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Brazilian Center for Research in Energy and Materials

LNLS
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System Identification and Robust Control for the LNLS Fast Orbit Feedback System

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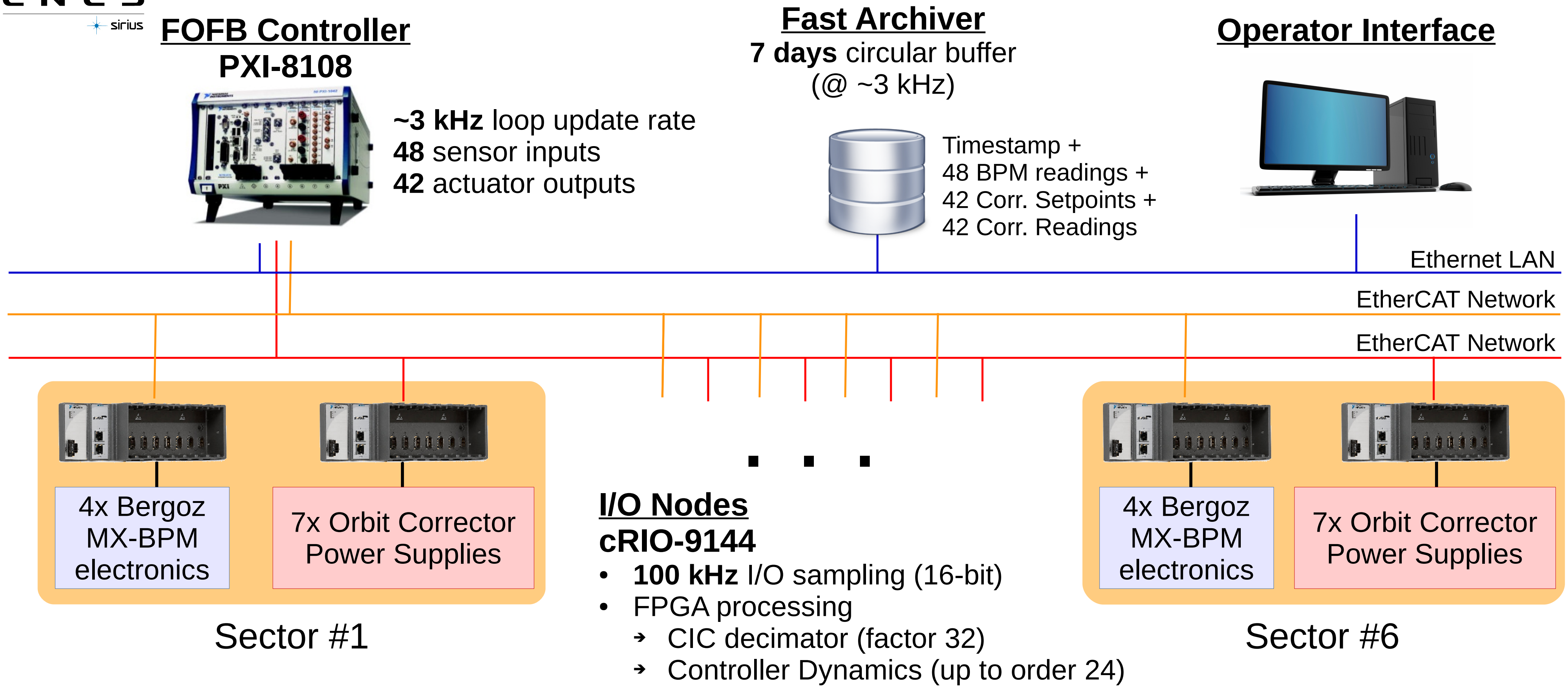
Outline

- **LNLS Fast Orbit Feedback Overview**
- **System Identification**
  - Model Structure
  - Experiments
  - Black-box Modeling
  - Results
  - Model Uncertainty
- **Control Design**
  - Controller Structure
  - Performance and Robustness Metrics
  - Weights
  - Optimization
  - Simulation Results
- **Conclusion**

LNLS Fast Orbit Feedback Overview



LNLS Fast Orbit Feedback Overview

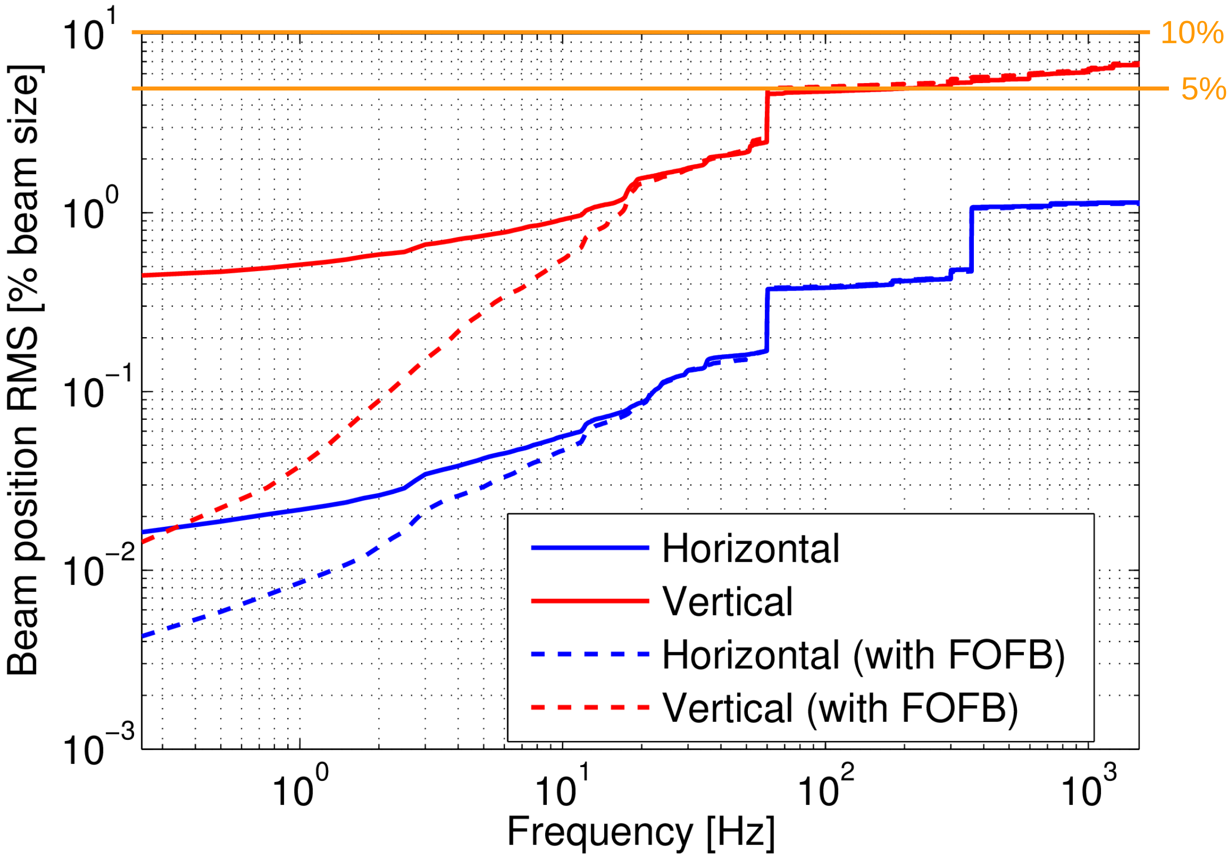
LNLS storage ring orbit stability: within 10% beam size without FOFB

Vibrations: < 2% beam size

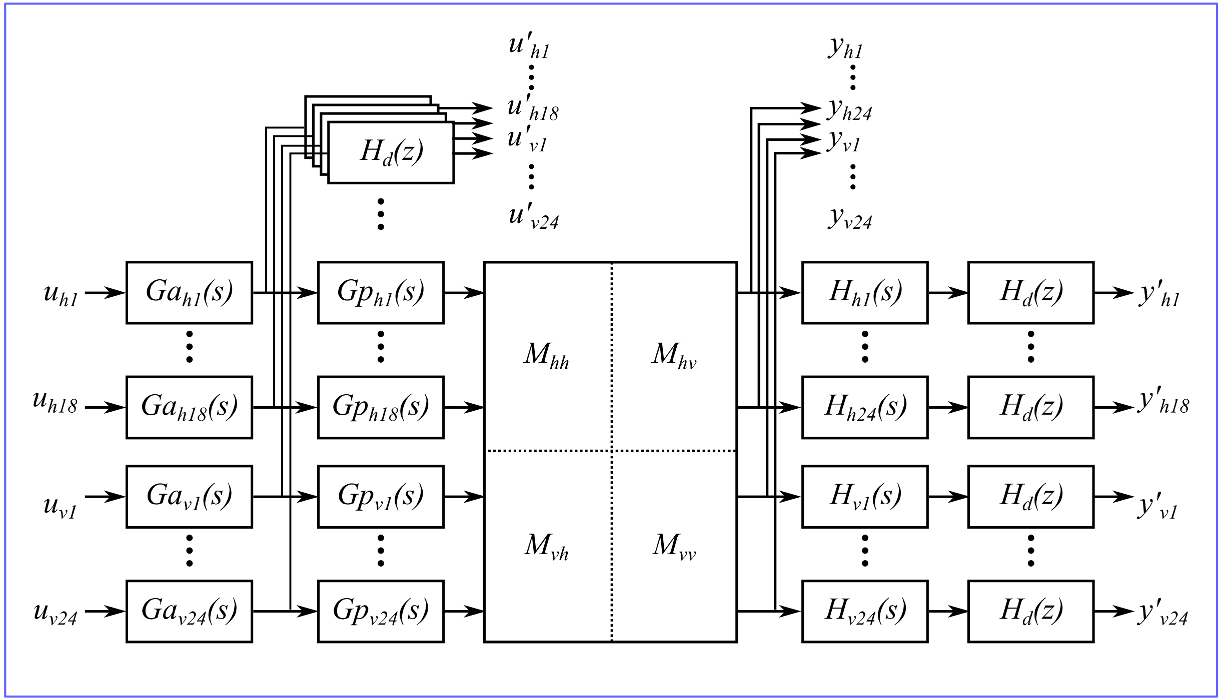
Power supply ripple: 5% beam size

FOFB is essential for mitigating undulator (EPU) disturbances

Electron beam sizes (1-sigma) at BPMs:
Horizontal: 870 µm – 1.30 mm
Vertical: 58 µm – 86 µm



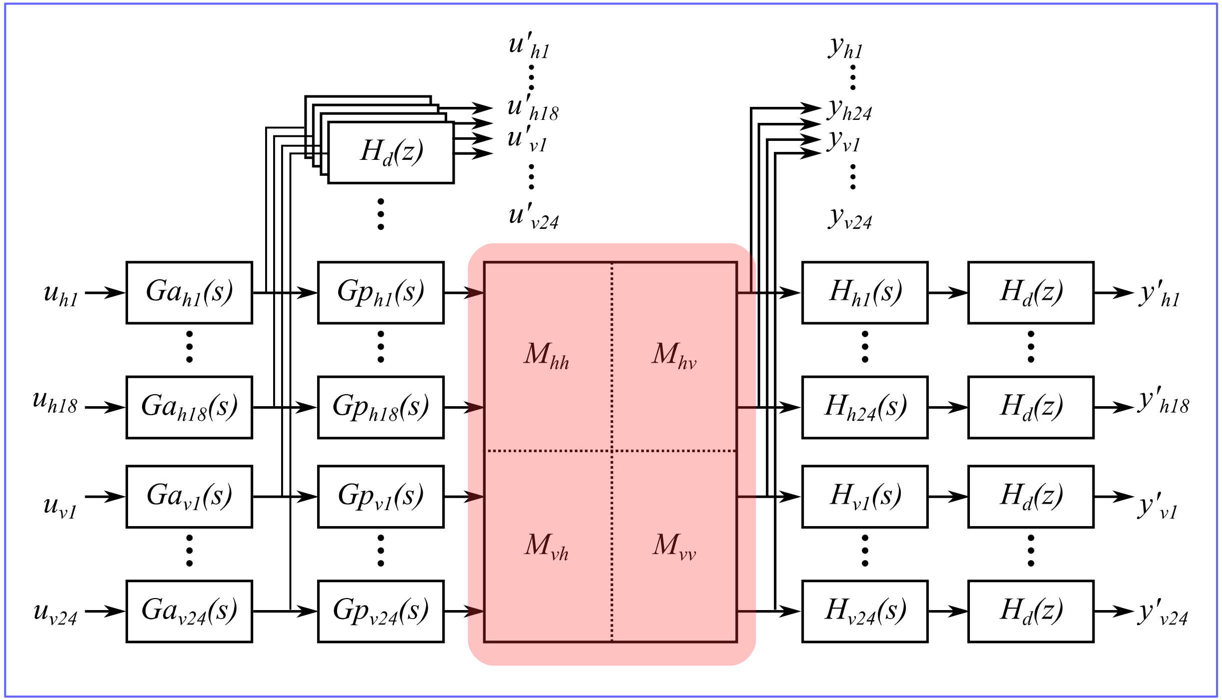
FOFB Model



u'_{h1}
u'_{h18}
u'_{v1}
u'_{v24}
$H_d(z)$
y_{h1}
y_{h24}
y_{v1}
y_{v24}
u_{h1}
u_{h18}
u_{v1}
u_{v24}
$Ga_{h1}(s)$
$Ga_{h18}(s)$
$Ga_{v1}(s)$
$Ga_{v24}(s)$
$Gp_{h1}(s)$
$Gp_{h18}(s)$
$Gp_{v1}(s)$
$Gp_{v24}(s)$
M_{hh}
M_{hv}
M_{vh}
M_{vv}
$H_{h1}(s)$
$H_{h24}(s)$
$H_{v1}(s)$
$H_{v24}(s)$
$H_d(z)$
$H_d(z)$
$H_d(z)$
$H_d(z)$
y'_{h1}
y'_{h18}
y'_{v1}
y'_{v24}

System Identification – Model Structure

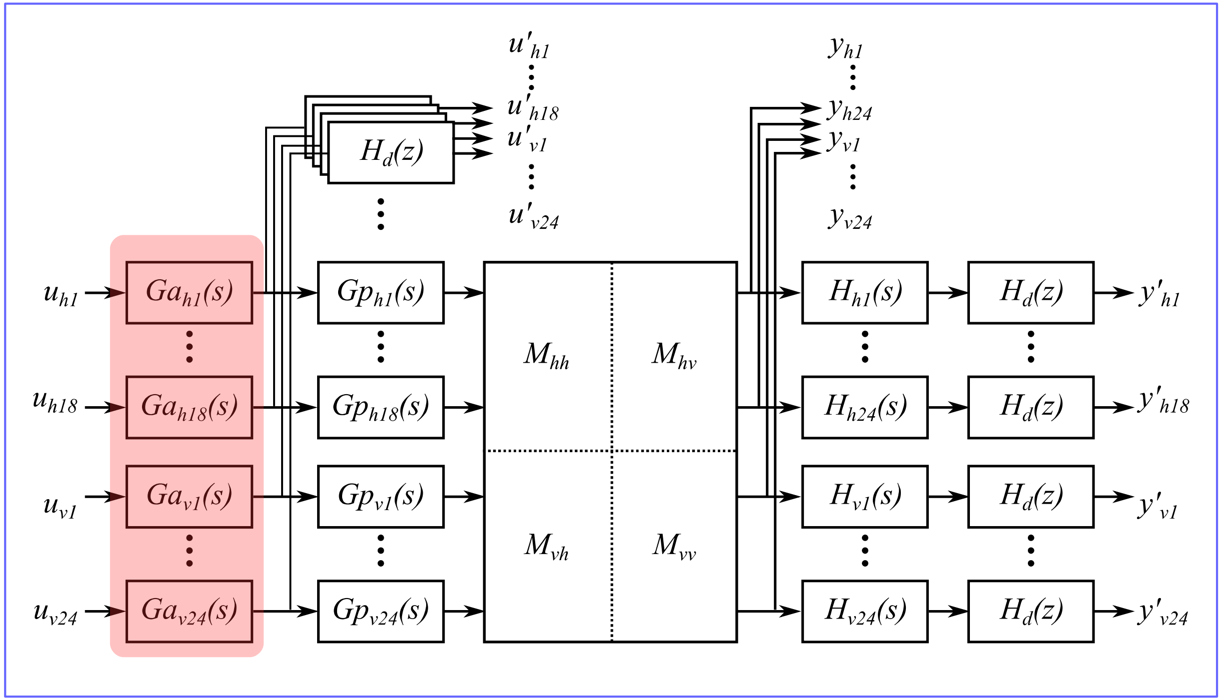
FOFB Model



- **Static Orbit Response Matrices**

System Identification – Model Structure

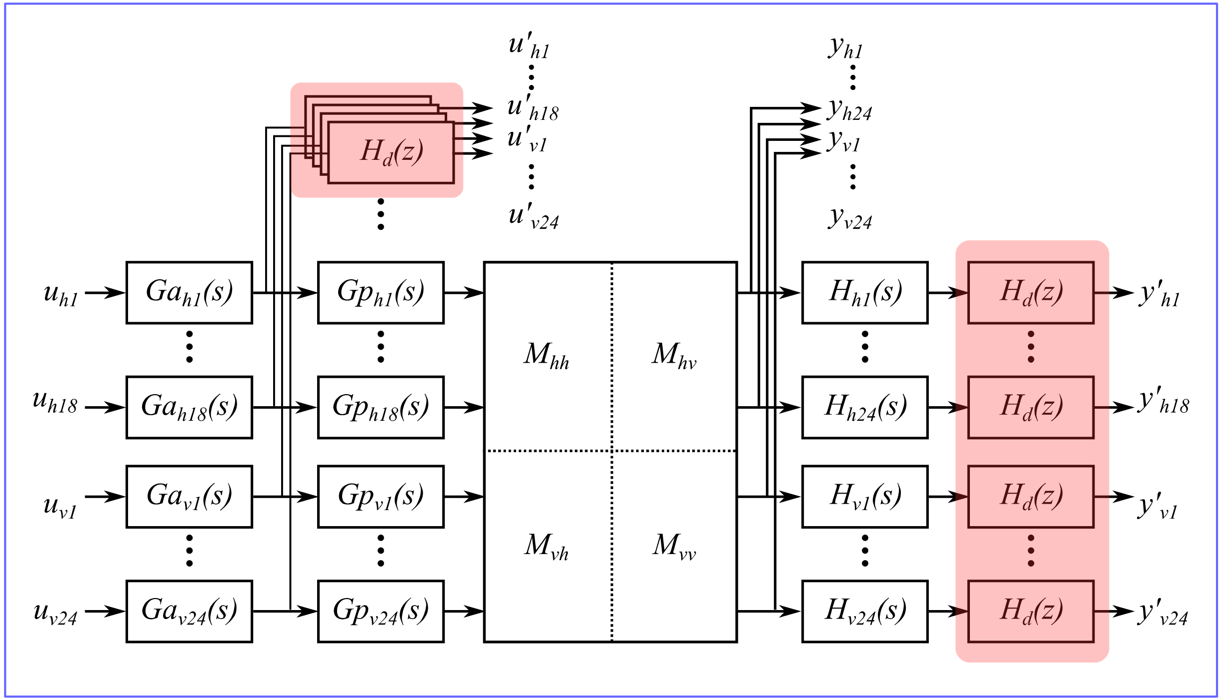
FOFB Model



- Static Orbit Response Matrices
- **Orbit Corrector Power Supply + Magnet Impedance**

System Identification – Model Structure

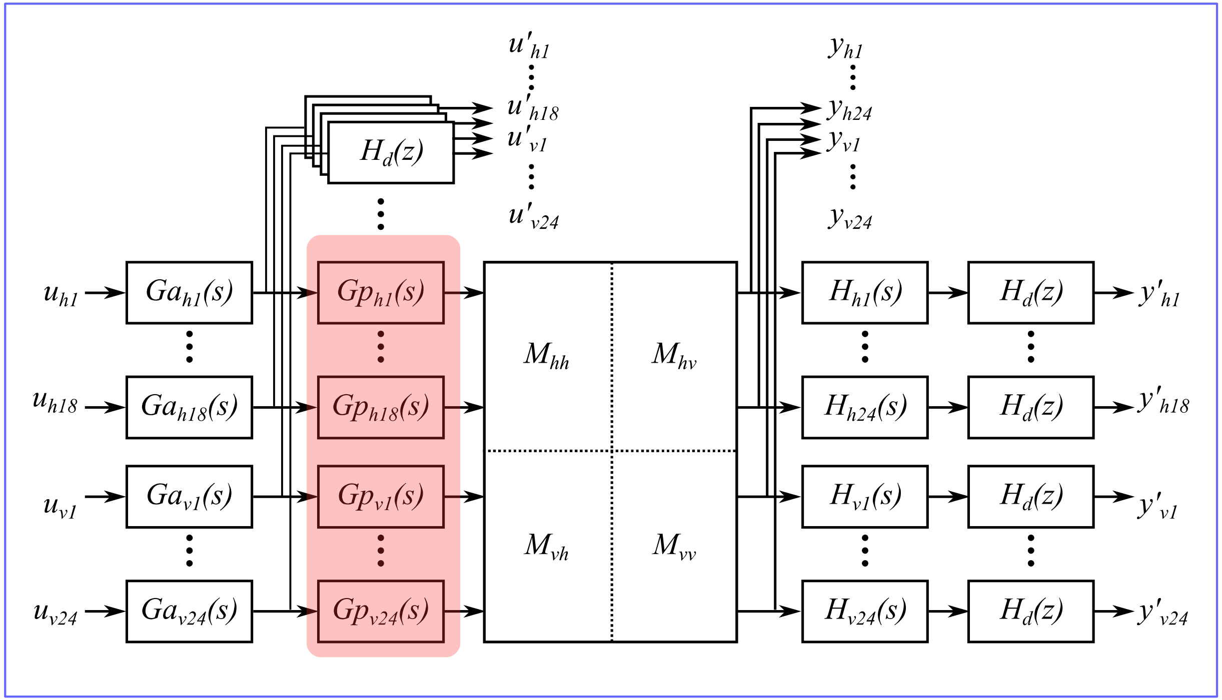
FOFB Model



- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
- **CIC Decimation Filter + Network Delay**

System Identification – Model Structure

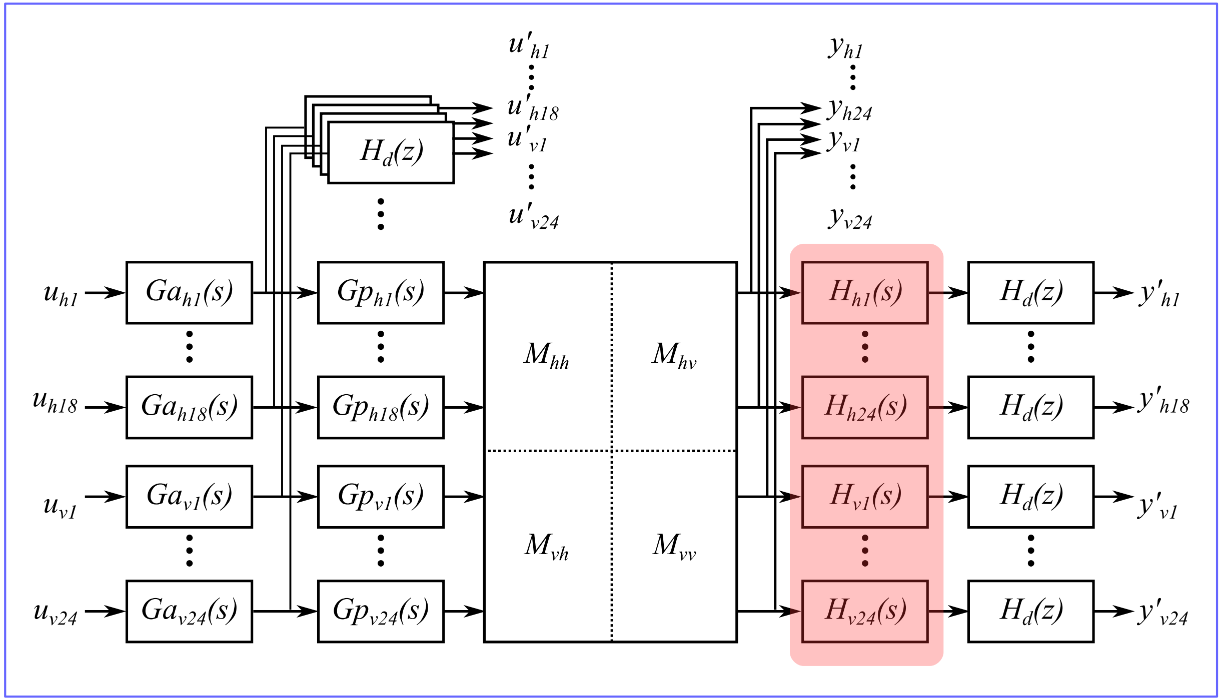
FOFB Model



- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
- CIC Decimation Filter + Network Delay
- **Magnet Core + Vacuum Chamber**

System Identification – Model Structure

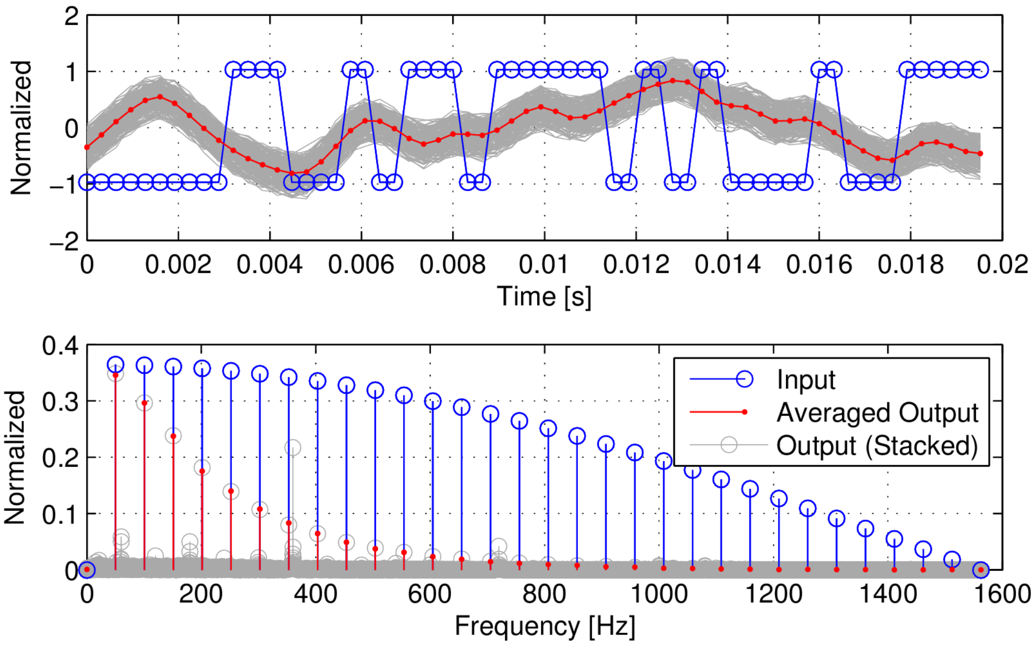
FOFB Model



- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
- CIC Decimation Filter + Network Delay
- Magnet Core + Vacuum Chamber
- **BPM Electronics**

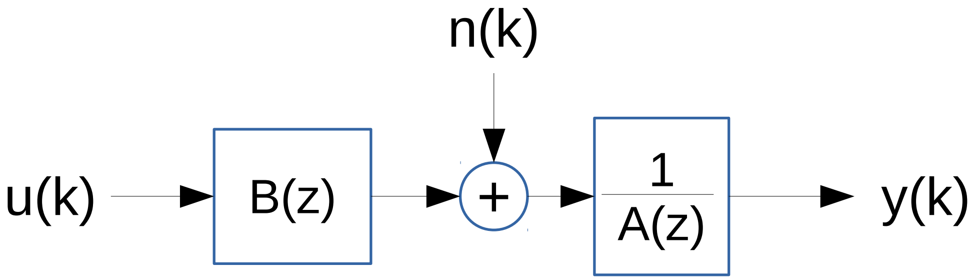
System Identification – Experiments

- Pseudo Random Binary Sequence (PRBS)
- One corrector excited at a time
- **62-point** PRBS sequence
- **750 Hz** bandwidth (-3 dB)
- **9.2 µrad** peak-to-peak excitation
- 42 input-output datasets for orbit correctors
- 48 input-output datasets for BPMs
- **Input signal spectral lines should not align with output spurious lines**



System Identification – Black-Box Modeling

- **Method:** Auto Regressive Model with Exogenous Input (ARX)
- Time-domain average
- **160 sequences** (62-sample long)
- **50% / 50%** of sequences are used for estimation and validation
- Bandwidth of interest: **0 – 500 Hz**

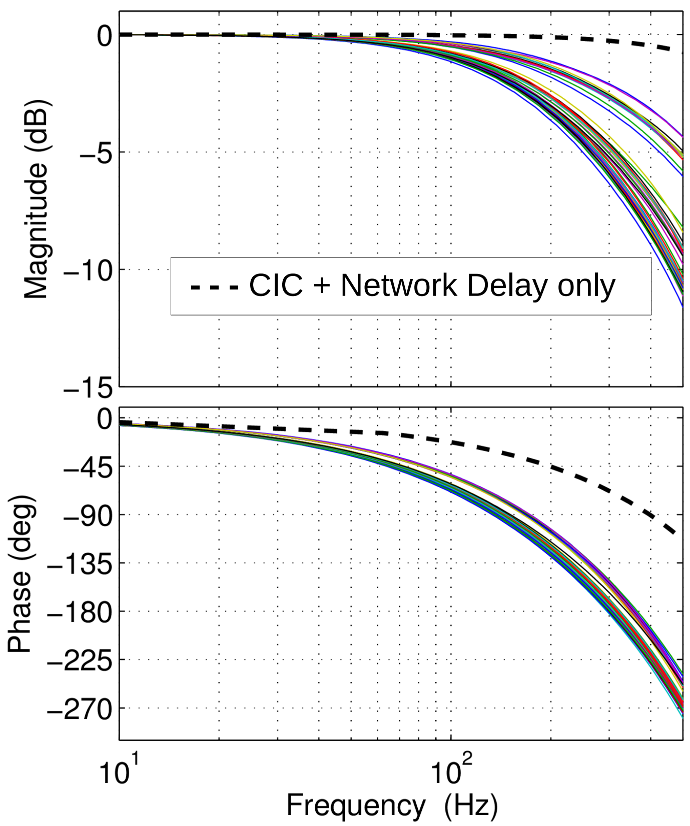


- **Orbit corrector Power Supply + CIC Decimator + Network Delay**
  - order 8 (16 parameters)
  - 3-sample delay

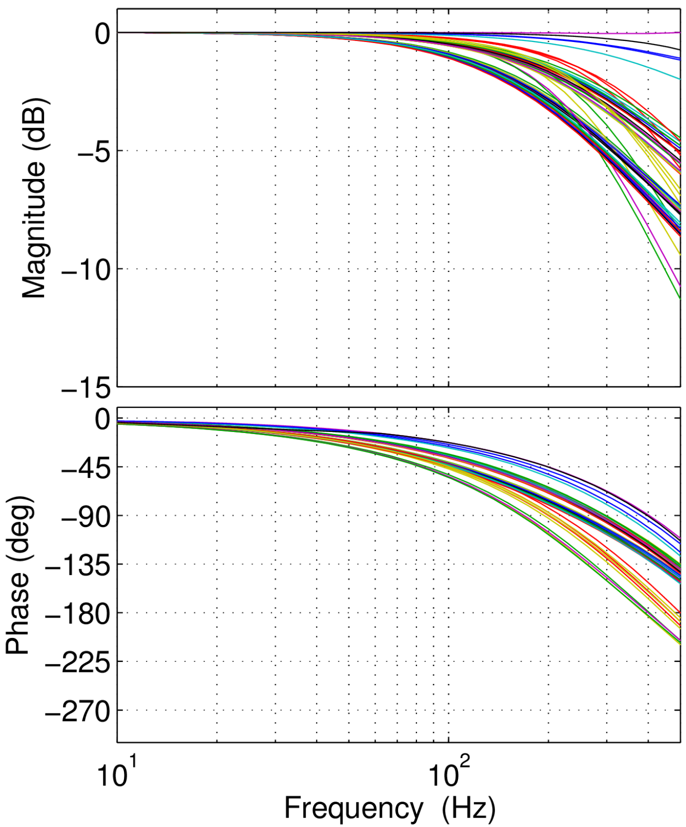
- **BPM + Magnet Core + Vacuum Chamber**
  - order 2 (4 parameters)
  - 1-sample delay

System Identification – Results

Orbit Corrector + CIC Decimator + Network Delay
Frequency Response



BPM + Corrector Magnet Core + Vacuum Chamber
Frequency Response



Data model validation

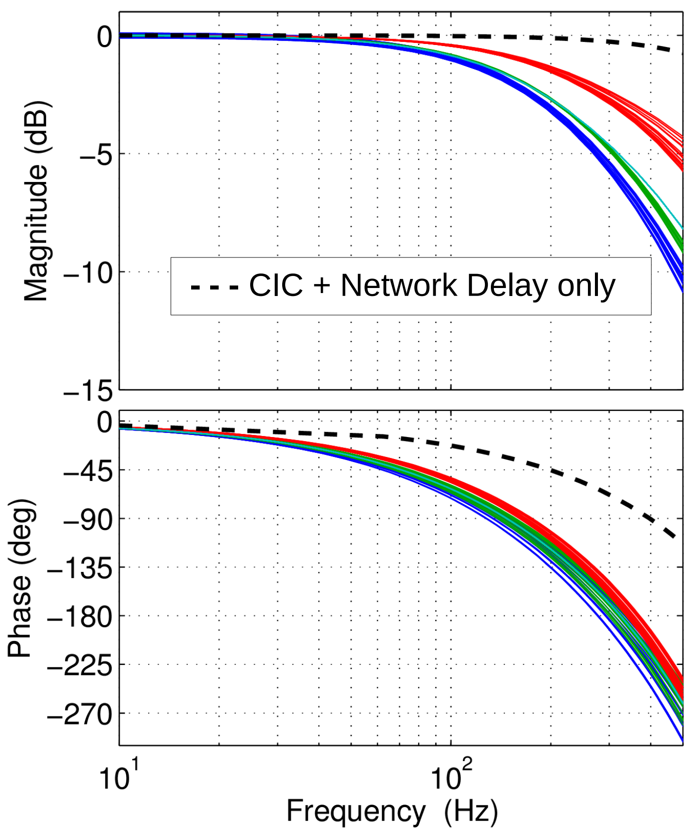
$$Fit_{\%}=100\left(1-\frac{\|y_{measured}-y_{model}\|_2}{\|y_{measured}-\overline{y_{measured}}\|_2}\right)$$

Orbit Correctors	BPMs
> 97%	> 91%

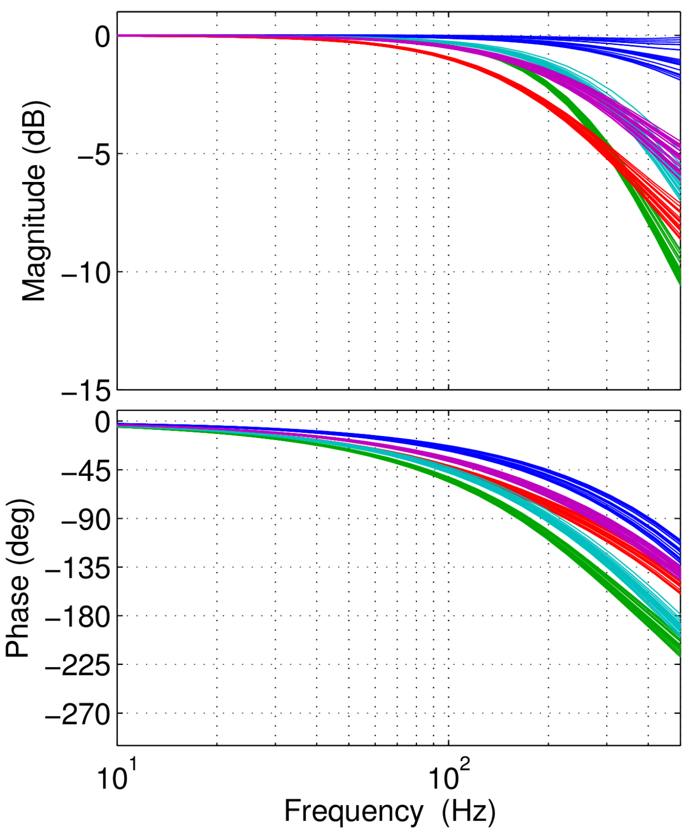
Residual analysis: no correlation between residues and inputs

Model Uncertainty

Orbit Corrector + CIC Decimator + Network Delay
Frequency Response Classes



BPM + Corrector Magnet Core + Vacuum Chamber
Frequency Response Classes



Input multiplicative uncertainty:

$$G_{uncertain}(z) = G_{nominal}(z)(1 + W(z)\Delta(z))$$

Norm-bounded uncertainty:

$$\|H(\Delta)\|_\infty < 1$$

Weighting transfer function (order 1): $W(z)$

- **4** classes for orbit correctors
- **5** classes for BPMs

Control Design – The Approach

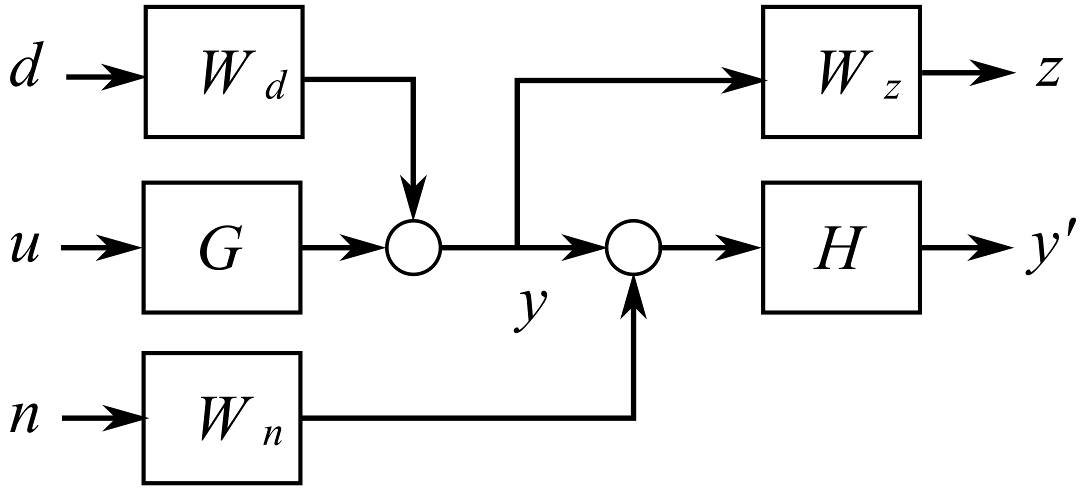
Signal-based Control
Detailed characterization of:
- Disturbances
- Noise
- Performance Goals

Robust Control Analysis
- Uncertainty Modeling
- Worst-case analysis

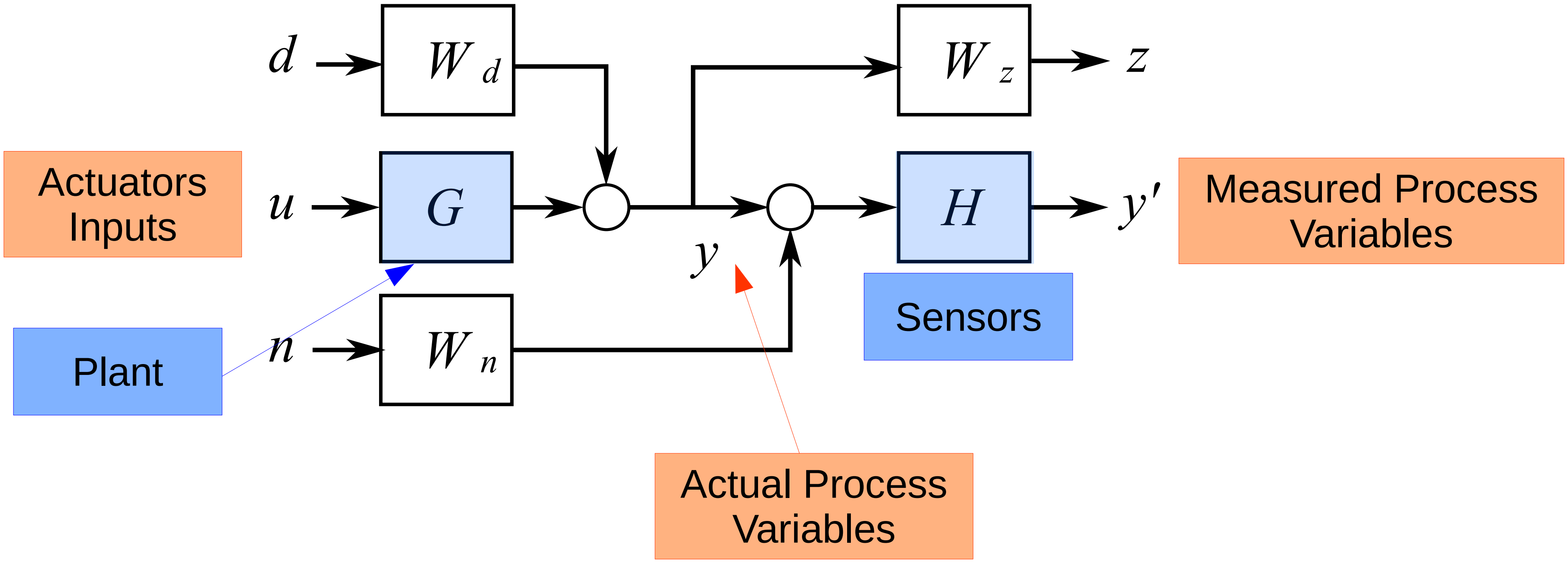
FOFB Control Design

Mixed H_2/H_∞ Optimal Control
- **H_2** to analyze and optimize performance
- **H_∞** to analyze and optimize nominal worst-case

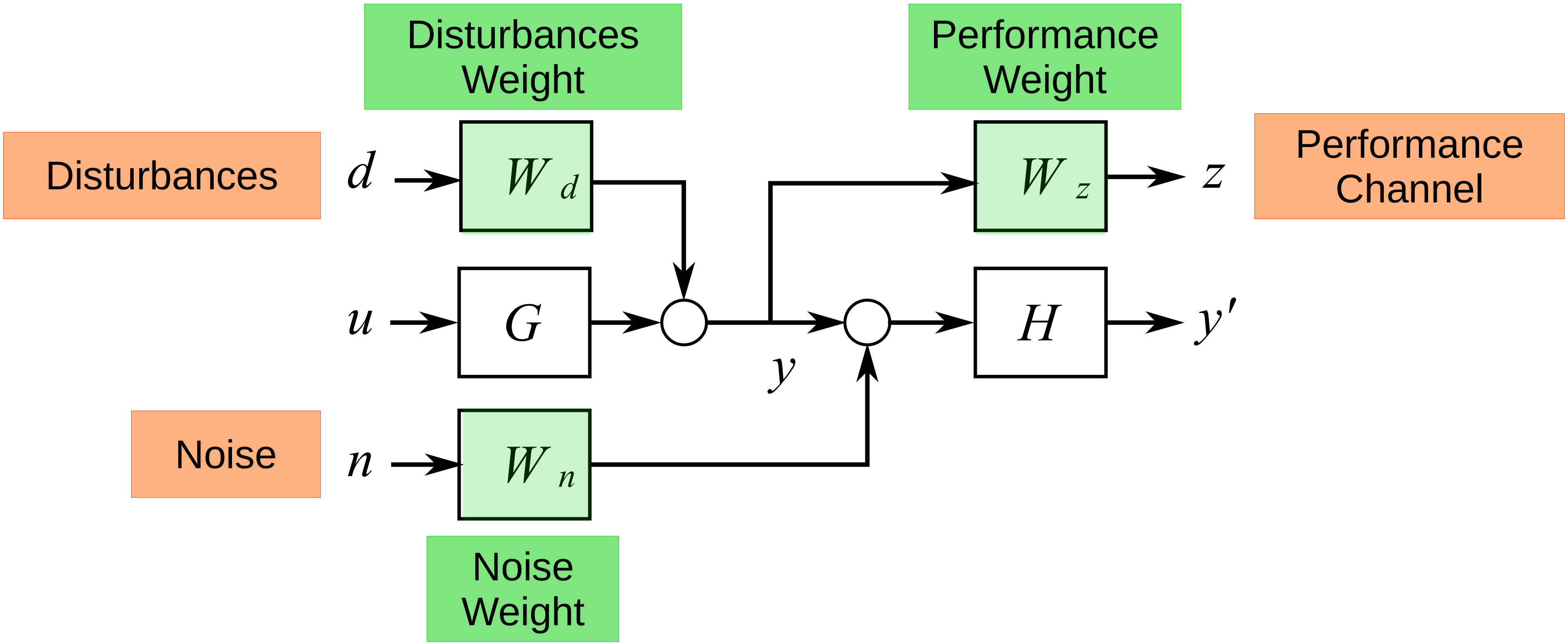
Control Design – Augmented Plant



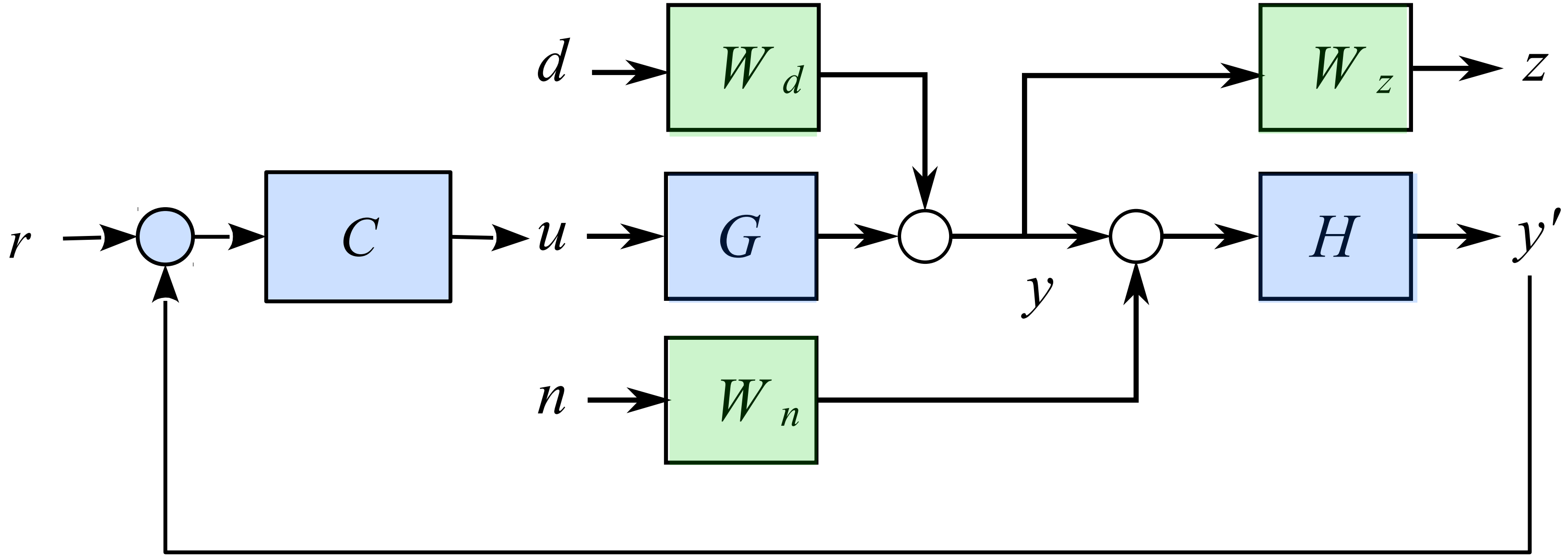
Control Design – Augmented Plant



Control Design – Weights



Control Design
Performance and Robustness Metrics



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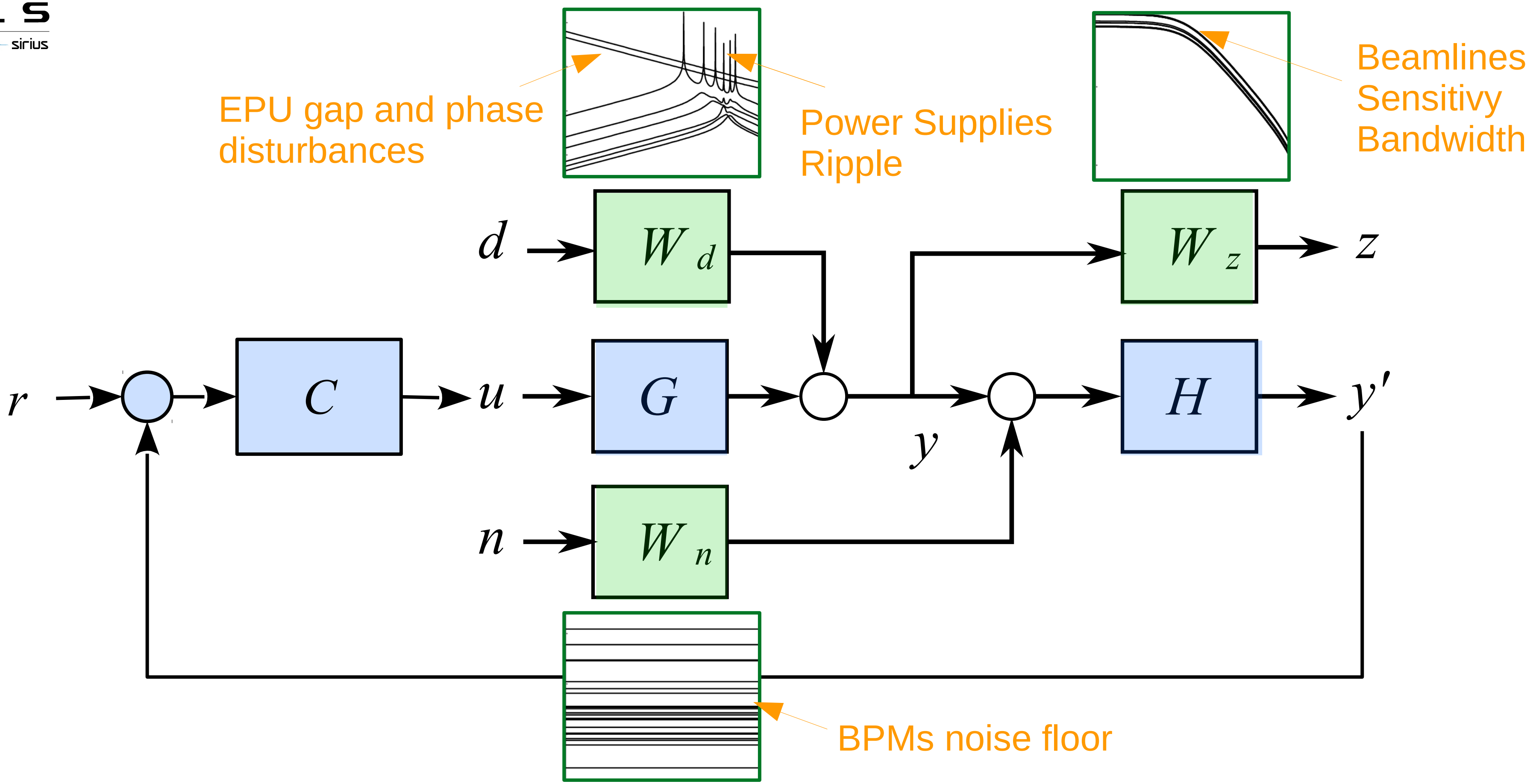
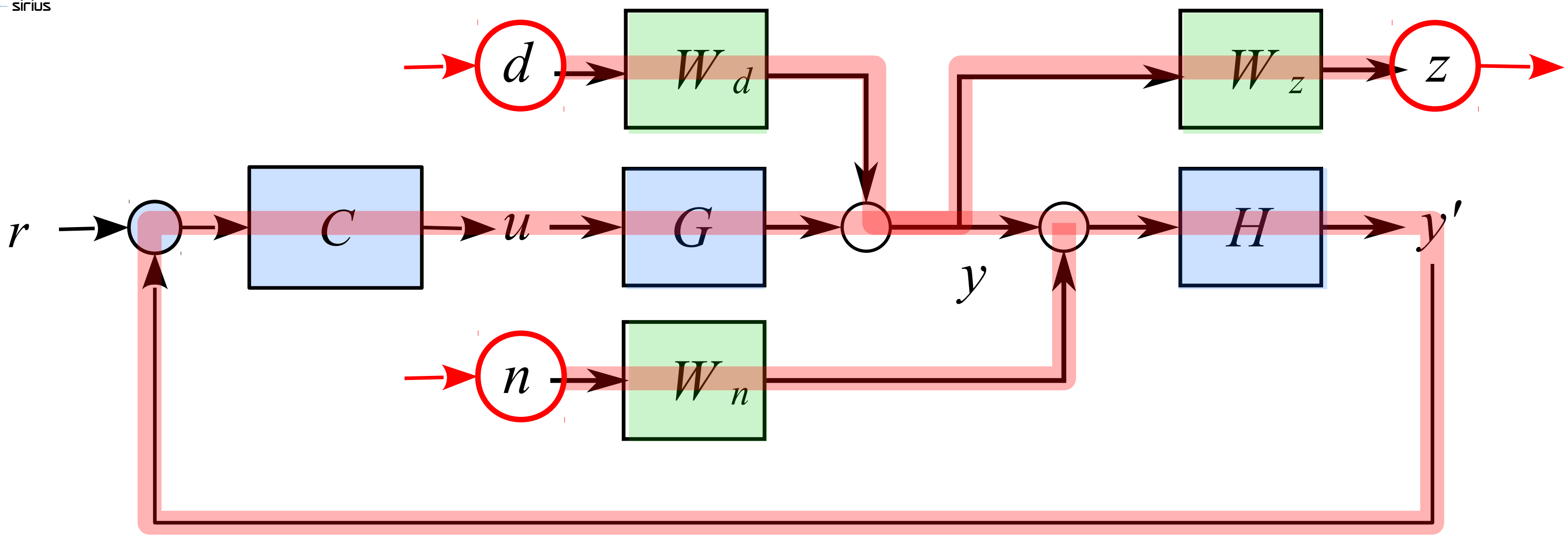


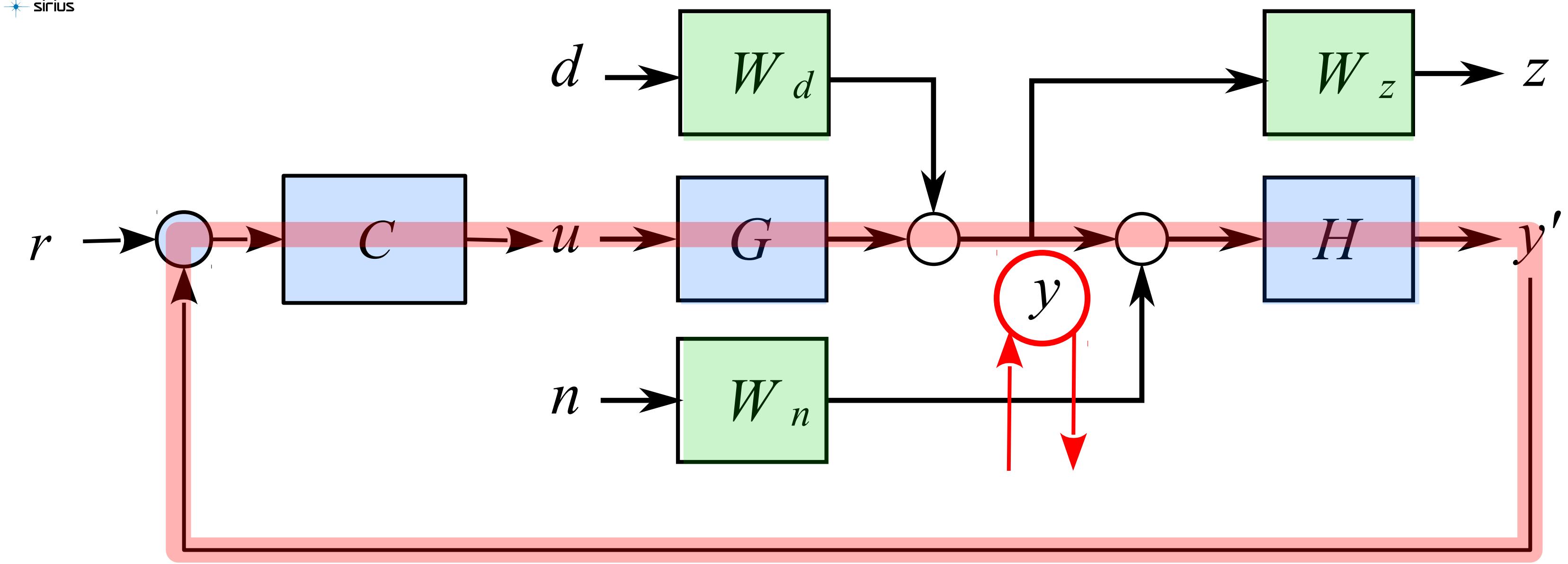
Control Design
Performance Metrics



$$||T_{d,n \to z}||_2$$

Quadratic cost (2-norm) between normalized input ***d*** + input ***n*** and output ***z***

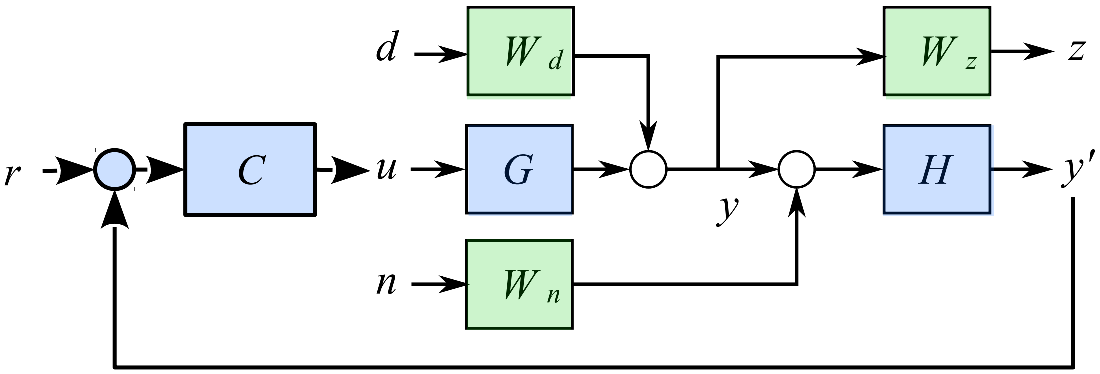
Control Design
Robustness Metrics



$$\|S_y\|_\infty$$

Worst-case multivariable gain on sensitivity function

Control Design – Simulation Results



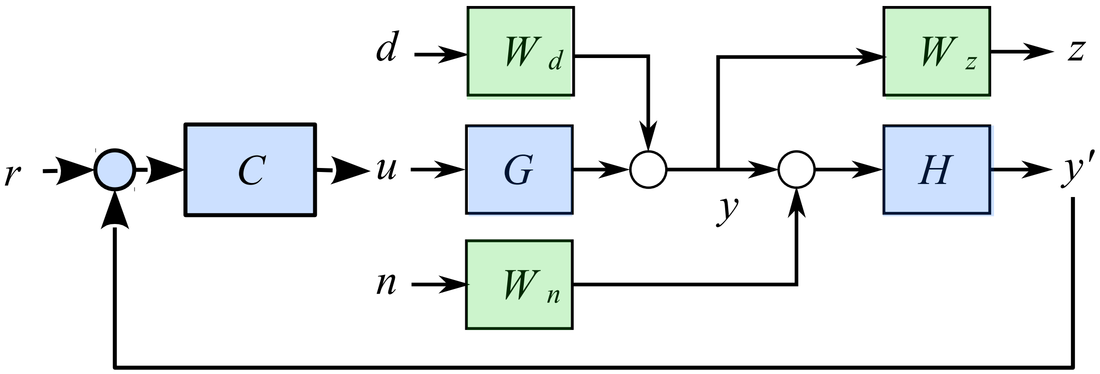
Controller Structure

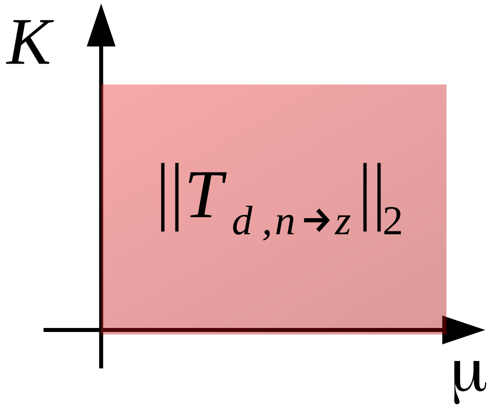
$$C(z) = M_C \frac{K \cdot T_s}{z-1}$$

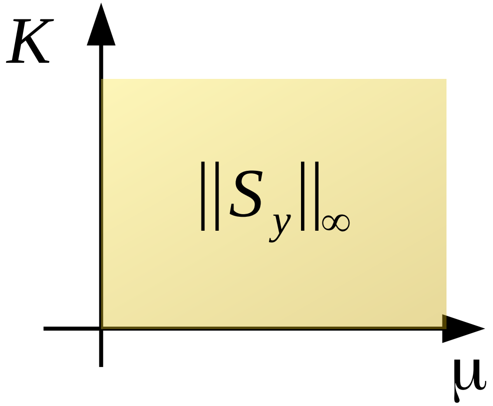
Tikhonov Regularization on Matrix M_c

$$\hat{\sigma}_i = \frac{\sigma_i}{\sigma_i^2 + \mu}$$

Control Design – Simulation Results







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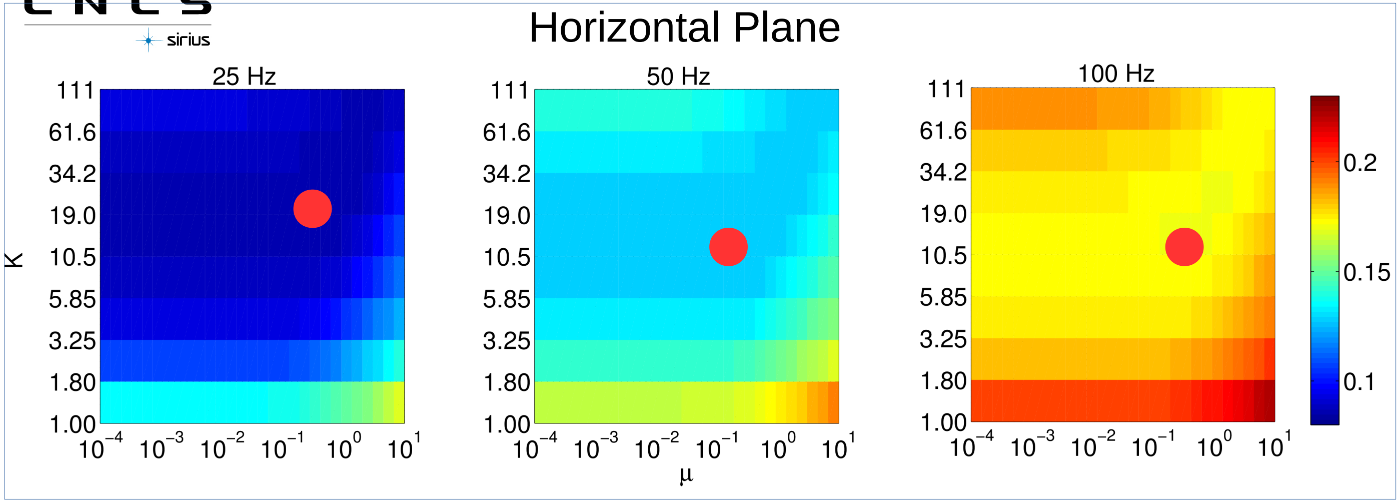

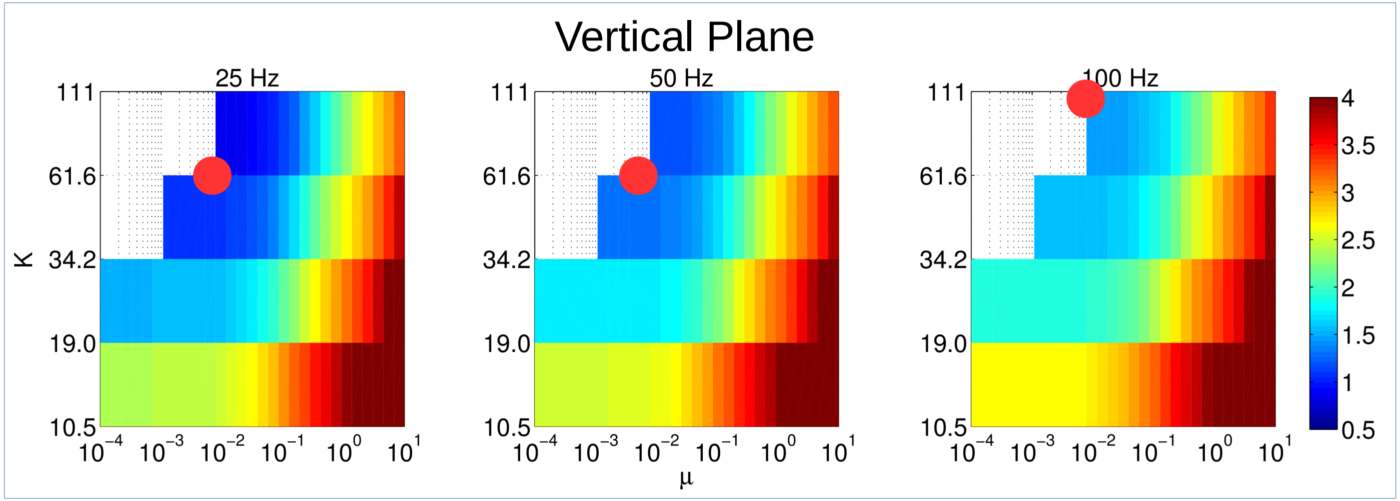

● *Optimal Controllers*

Plane	BW Hz	$\|T_{d,n\rightarrow z}\|_2$	$\|S_y\|_\infty$	K	μ
H	**25**	0.0855	0.7467	19	4e-1
H	**50**	0.1271	0.7294	10	3e-1
H	**10**	0.1710	0.7293	10	4e-1
V	**25**	0.7837	0.9746	111	1e-2
V	**50**	1.160	0.8585	62	5e-3
V	**100**	1.466	0.8480	62	8e-3

Conclusion – LNLS FOFB

- LNLS FOFB performance is fundamentally limited by an overall latency of ~1.5 ms
  - Rule of thumb: 0 dB crossover frequency on disturbance rejection = 1/(20 * closed-loop delay) → ~30 Hz at maximum

- Uncertainty on sensor and actuator transfer functions are relevant only above maximum closed-loop bandwidth (30 Hz) so they cause little harm in practice

- Uncertainty on response matrix does not degrade closed-loop robustness

- Tikhonov regularization “buys” robustness with low degradation of performance

- Simulation results still to be confirmed with experimental data

Conclusion – General

- Signal-based control approach makes the loop optimization straight forward

- Effort should be put on modeling not only plant and sensor, but also disturbance, noise and performance goals

- Transition from trial and error tuning of FOFB systems to optimization-based techniques allows reaching performance and robustness limits

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Thank you

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Control Design – Simulation Results