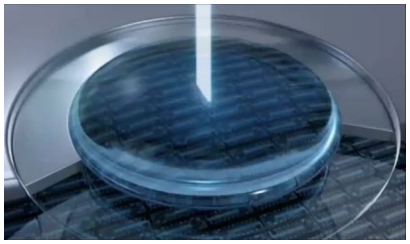
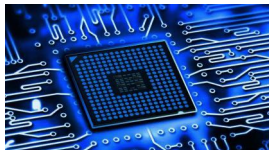
University of Washington

Precise and Intelligent Machines

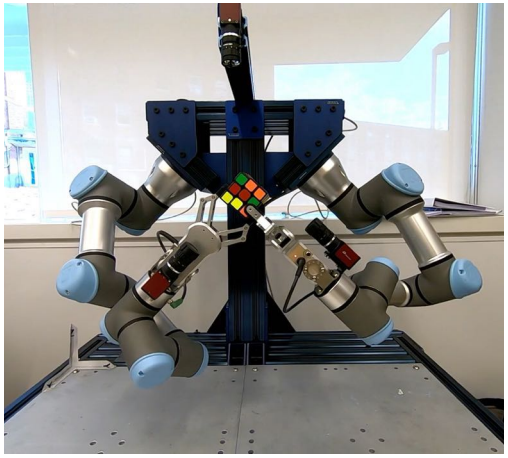




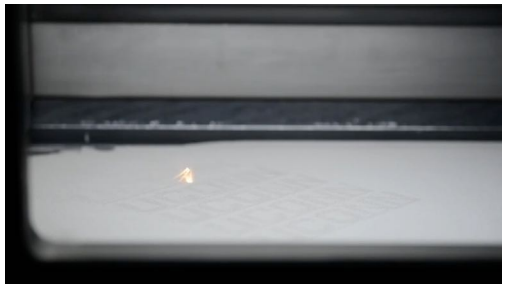
Semiconductor manufacturing

Courtesy of ASML

Information storage



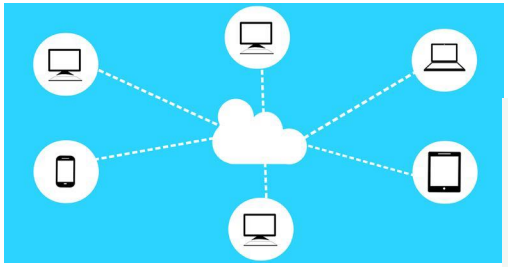
Vision-based robotic inspection & manufacturing



Additive manufacturing (AM)

Courtesy of Xilloc Medical B.V

Impacts to everyday lives



aws

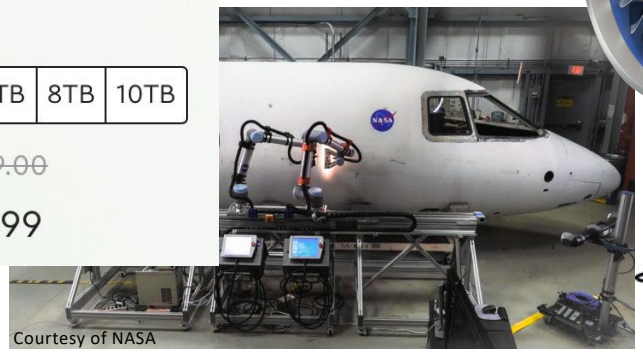
Dropbox

Capacity

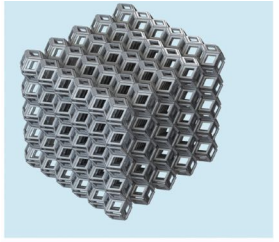
2TB | 3TB | 4TB | 6TB | 8TB | 10TB

Regular Price ~~$109.00~~

Promo Price $79.99

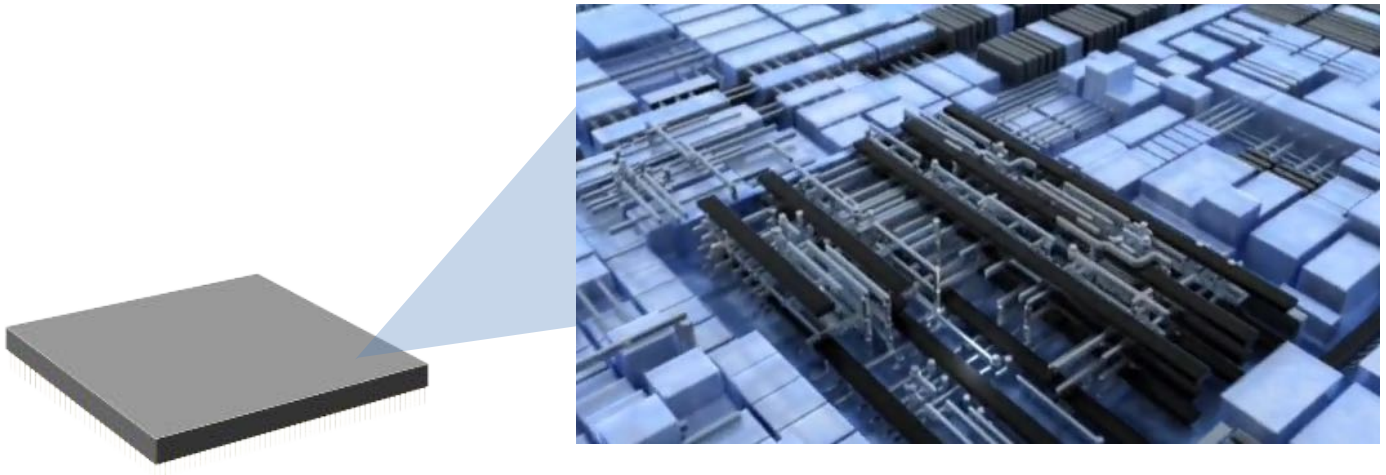


Courtesy of NASA

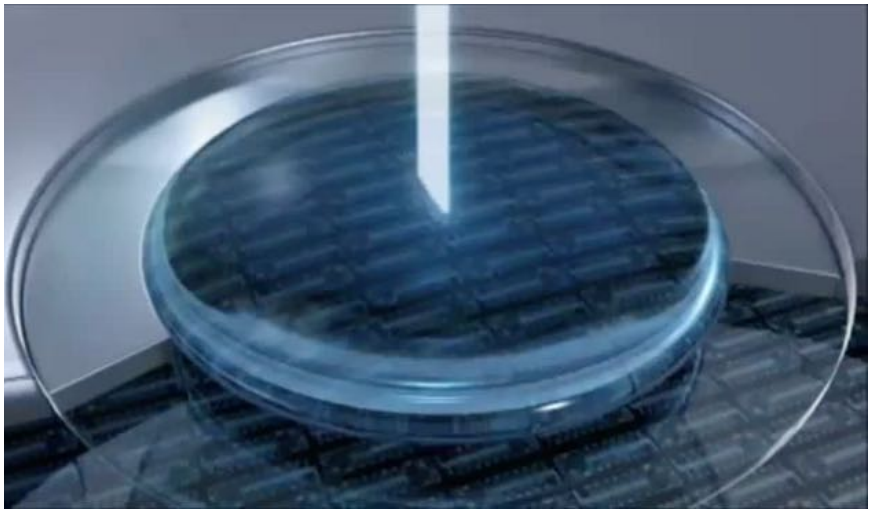


Science, 2017, vol. 3, no. 11

Example 1: Semiconductor Manufacturing

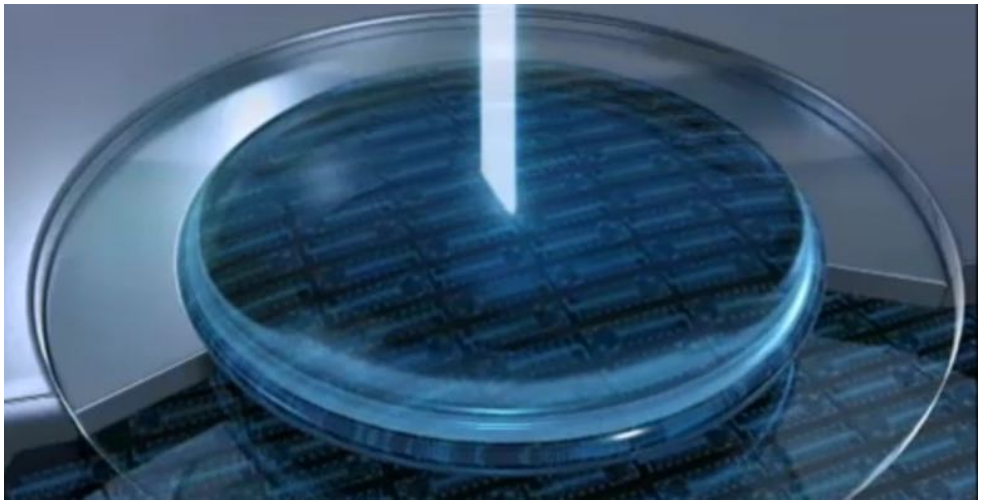


Billions of transistors are “built” into chips at the size of a fingernail via photolithography.



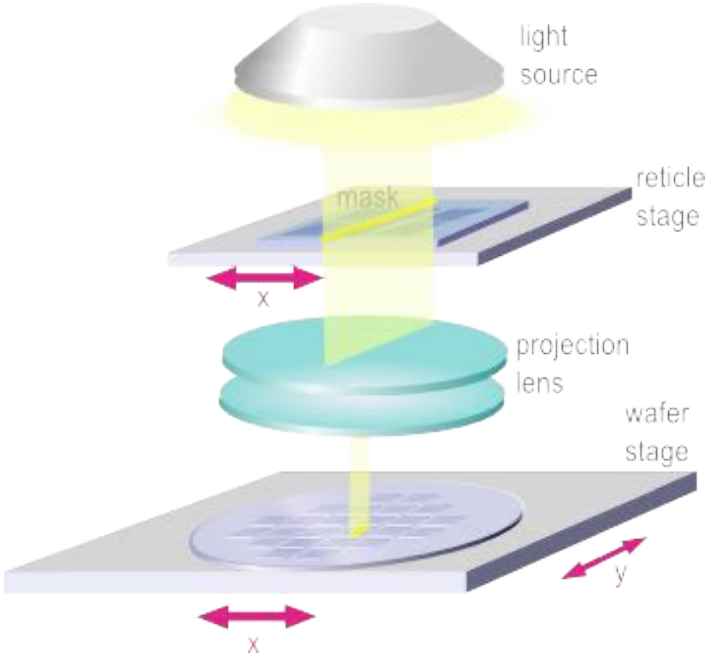
Courtesy of ASML

The Control Problem



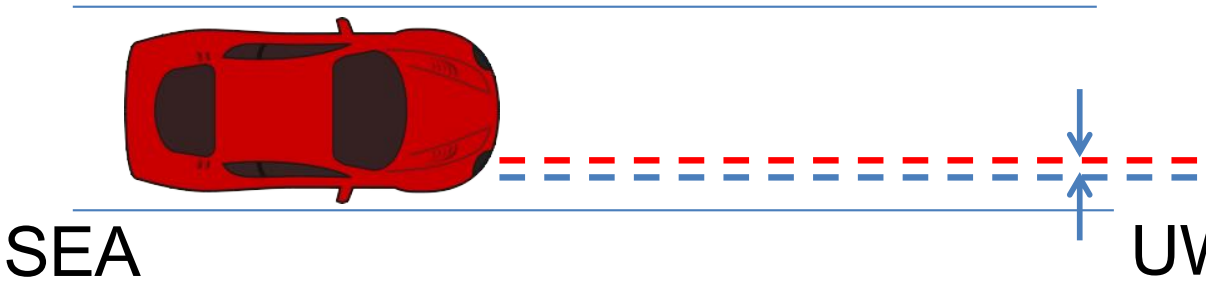
Courtesy of ASML

Photolithography



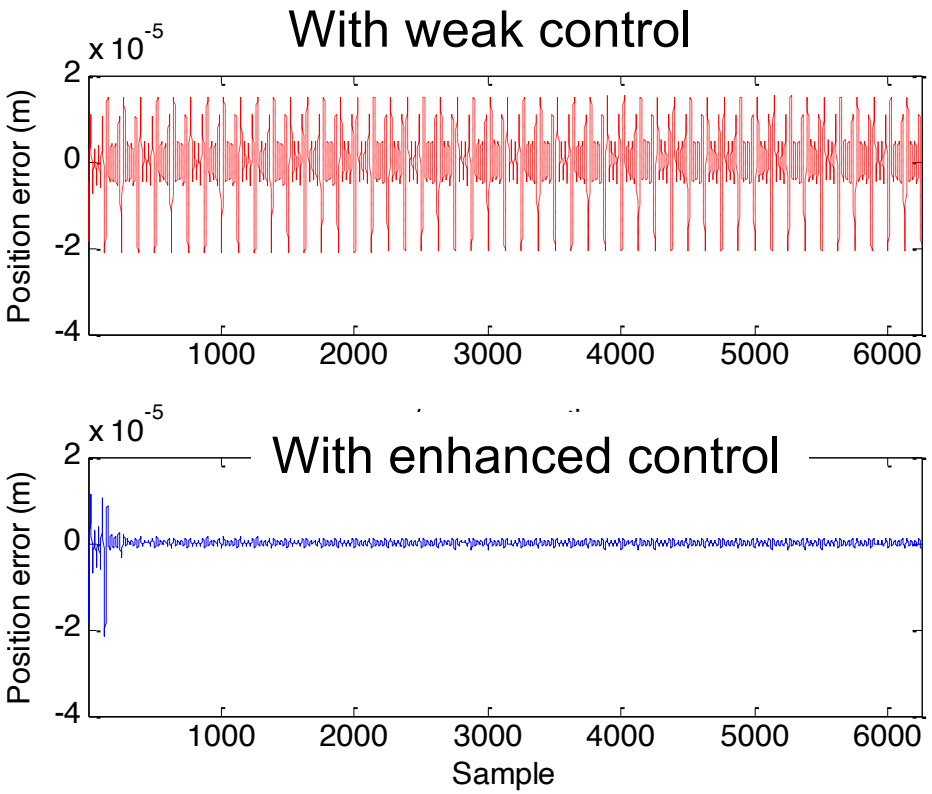
nm-scale precision manufacturing

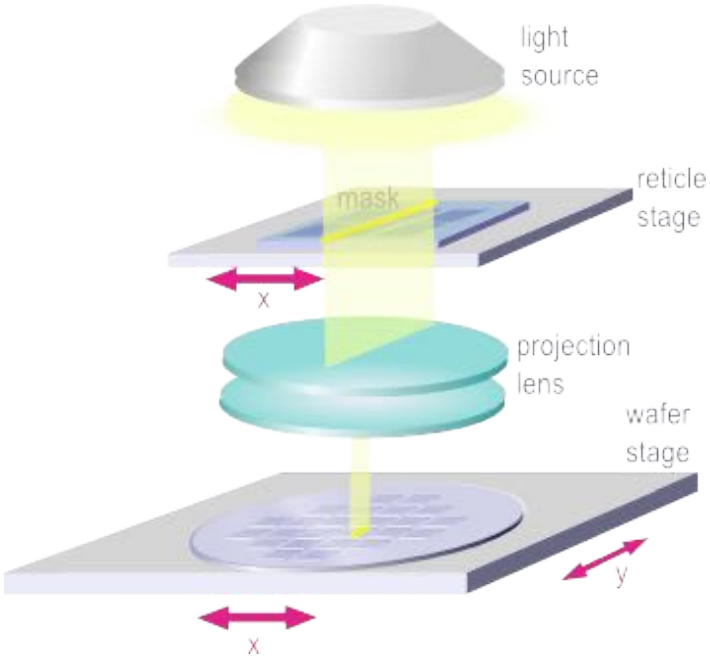
Analogous to driving:



mm-scale error tolerance
between two runs
same resolution everyday

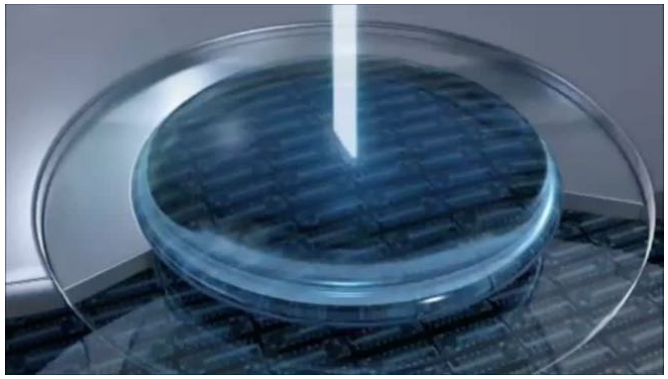
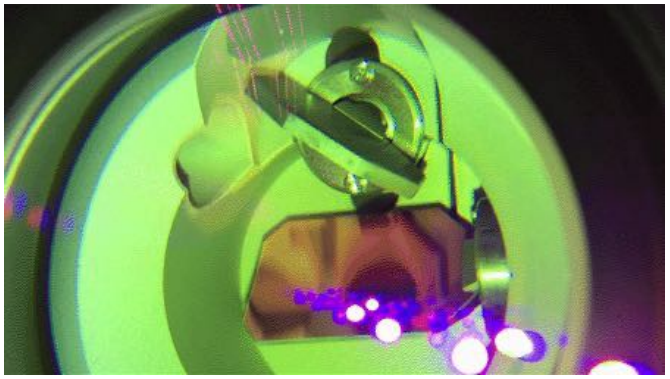
The Power of Feedback and Prediction





A. Emami-Naeini and D. de Roover, 'Control in Semiconductor Wafer Manufacturing':1--12, November, 2008.
X. Chen and M. Tomizuka, 'Overview and new results in disturbance observer based adaptive vibration rejection with application to advanced manufacturing'. *International Journal of Adaptive Control and Signal Processing*, 29:1459-1474, 2015. http://dx.doi.org/10.1002/acs.2546.

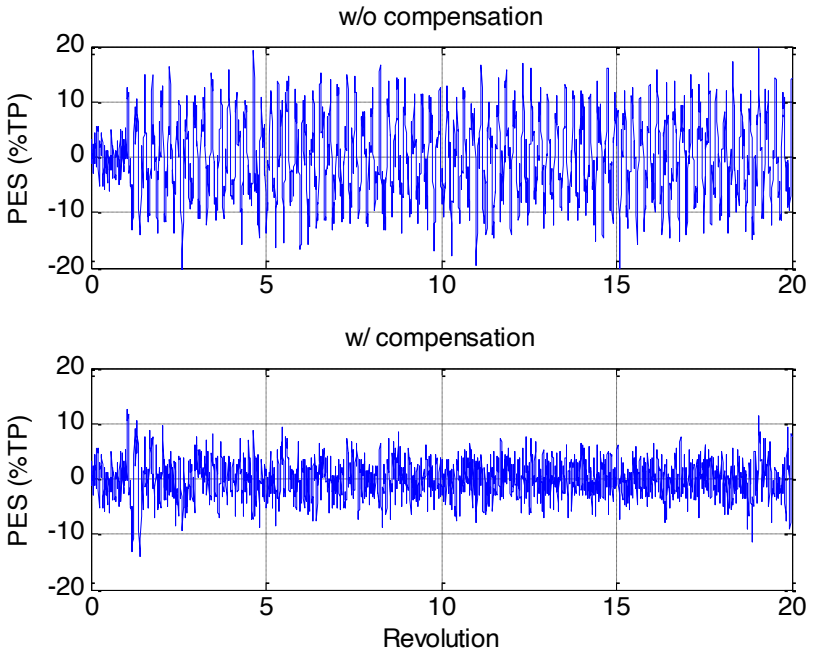
More Broadly: High-Speed Precision Mechatronics Under Nano/micro-meter Error Bounds

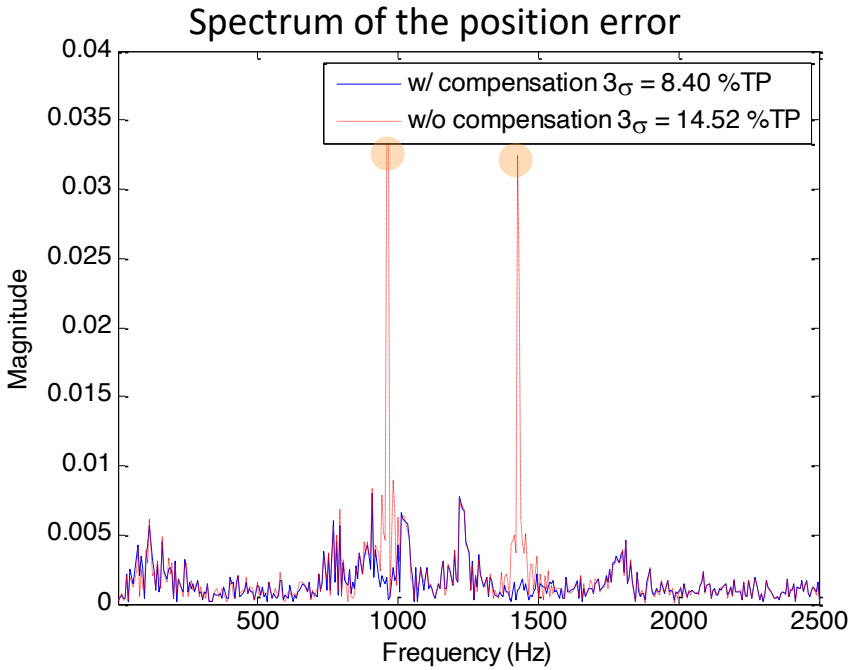




Imagine an airplane flying at **500,000 miles per hour** but only **1/16 inch** above the ground on a highway with **100,000 lanes** where the width of each lane is **only fraction of an inch**. The challenge of the problem is further intensified by the fact that the airplane is expected to **switch lanes frequently** and then follow the new lane with the same precision. A scaled down version of this scenario is what one finds in the head positioning servomechanism of a hard disk drive.

Abdullah Al Mamun, Guoxiao Guo, and Chao Bi, 'Hard disk drive: mechatronics and control', 2007.

Challenge from Hardware Imperfection





Complicated vibration sources:

- Complex air dynamics
- Product-dependent characteristics

X. Chen and M. Tomizuka. “A Minimum Parameter Adaptive Approach for Rejecting Multiple Narrow-Band Disturbances with Application to Hard Disk Drives”. In: IEEE Transactions on Control Systems Technology 20.2 (Mar. 2012), pp. 408–415.

Challenge from Operation Environment

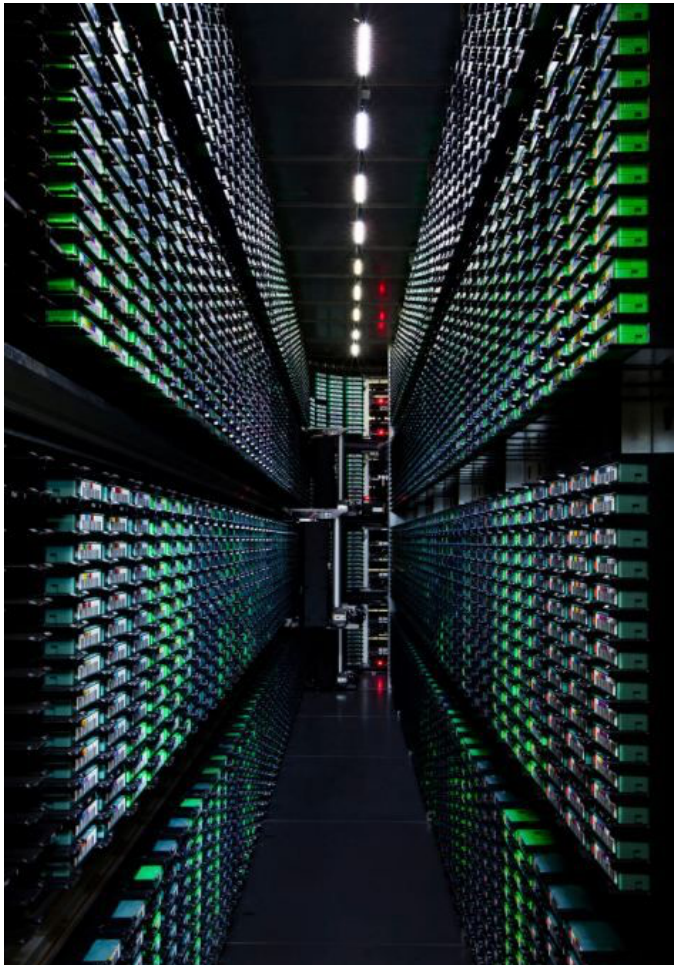


Image Credit: Facebook

Challenge from Operation Environment

A Loud Sound Just Shut Down a Bank's Data Center for 10 Hours

Dozens of hard drives were knocked down during a fire drill that involved inert gas deployment.

SHARE TWEET

Andrada Fiscutean
Sep 11 2016, 2:00pm

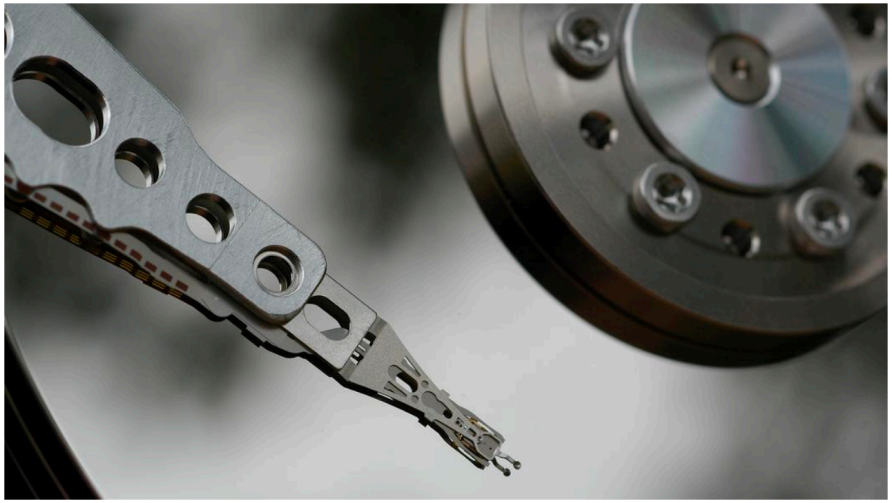
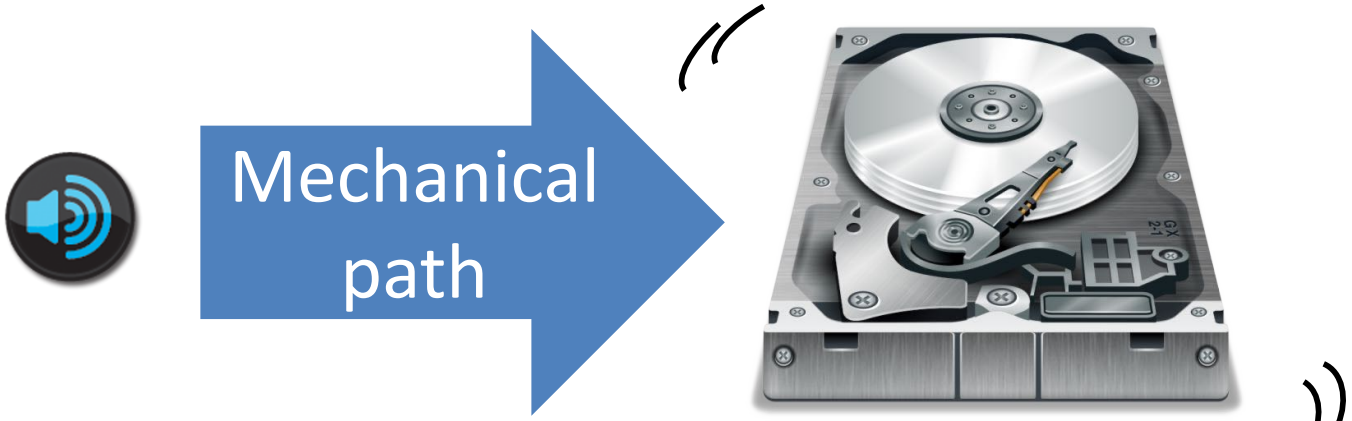
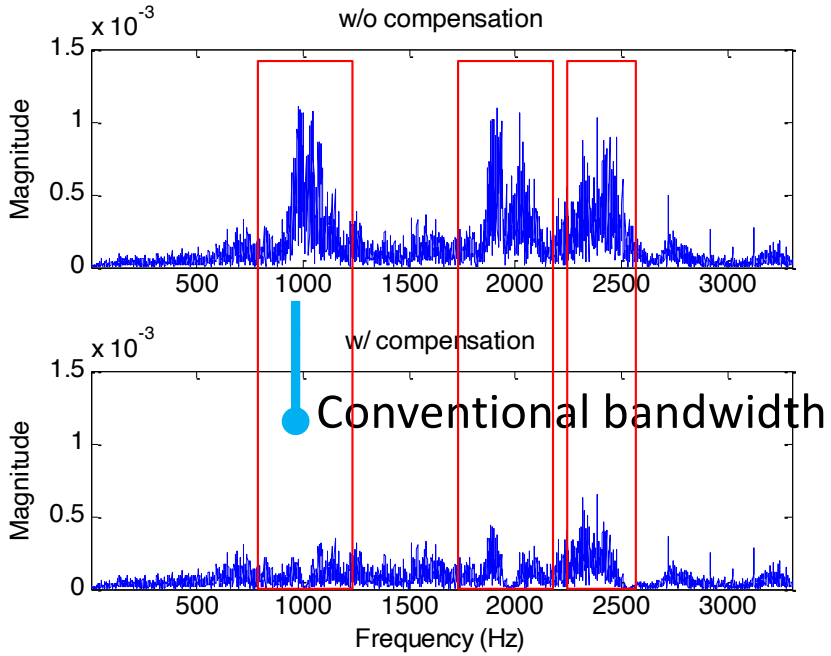


Image: Jeff Kubina/Flickr.

The Need for Advanced Controls



Position Error spectrum

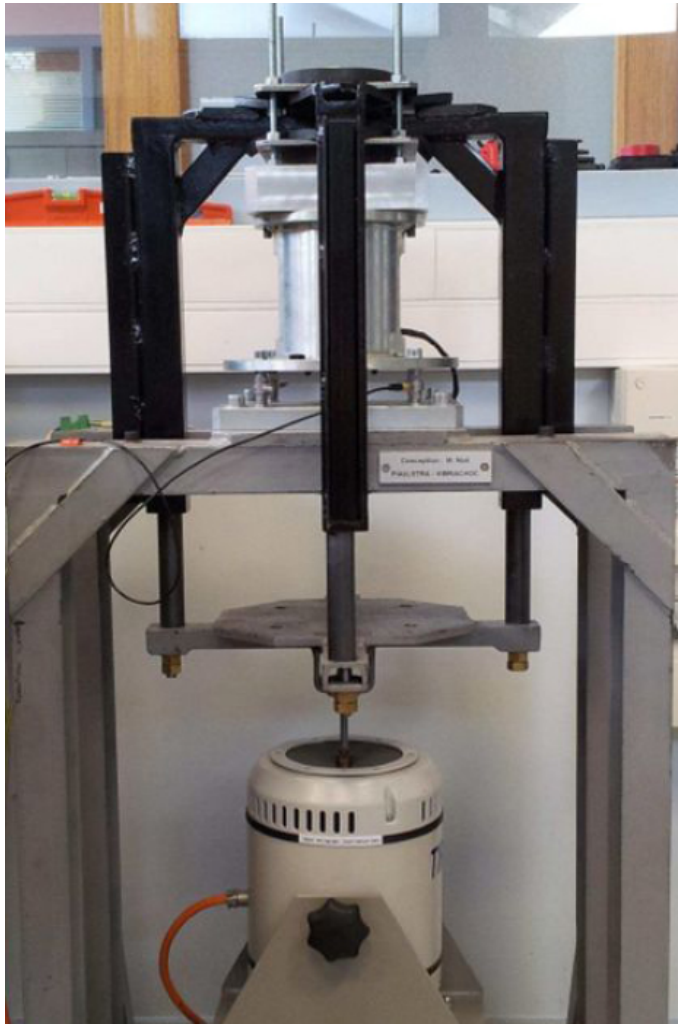


- Multiple resonances
- Wide spectral peaks
- Environment dependent
- Wide frequency range

X. Chen, T. Jiang, and M. Tomizuka. “Pseudo Youla-Kucera Parameterization with Control of the Waterbed Effect for Local Loop Shaping”. In: Automatica 62 (2015), pp. 177–183.

L. Sun, T. Jiang, and X. Chen. “Adaptive Loop Shaping for Wideband Disturbances Attenuation in Precision Information Storage Systems”. In: IEEE Transactions on Magnetics 53.5 (May 2017), pp. 1–13.

Example 2: Active Suspension and Adaptive Control

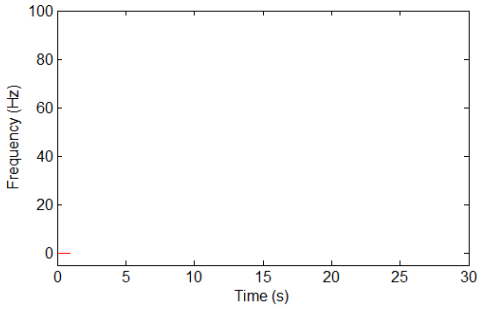


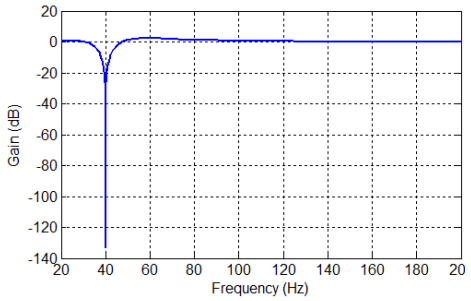
Applications:

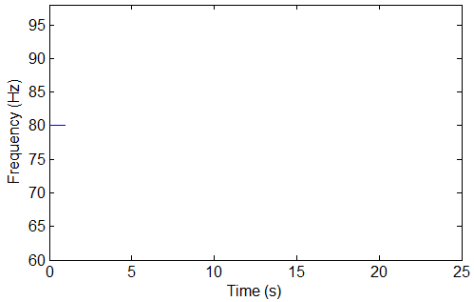
- Vibration isolation for precision machines
- Building protection
- Automotive vehicles

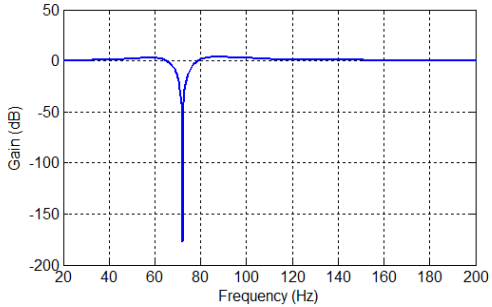
…

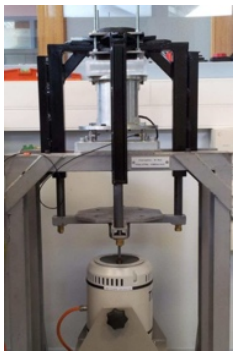
Adaptive Control Over Heterogeneous Uncertainties

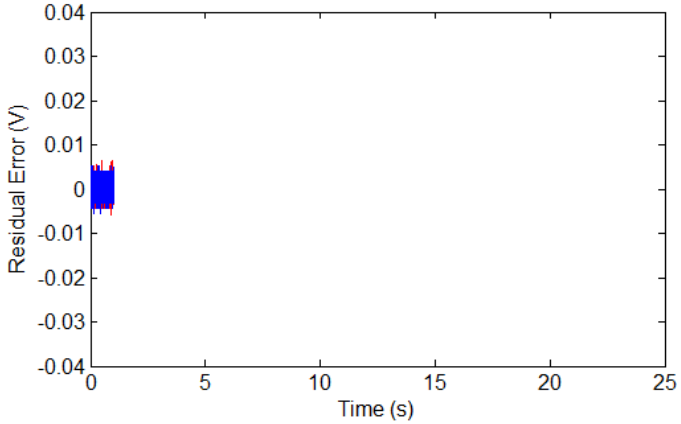












Red: w/o compensation

Blue: w/ adaptive compensation

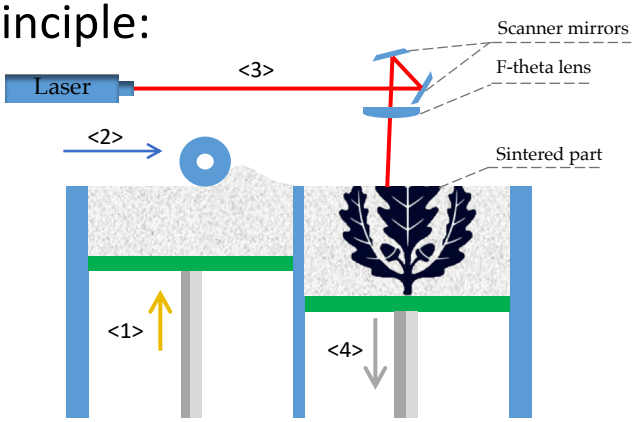
X. Chen and M. Tomizuka. “Selective Model Inversion and Adaptive Disturbance Observer for Time-Varying Vibration Rejection on an Active-Suspension Benchmark”. In: European Journal of Control 19.4 (2013), pp. 300–312.

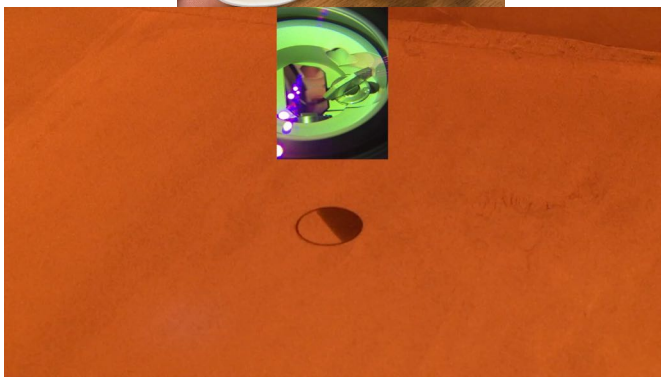
H. Xiao *, I. D. Landau, and X. Chen. “A Robust Optimal Design for Strictly Positive Realness in Recursive Parameter Adaptation”. In: International Journal of Adaptive Control and Signal Processing 31.8 (2017), pp. 1205–1216.

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

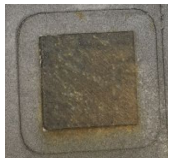
Example 3: Powder Bed Fusion AM

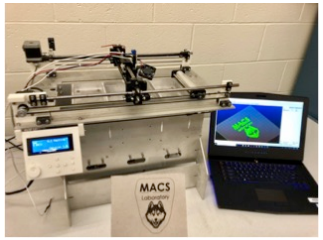
Principle:

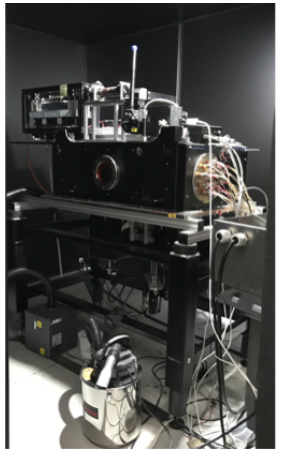




Realization:

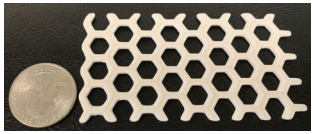






- In-House Developed Software in NI Labview
- 270x270x270mm^3 build volume
- 30kW Multi-zone heated chamber and bed
- High-precision laser galvoscanner
- Coaxial sensing and multi-sensory control

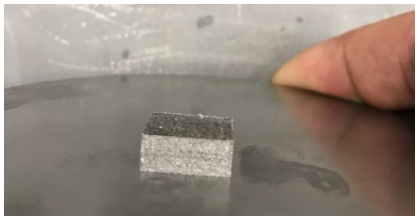
Selected Results:



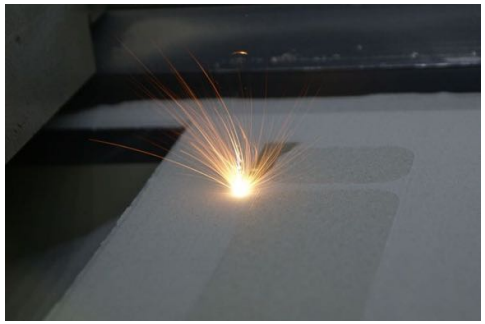
PA12 PCL bead

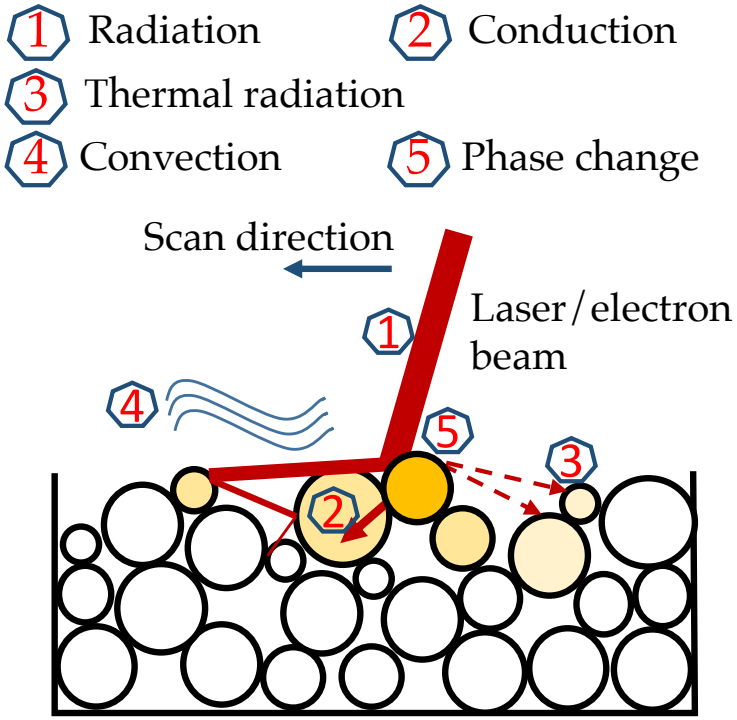
100% recycled PA12

Inconel 718



Challenge from Intricate PBF Thermal Physics





GOVERNING HEAT TRANSFER

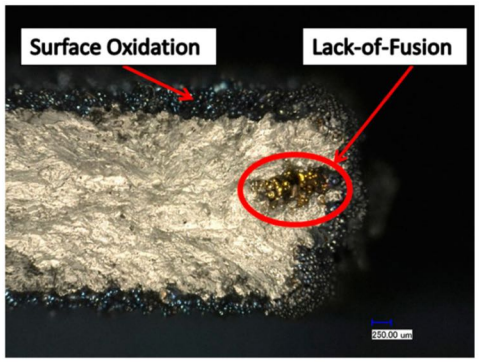
$$\rho\sigma\dot{T} = -\mathbf{div}\ \mathbf{\Phi} + q$$
$$\mathbf{\Phi} = -\mathbf{k}\nabla T$$
$$T(\mathbf{x}_T, t) = \bar{T},\ \text{on powder-bed boundary}$$
$$\mathbf{\Phi}(\mathbf{x}_q, t) = \bar{\mathbf{\Phi}} \cdot \mathbf{n},\ \text{on object boundary}$$
$$T(\mathbf{x}, 0) = T_o,\ \text{initial condition}$$

(Lawrence Livermore National Lab 2014-2017)

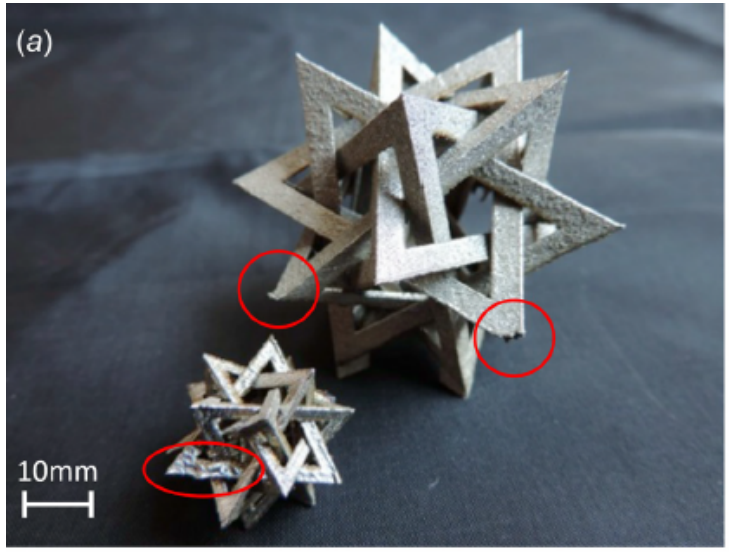
ρ : powder density
σ : specific heat
$\mathbf{\Phi}$: heat flux density
q : forcing term
$\mathbf{k}$: thermal conductivity
$\mathbf{n}$: normal direction to boundary

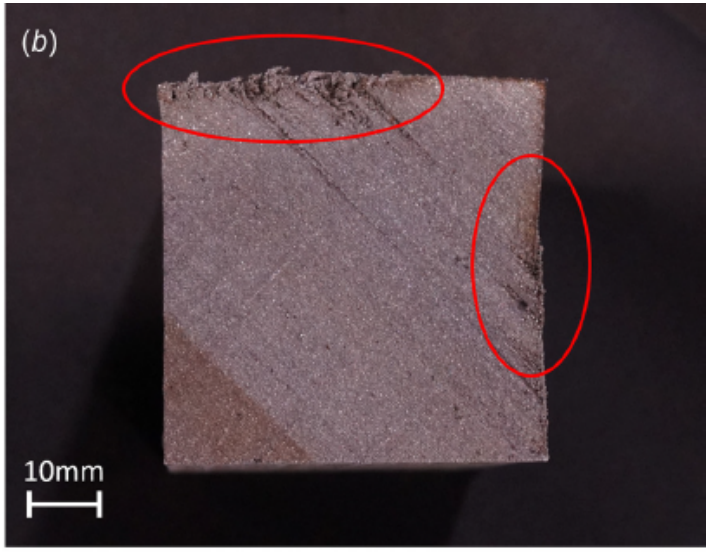
phase change: Stefan problem

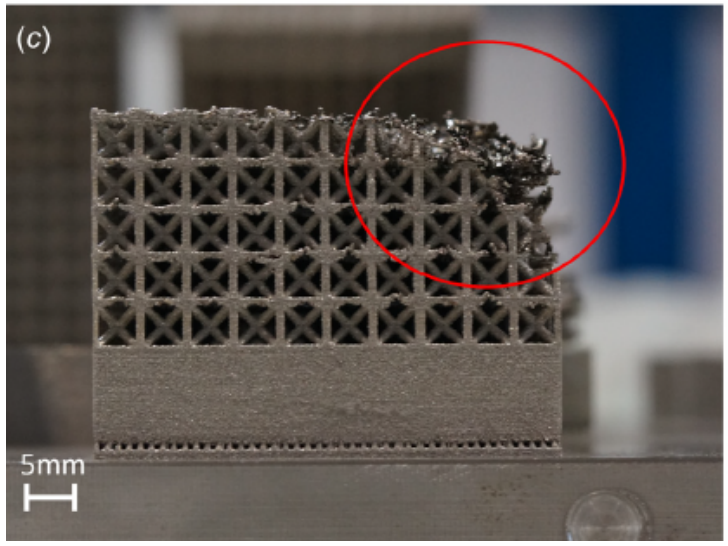
Gaps in Quality Assurance

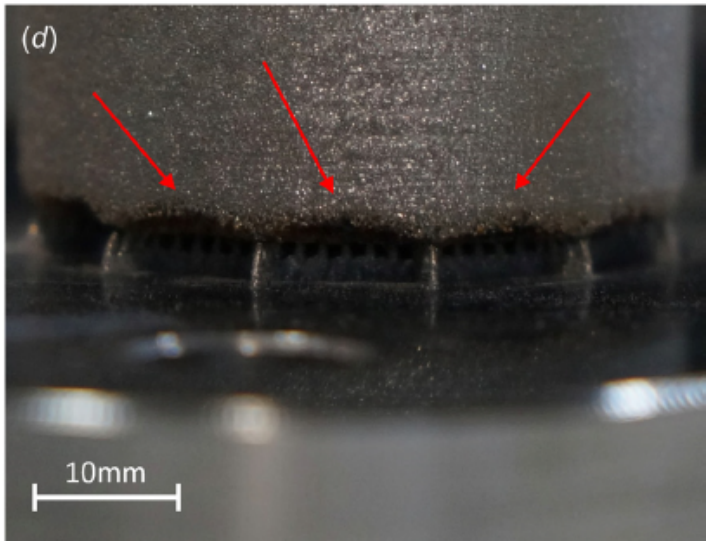


Thin-wall Inconel 718
(Sames et al. 2016)









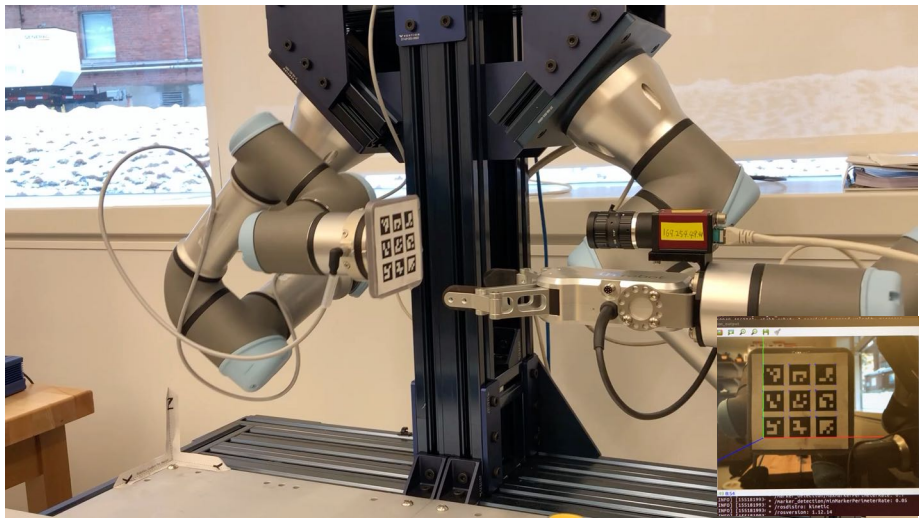
Defective parts (AISI 316L): (a)(c). Improper heat conduction; (b). Worn blade deposition (d). Overhang structure (Marco et al. 2016)

Example 4: Quality Controls beyond the Sensing Limit

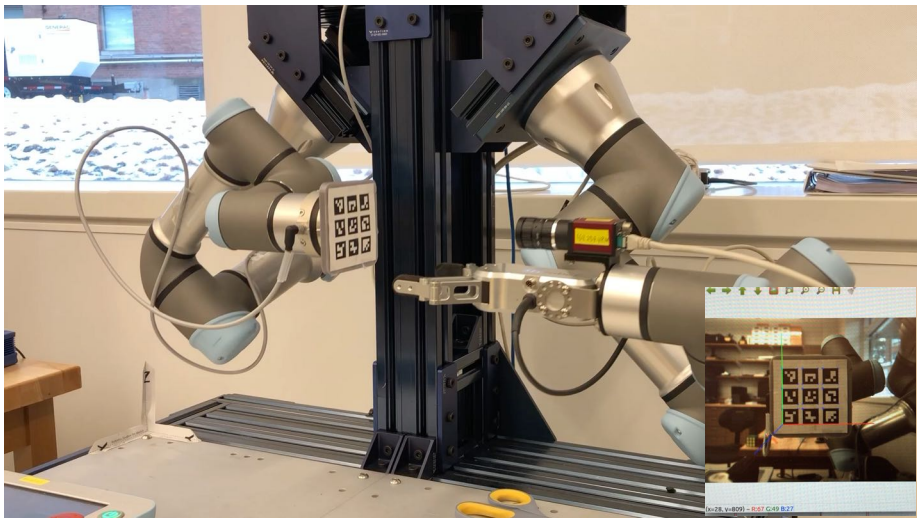
https://www.youtube.com/watch?v=BVlFq1WZZaY

https://www.youtube.com/watch?v=XeU3bcX_vTA

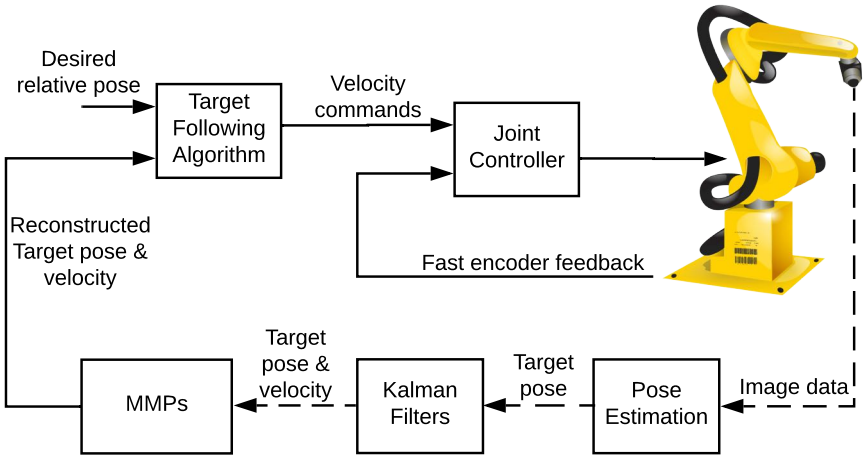
Vision Servo beyond the Nyquist Limit



w/ standard control



w/ proposed control



Multirate model-based predictions

Challenges:

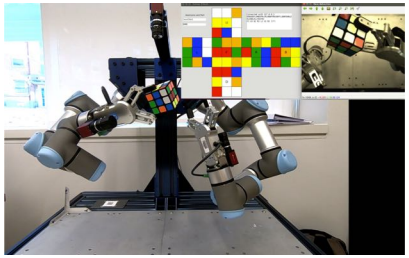
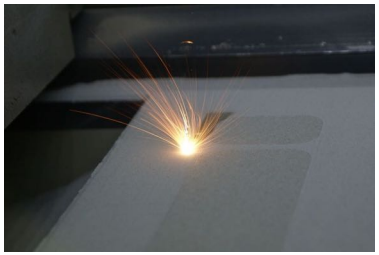
- Slow sensor, fast dynamics
- Communication delay

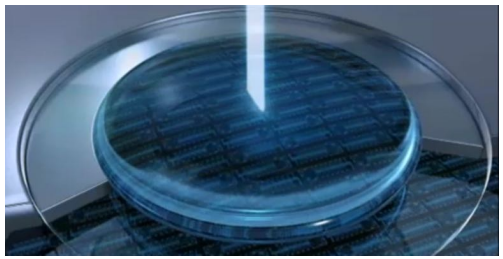
Approaches:

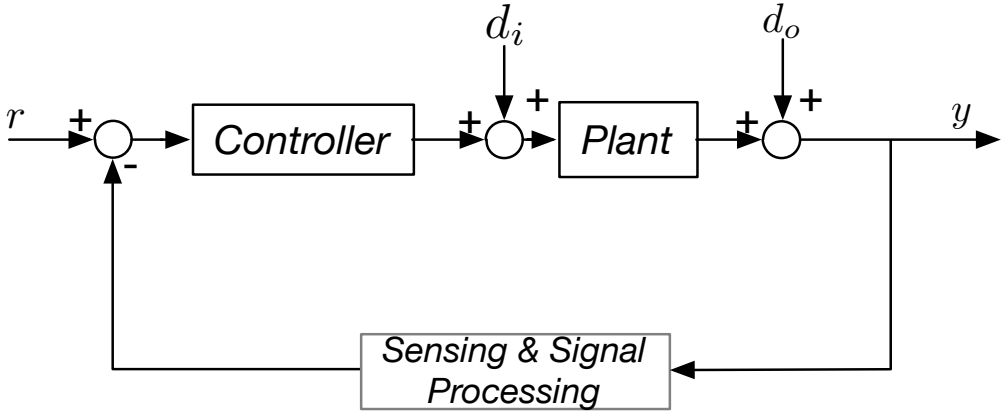
- Tailored target modeling
- Advanced sensor control
- Multirate controls

H. Xiao and X. Chen. Robotic Target Following with Slow and Delayed Visual Feedback. International Journal of Intelligent Robotics and Applications, 4, 378-389, 2020. https://doi.org/10.1007/s41315-020-00151-2

Summary: Roles of Systems and Control Engineering

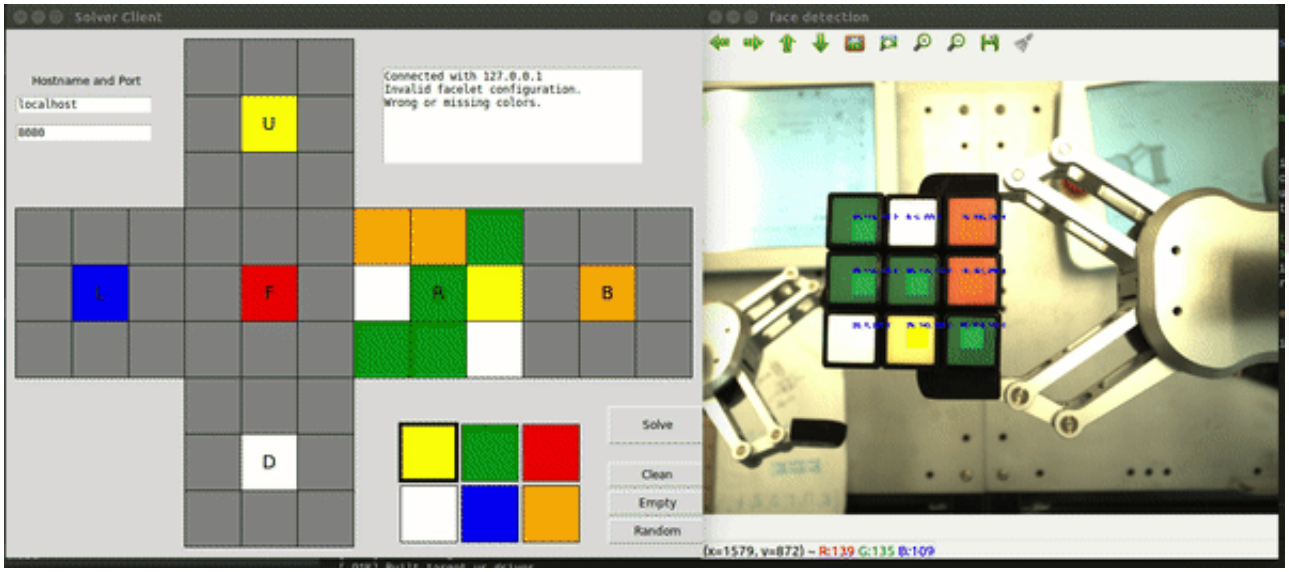



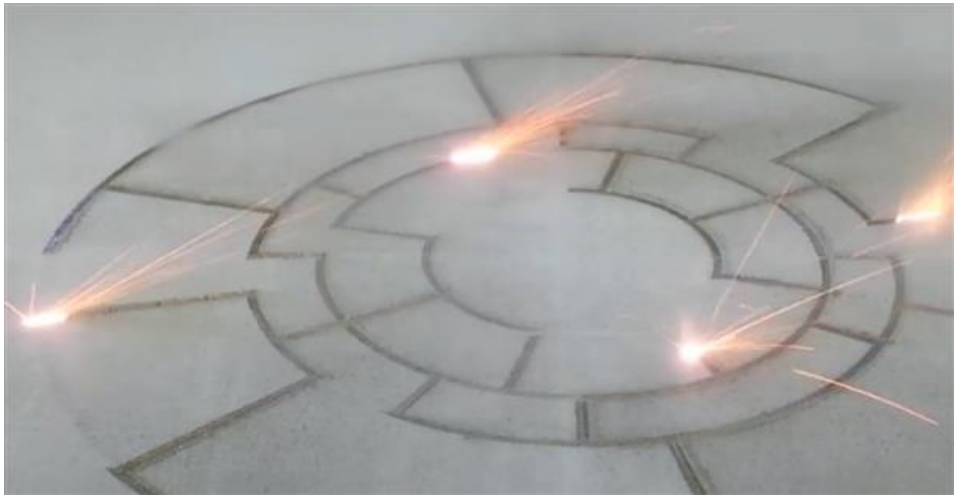


Hardware	Precision Mechatronics
Task Arrangement	System Automation and Supervision
Dedicated Control	Vibration Suppression, Trajectory Tracking, Temperature Regulation, etc

Many Exciting Problems Remain





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