THE UNIVERSITY OF NEWCASTLE AUSTRALIA

Measurement and Control for High-Speed Sub-Atomic Positioning in Scanning Probe Microscopes

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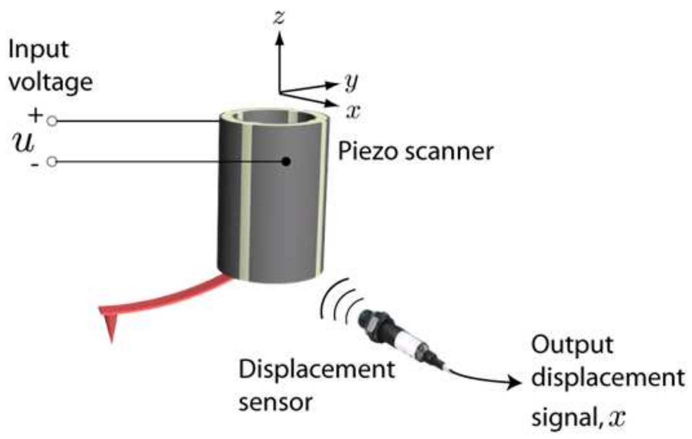
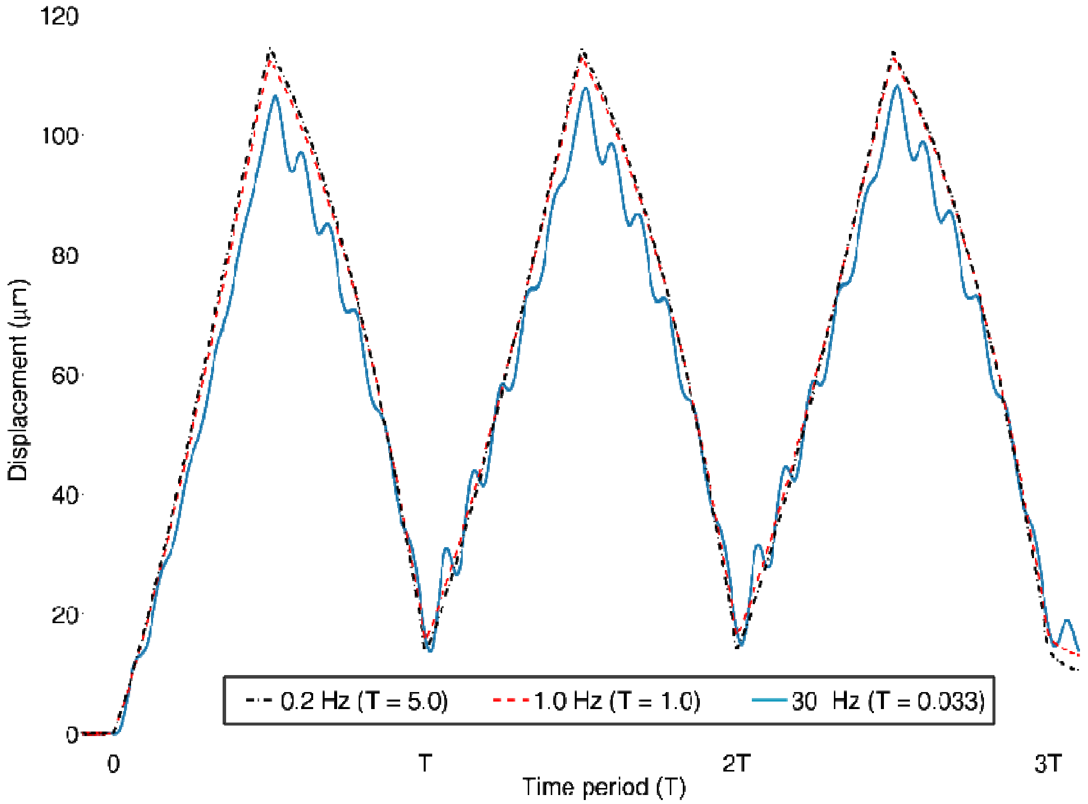
Outline

- Challenges and benefits of feedforward control
- System inversion
  - Linear dynamics (creep and vibration)
  - Nonlinearity (hysteresis)
- Iteration-based feedforward
- Conclusions

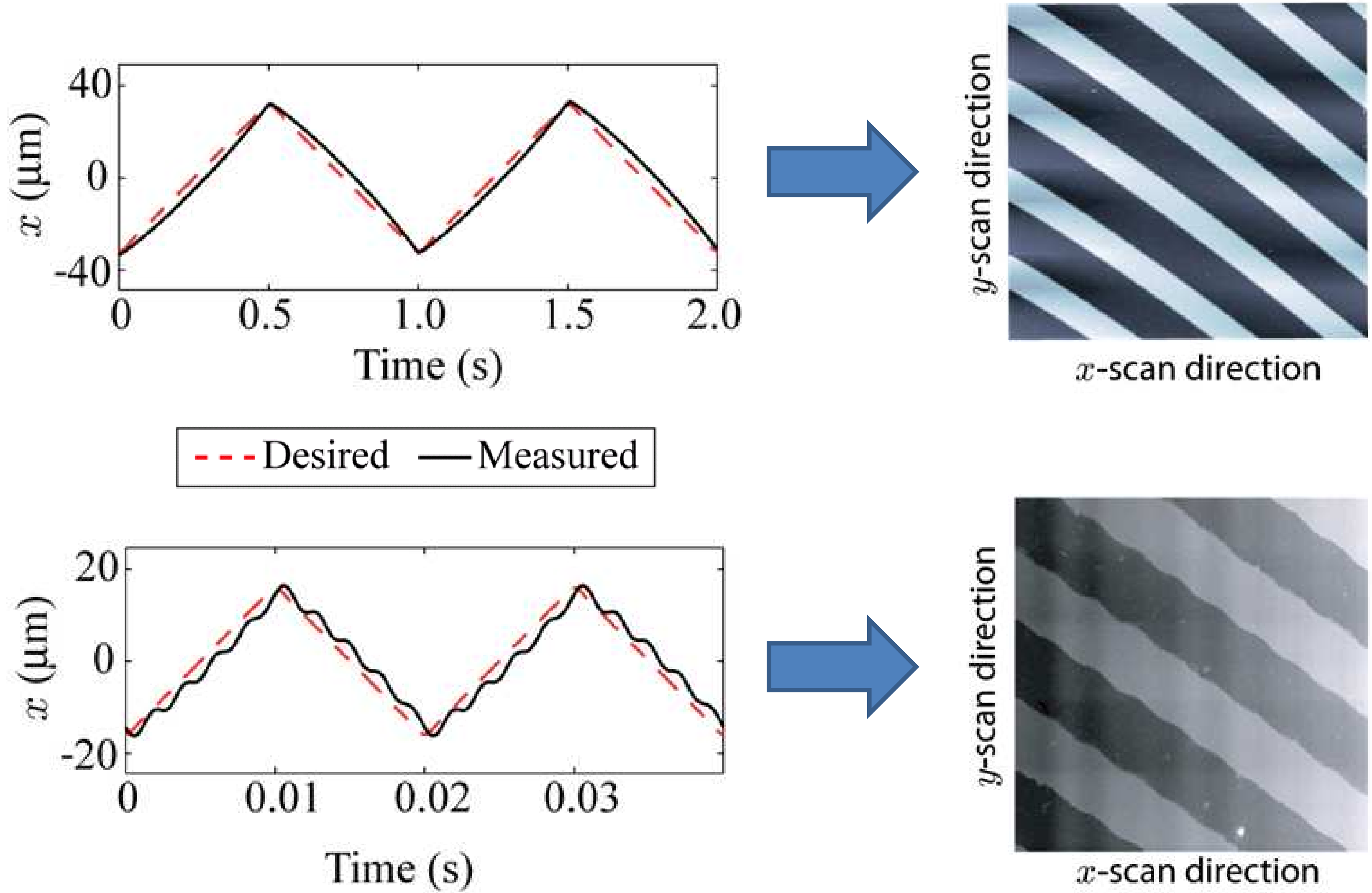
Key challenges in SPMs using piezoelectric actuators



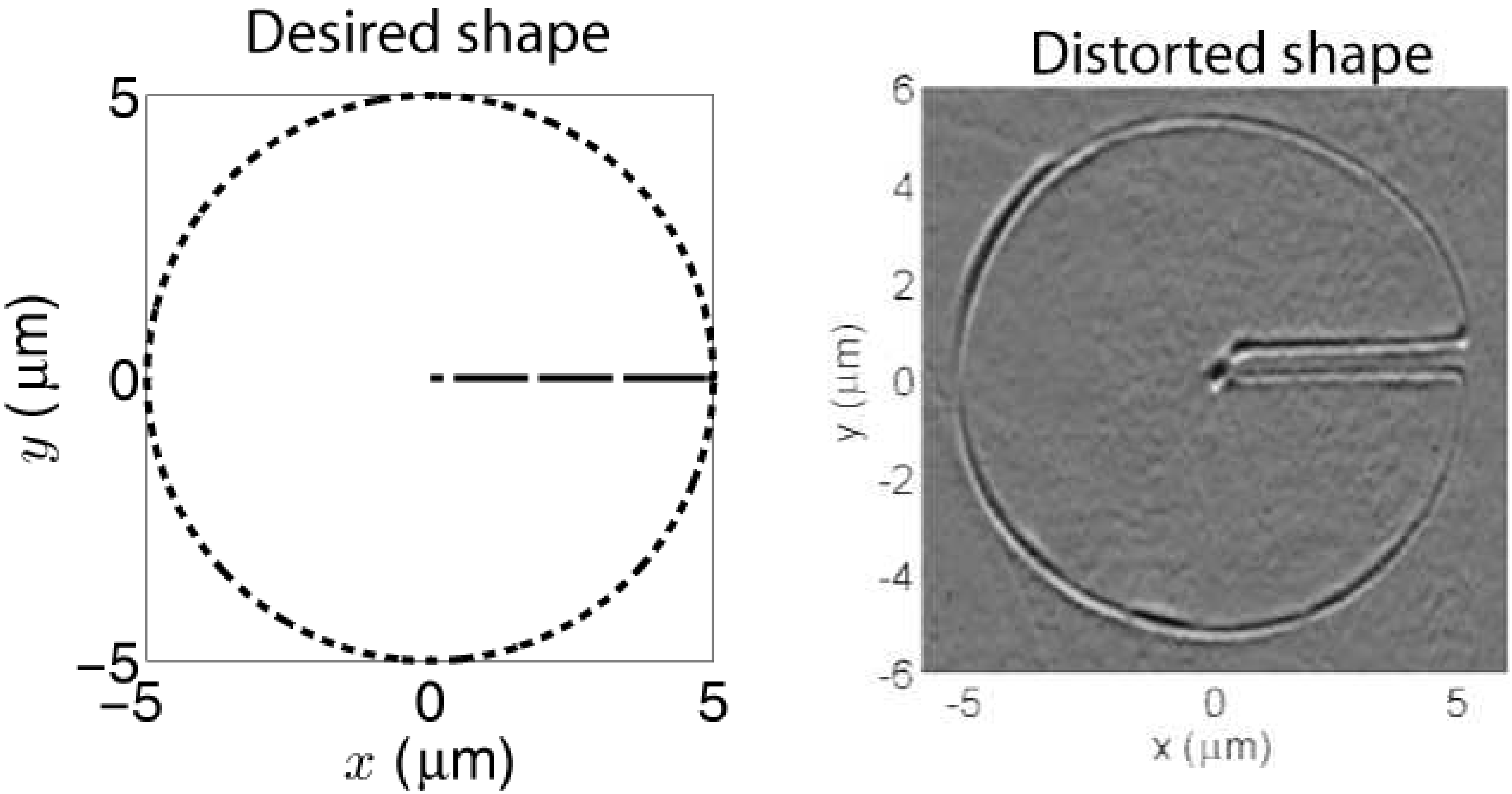


1. Creep: causes drift
2. Hysteresis: causes distortion
3. Vibration: limits bandwidth

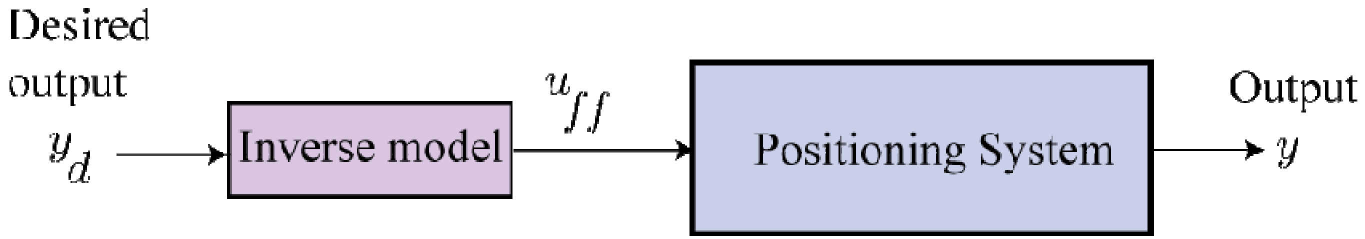
Positioning errors effect SPM imaging



Positioning errors effect SPM fabrication



The feedforward control concept



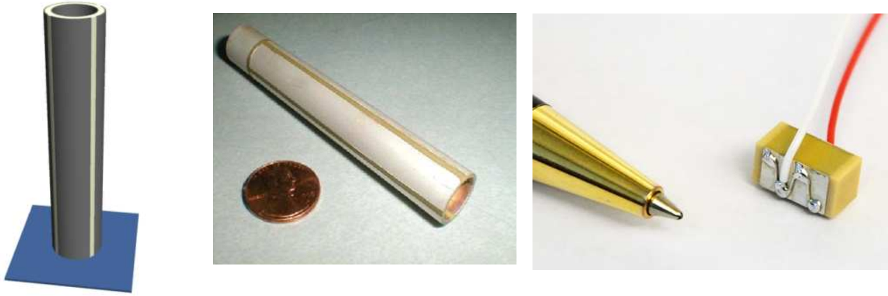
" Anticipates "

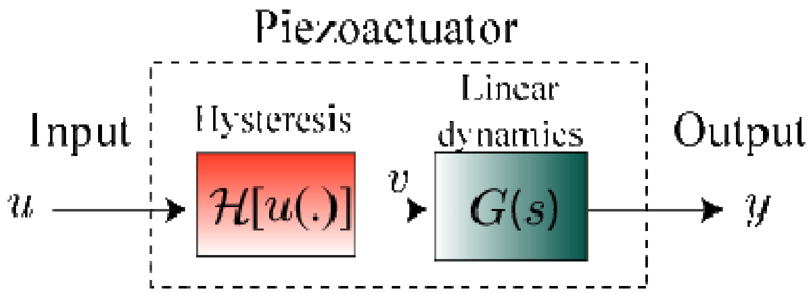
Benefits of feedforward control

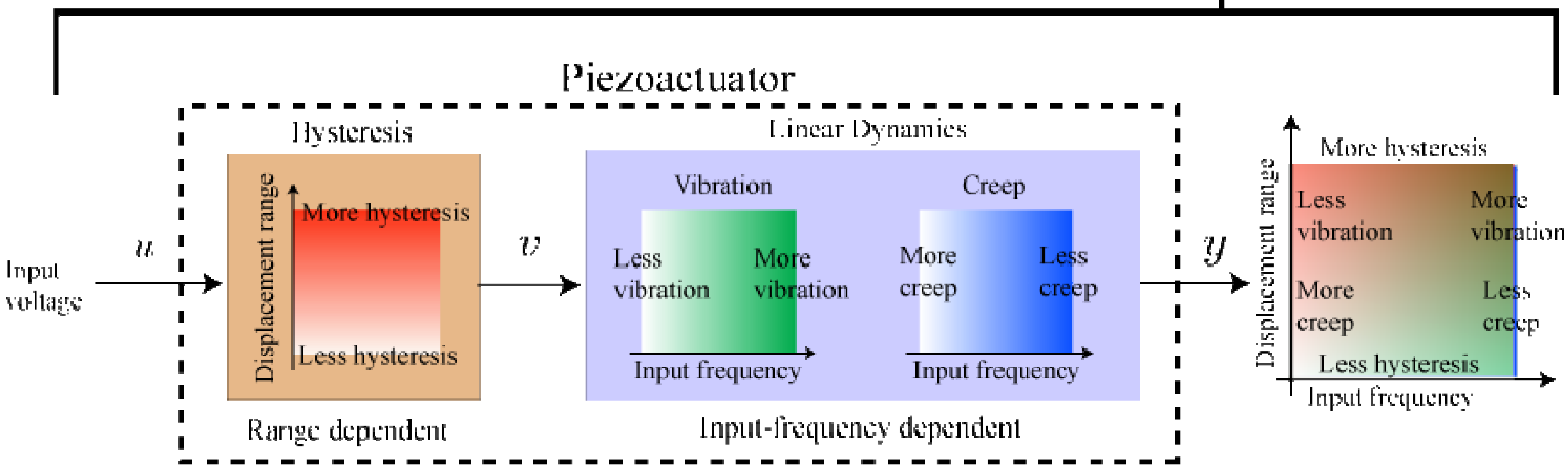
- High-bandwidth positioning (compensates for lag)
- Small tracking error with good models
- Stable
- Cost effective (no sensors for feedback)

Hammerstein-based model for piezoactuators

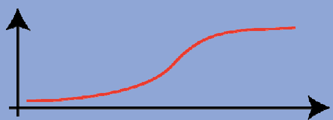
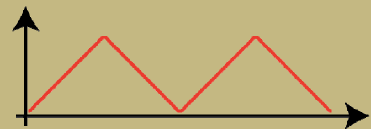
Piezoelectric actuators



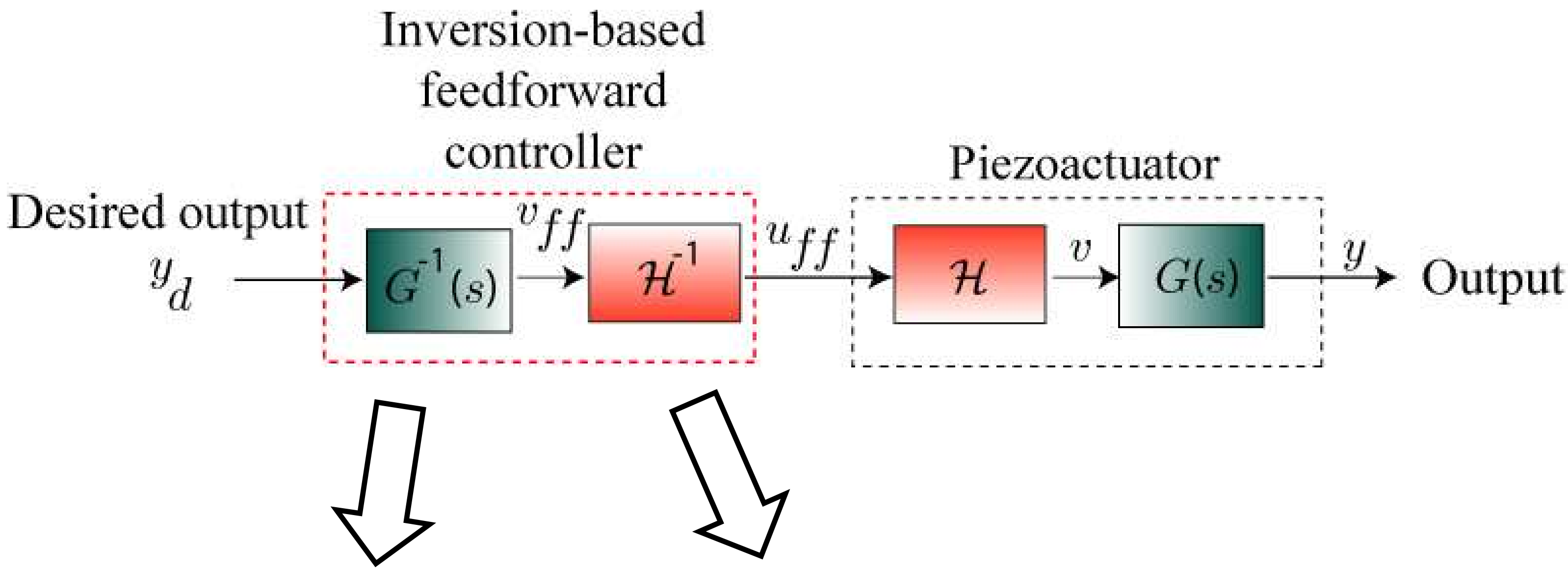




What's the 'best' approach?

Type of SPM operation	
A. Nonrepeating trajectory Example: nanofabrication 	**B. Repeating trajectory** Example: imaging 
Preferred feedforward-based method	
A1. Model and invert all effects *Challenges:* Computationally intense; lacks robustness. *Advantage:* Best performance because all effects are inverted.	**B1. Model and invert dynamics; then iterate** *Challenges:* Causality; convergence; nonlinearity of inverse. *Advantage:* Ability to correct for model uncertainty compared to A1.
A2. Model and invert dynamics; use high-gain feedback or charge control for hysteresis *Challenges:* Low gain margin; complex circuitry; sensor-induced noise; tracking performance lower than A1. *Advantage:* Linear inverse vs. nonlinear inverse.	**B2. Model and invert dynamics; use high-gain feedback or charge control for hysteresis; then iterate** *Challenges:* Low gain margin; complex circuitry; sensor-induced noise; large input error compared to B1. *Advantage:* Each iteration does not require a nonlinear inverse.

A1. Model and invert all effects



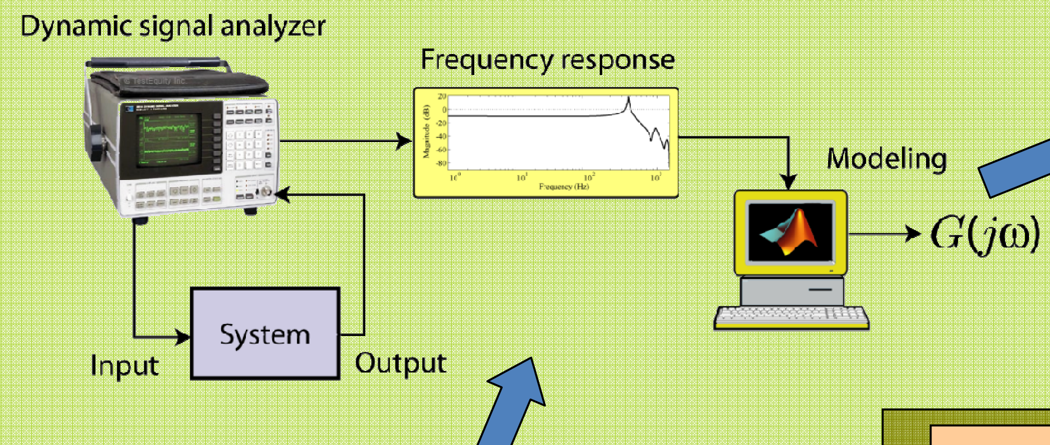
Linear	Nonlinear
• Creep + Vibration • Short-range • Low-to-high speed	• Hysteresis • Long-range • Low-speed

Short-range, low/high-speed

Long-range, low-speed

Short-range, low- and high-speed

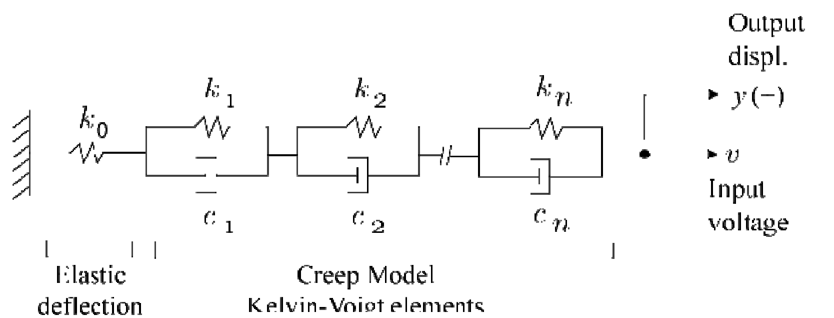
Step 1: model system



Vibration model

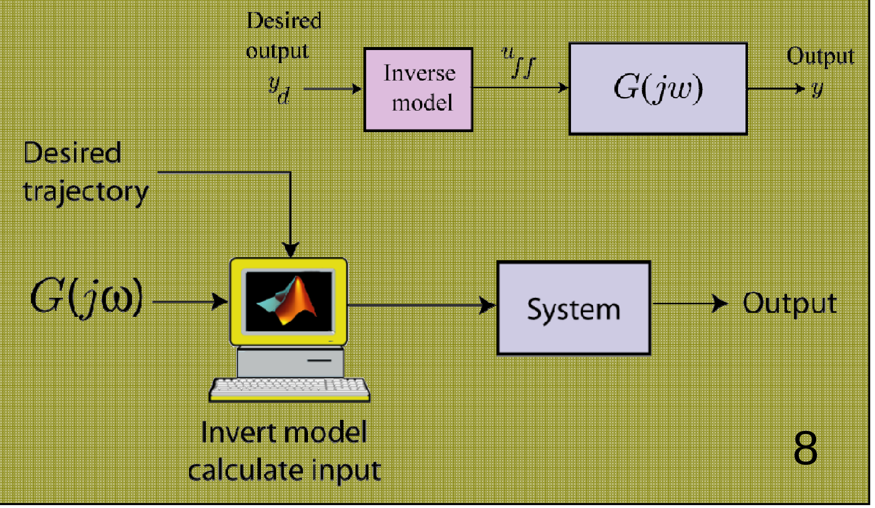
$$G(j\omega) = \frac{\prod^m (j\omega - z_i)}{\prod^n (j\omega - p_k)}; \quad m \leq n$$

Creep model

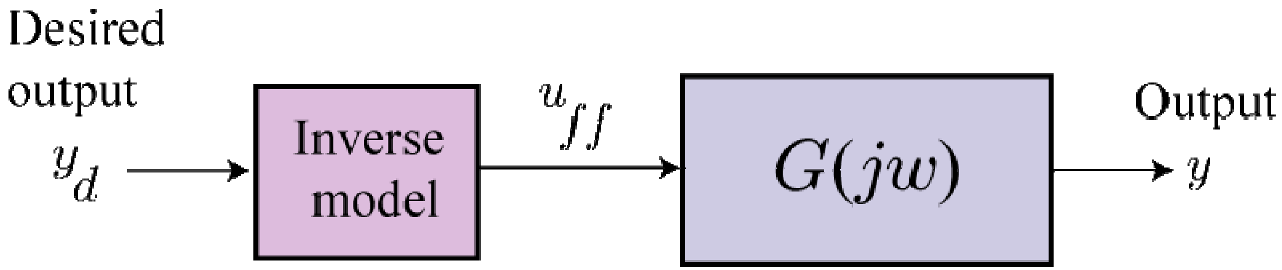


$$\frac{y(s)}{u(s)} = \frac{1}{k_0} + \sum_{i=1}^{n} \frac{1}{sc_i + k_i},$$

Step 2: Invert, then apply



Inversion-based feedforward control: time domain



Consider the (square) linear system:

$$
\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t)
\end{aligned}
$$

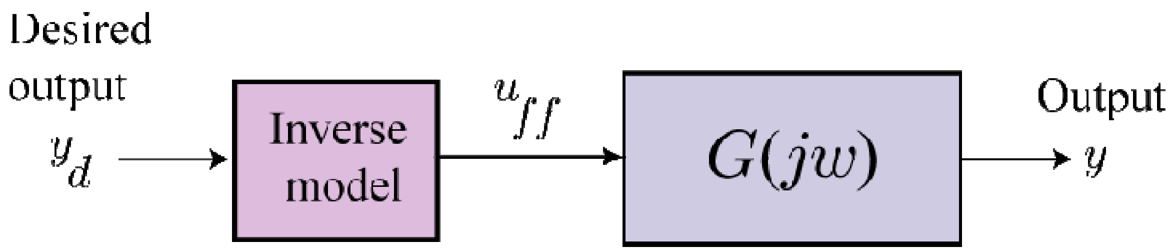
Differentiate the output until the input appears explicitly

$$
\begin{aligned}
\dot{y}(t) &= C\dot{x}(t) \\
\dot{y}(t) &= CAx(t) + CBu(t); \quad \text{continue until } CA^{r-1}B \neq 0 \\
\vdots &= \vdots
\end{aligned}
$$

Solve for the feedforward input $u(t)$:

$$
u_{ff}(t) = (CA^{r-1}B)^{-1}\left[y_d^{(r)}(t) - CA^r\bar{x}(t)\right] \qquad (r = \text{relative degree})
$$

Inversion-based feedforward: frequency domain



$$u_{ff}(j\omega) = G^{-1}(j\omega)y_d(j\omega) \qquad \text{(Exact Inversion)}$$

But inputs may be excessively large!

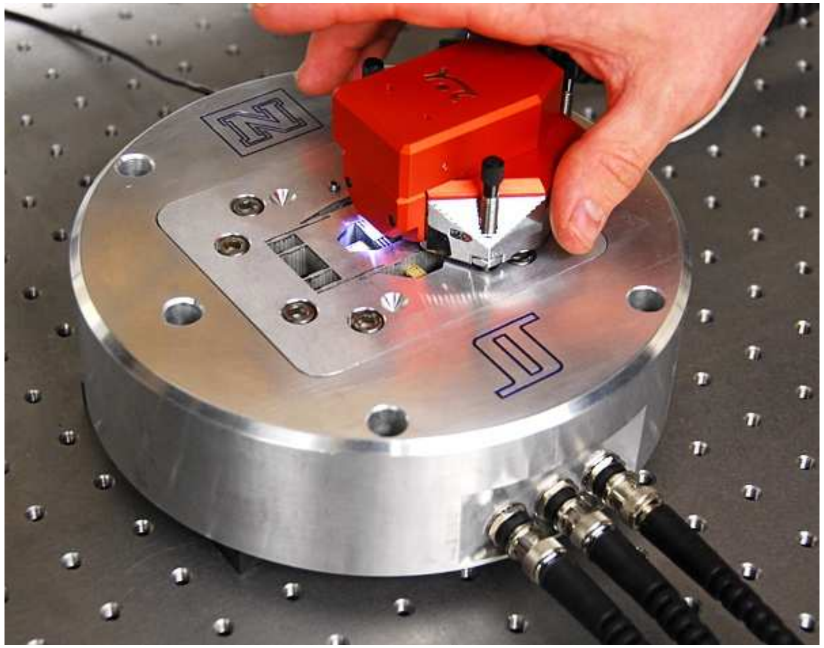
Find input subject to the cost:

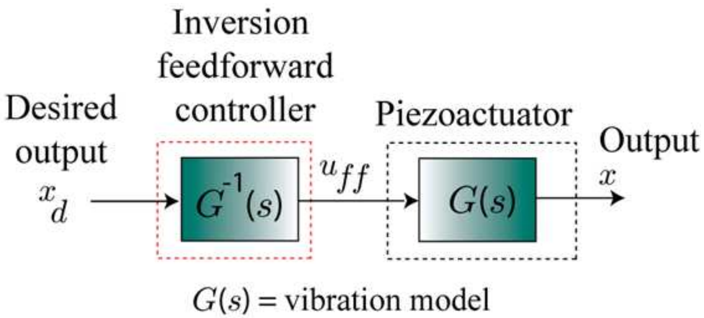
$$J(u) = \int_{-\infty}^{\infty} \left(u^*(j\omega)R(j\omega)u(j\omega) + \left[y(j\omega) - y_d(j\omega)\right]^* Q(j\omega)\left[y(j\omega) - y_d(j\omega)\right] \right) d\omega$$

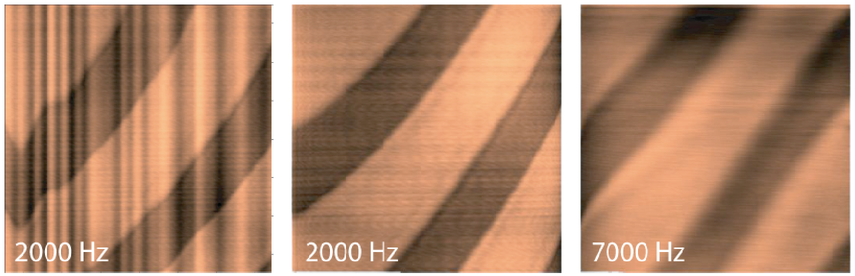
$$u_{opt}(j\omega) = \left[\frac{G^*(j\omega)Q(j\omega)}{R(j\omega) + G^*(j\omega)Q(j\omega)G(j\omega)} \right] y_d(j\omega) \qquad \text{(Optimal)}^{\dagger}$$

* e.g., Leang and Devasia, 2007.

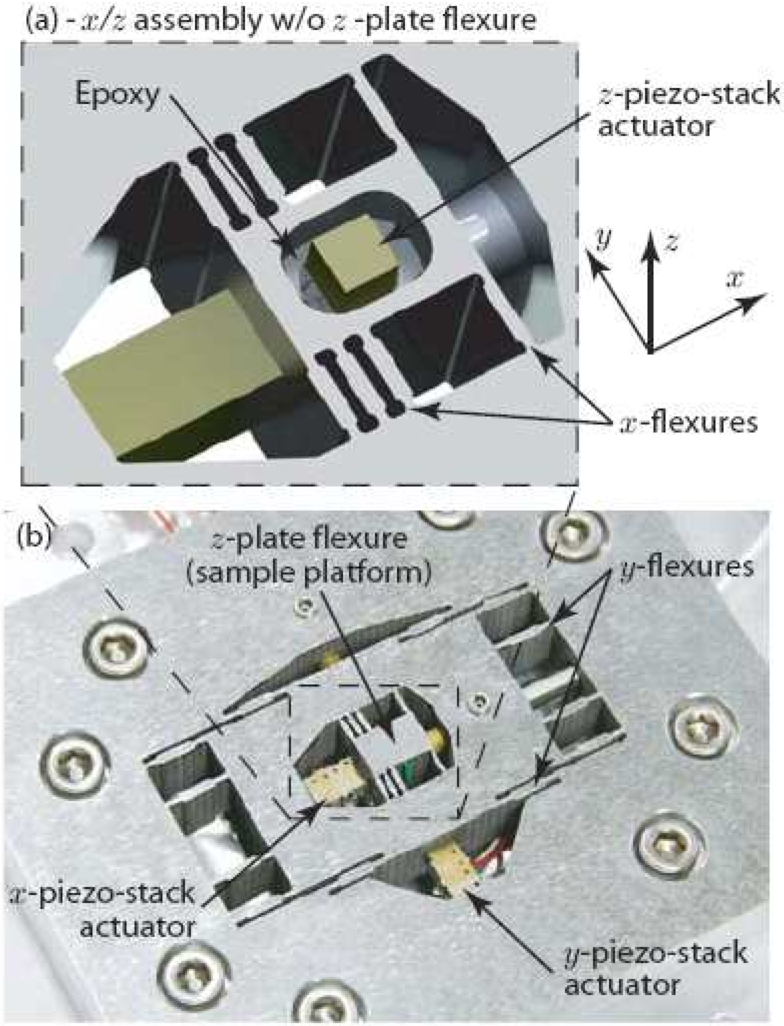
High-speed AFM imaging example





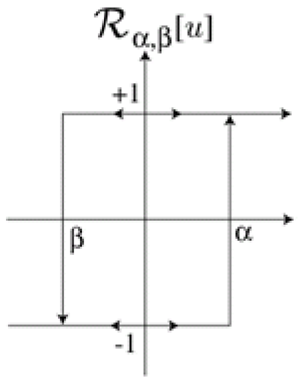


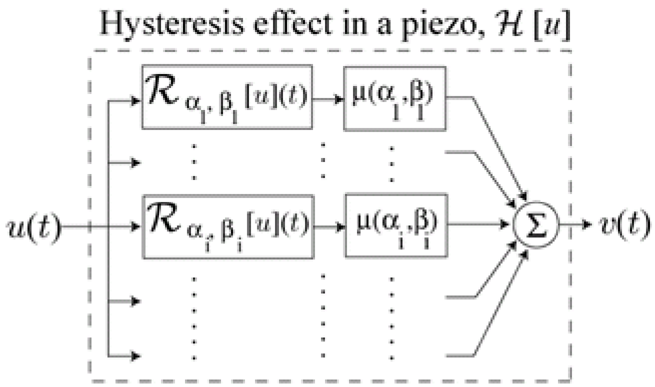
w/o FF | w/ FF | w/FF

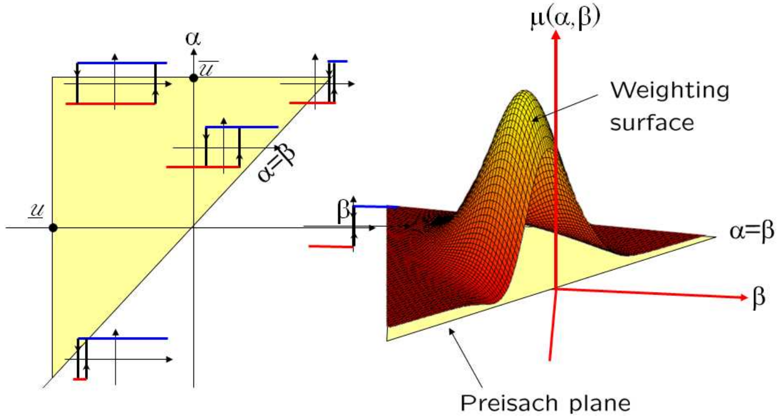


Range: 10 x 10 x 2 μm
Resonances: 25 kHz (x),
6 kHz (y),
>80 kHz (z)
AFM imaging rate: >70 fps (100x100 pixels)

The Preisach hysteresis model







- Assume material consists of an infinite collection of basic relays,

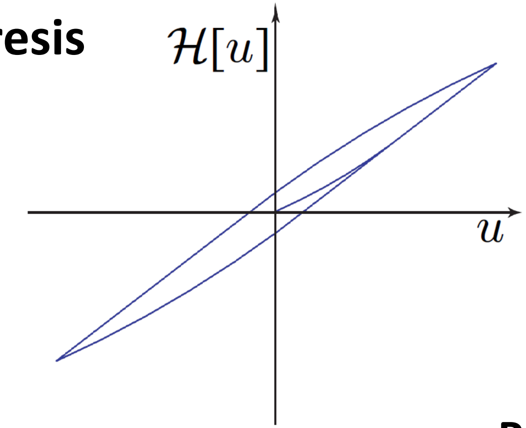
$$\text{(Basic relay) } \mathcal{R}_{\alpha,\beta}[u](t) = \begin{cases} +1 & u(t) > \alpha, \\ -1 & u(t) < \beta, \\ \text{unchanged} & \beta \leq u(t) \leq \alpha, \end{cases}$$

- Assume output is a weighted sum of such relays, i.e.,

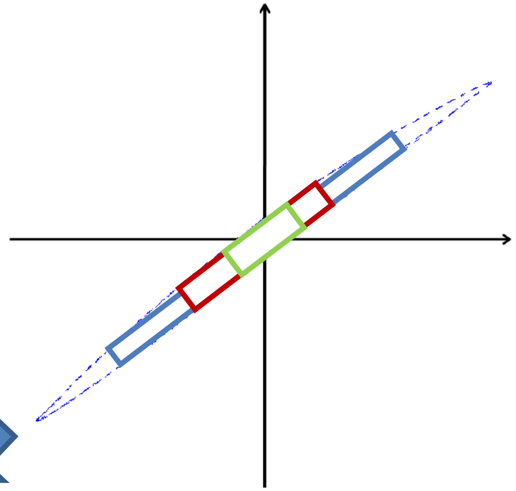
$$v(t) = \mathcal{H}[u](t) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta)\mathcal{R}_{\alpha,\beta}[u](t)d\alpha d\beta,$$

Prandtl-Ishlinskii hysteresis model

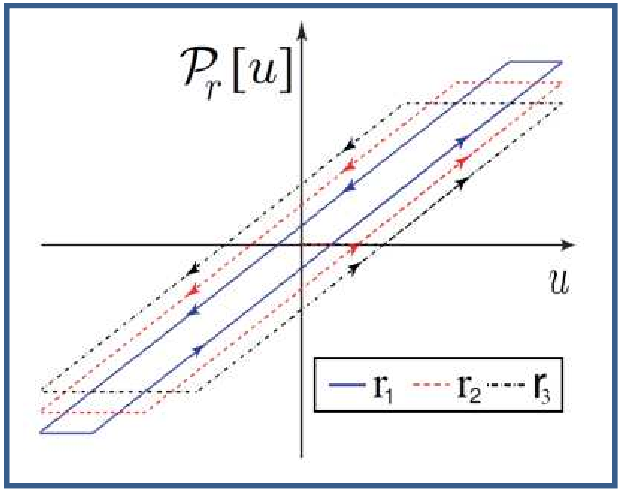
Hysteresis curve:



Sum of basic relays



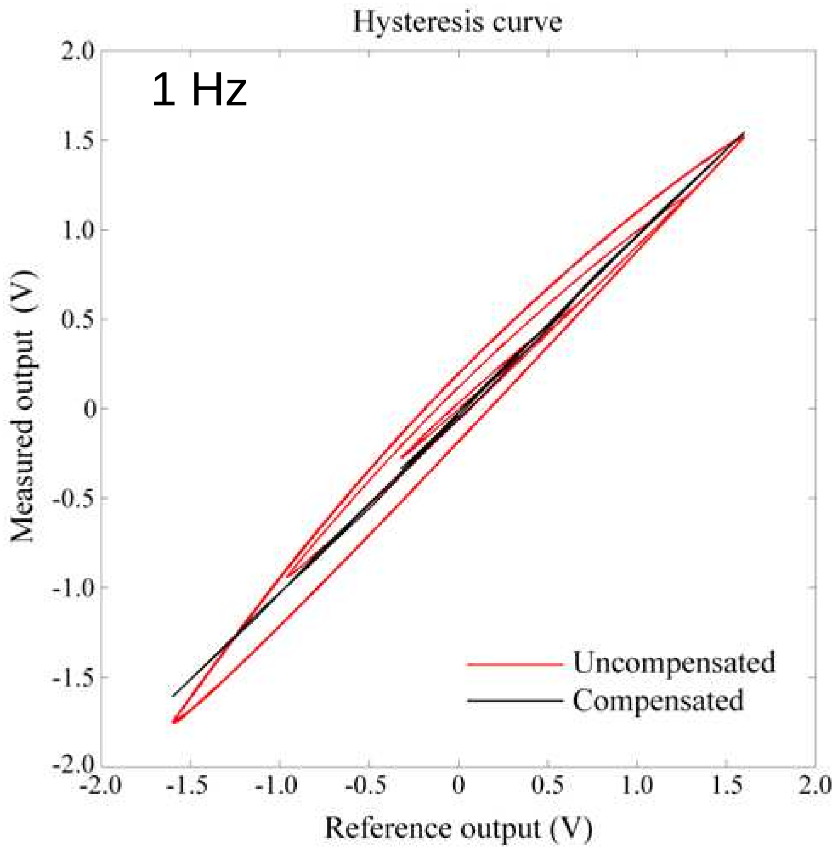
Play operator



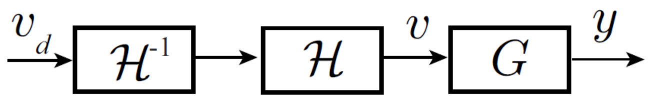
$$v(t) = \mathcal{H}[u](t) \triangleq kf(t) + \int_0^R d(r)\mathcal{P}_r[u](t)dr$$

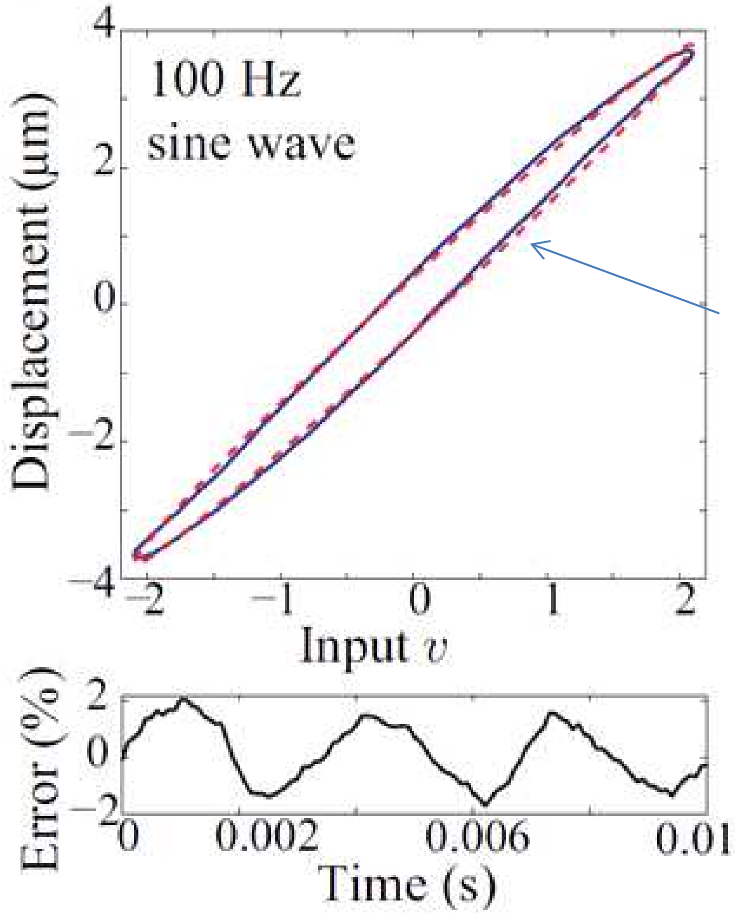
Advantages of relay-based hysteresis models

- Inverse model can be obtained from measured input/output data
- Can be use for real-time feedforward control



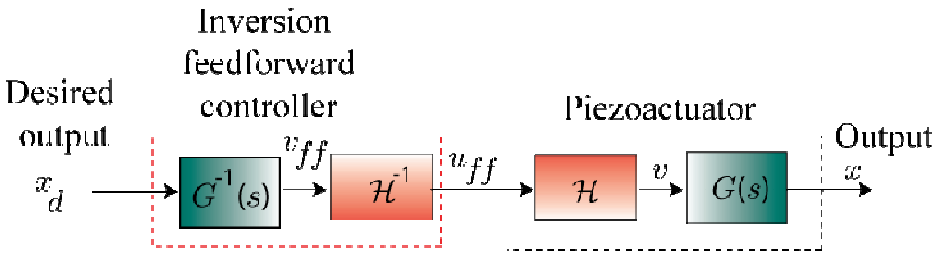
— Measured response with $\mathcal{H}^{-1}$ - - - Simulated output of G





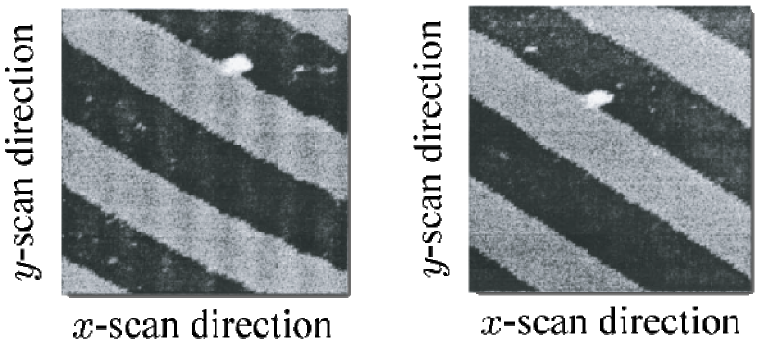
Loop due to phase shift

Creep, hysteresis, and vibration compensation



$G(s)$ = vibration + creep model

(30 Hz scanning)

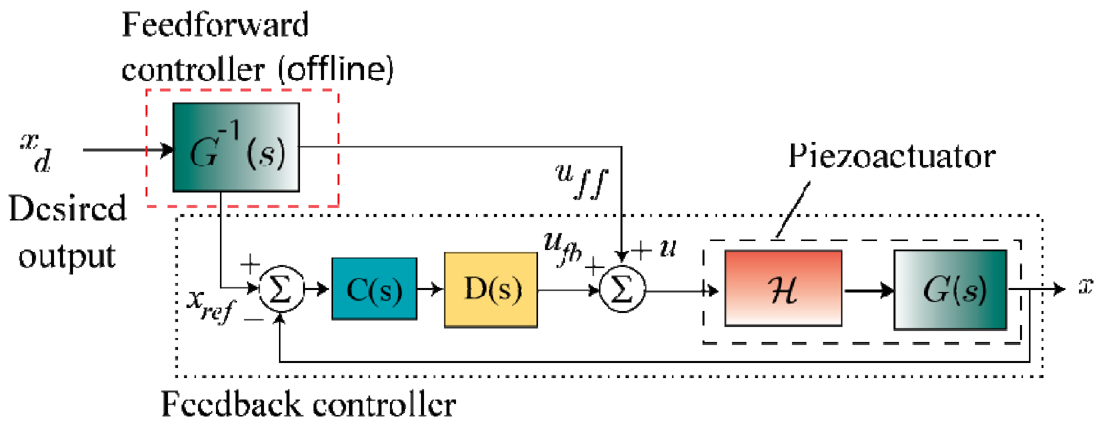


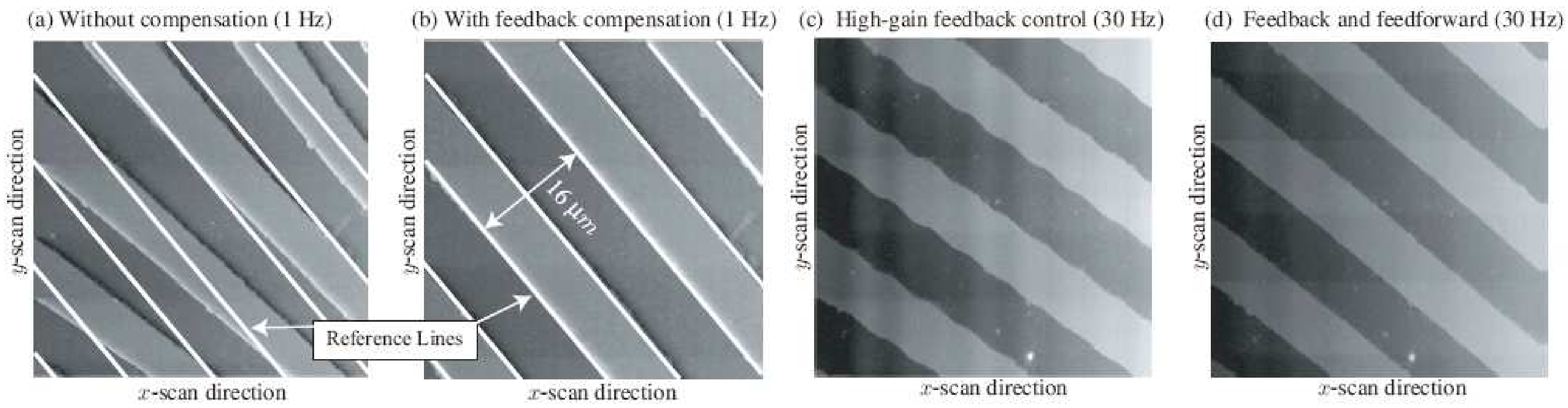
(w/o FF) (w/ FF)

Advantage: offers best performance with good models

•Croft et. al., **Creep, Hysteresis, and Vibration Compensation for Piezoactuators: Atomic Force Microscopy Application,**
•**ASME J. Dyn. Sys. Meas. Cont.,** 2001

A2. Model and invert G(jω), use feedback for *H*

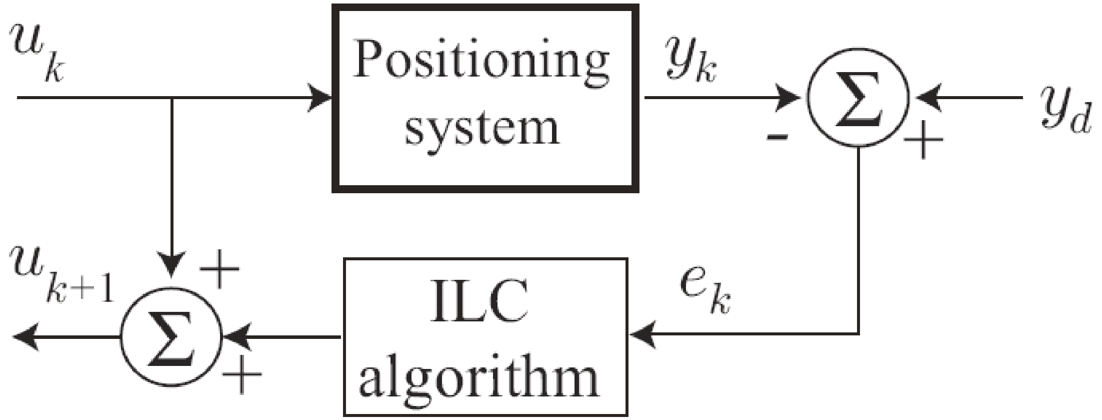




Advantage: avoids modeling nonlinearity

B1. What if you don't know the model?

Iteratively find the feedforward input



$$u_{k+1}(t) = u_k(t) + f\big(e_k(t)\big), \quad \text{for all } t \in I \triangleq [t_0, T]$$

Advantages

- Does not require an accurate model
- Provides high-precision tracking
- Can be automated, but requires a sensor
- Stable

Types of update laws: time-domain

1. System is linear[1]

$$u_{k+1}(t) = u_k(t) + \rho[y_d^{(r)}(t) - y_k^{(r)}(t)]$$

ρ satisfies $\|I - CA^{r-1}B\rho\|_\infty < 1$

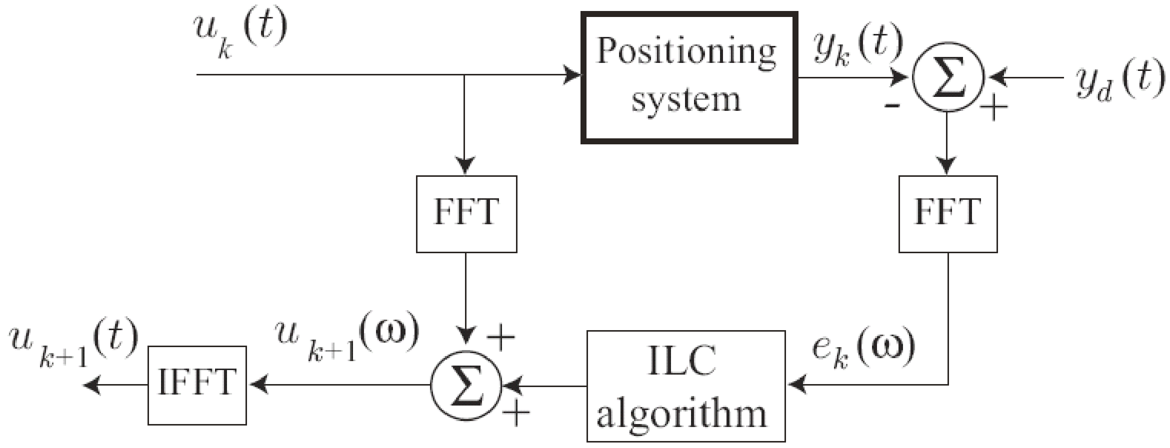
2. System is hysteretic[2]

$$u_{k+1}(t) = u_k(t) + \rho\Big(v_d(t) - v_k(t)\Big)$$

$$0 < \rho \leq 1/\eta_2.$$

[1]Arimoto et. al., 1983; [2]Leang and Devasia, 2006

Frequency domain*



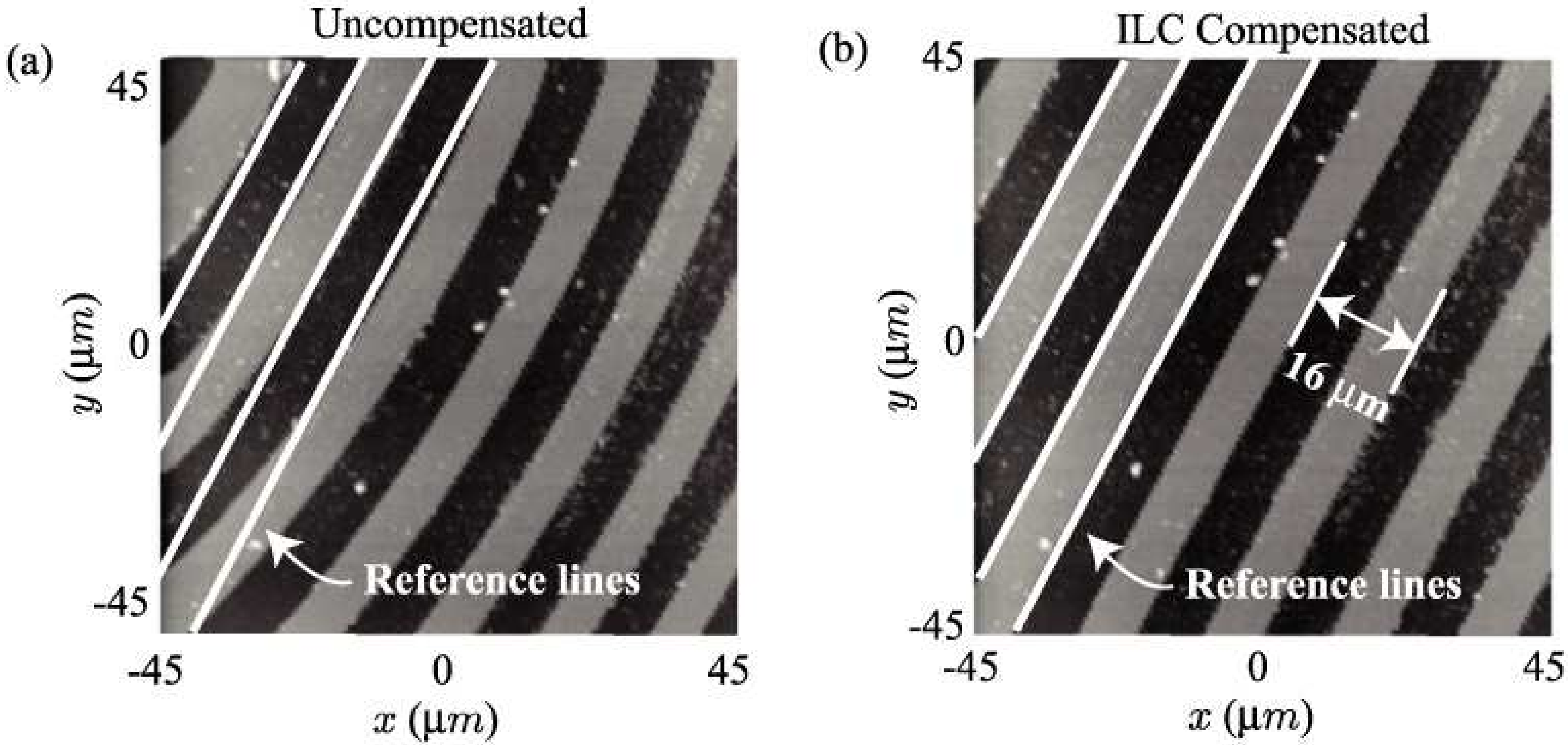
$$u_{k+1}(\omega) = u_k(\omega) + \rho(\omega)\hat{G}^{-1}(\omega)\left[y_d(\omega) - y_k(\omega)\right]$$

$$0 < \rho(\omega) < \frac{2\cos(\Delta(\omega))}{A(\omega)}, \text{ for } \cos(\Delta(\omega)) > 0;$$

$$\rho(\omega) < \frac{2\cos(\Delta(\omega))}{A(\omega)} < 0, \text{ for } \cos(\Delta(\omega)) < 0;$$

* Wu et. al., 2007

AFM imaging example



1 Hz scanning; 100 iterations

Conclusions

- Feedforward control anticipates for deficit performance
- Feedforward control provides high-bandwidth, high-precision positioning (compensates for lag) with good models
- Feedforward-controlled system is stable
- Feedforward control does not require sensors