Control Design for MEMS Instruments Based on Force Feedback

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Thank you for introducing me to
a fascinating field for control applications

KJÅ: Lectures on Control of Microsystems

Outline

1. Introduction
2. Control Architecture for Force Feedback
3. A Tunneling Accelerometer
4. Experiments
5. Summary

Introduction

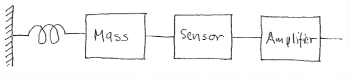
- Interesting and useful devices in dynamic development

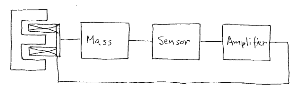
  AFM, Accelerometers, Gyroscopes, Hard disks, Optical memories ...
- Small scale and high Q (low damping)

  Scaling of surface l^2 vs volume l^3: friction important
- Oscillatory (nonlinear) dynamics with low damping
- Noise: Brownian motion, Johnson-Nyquist, tunneling, ...
- Parameter uncertainty and parameter variations
- Fast sampling MHz, challenging implementation
- Control is often mission critical, noise, robustness, dynamics, nonlinearities all have to be balanced
- Rich area for applying control

Force Feedback

- Classic idea with tremendous impact
- Game changer in instrument design





Open loop, all components matter

Bandwidth $\omega_b = \sqrt{k/m}$

Sensitivity = k_a/k

Invariant $\omega_b^2 S = k_a/m$

Closed loop, actuator only critical element

Bandwidth depends on feedback system

Error signal also useful!

Outline

Controler Architectuere

Models

$$\frac{dx}{dt} = Ax + B_w w + Bu, \qquad y = Cx, \qquad \text{instrument}$$
$$\frac{dz}{dt} = A_w z, \qquad w = C_w z, \qquad \text{sensorsignal}$$

Standard structure based on Kalman filter and state feedback

$$\frac{d\hat{x}}{dt} = A\hat{x} + B_w C_w \hat{z} + Bu + L_x(y - C\hat{x})$$
$$\frac{d\hat{z}}{dt} = A_w \hat{z} + L_w(y - C\hat{x}) = A_w \hat{z} + L_w(y - \hat{y})$$
$$u = -K_x \hat{x} - K_z \hat{z}.$$

- Design instrument to make $B_w C_w$ close to B
- Design filter gains L and L_w to shape frequency response
- Design feedback gains K and K_w to give small errors

Sensor Transfer Function

Transfer function from signal w to its estimate $\hat{w}$

$$G_{\hat{w}w} = \big(I+F(s)\big)^{-1}F(s),\ F(s) = C_w(sI-A_w)^{-1}L_w(sI-A-L_xC)^{-1}B_w$$

For $A_w = 0$ (constant but unknown or slowly varying acceleration) the expression simplifies to

$$G_{\hat{w}w} = \frac{L_zC(sI-A+L_xC)^{-1}B_w}{s+L_zC(sI-A+L_xC)^{-1}B_w}, \qquad G_{\hat{w}w}(0) = 1$$

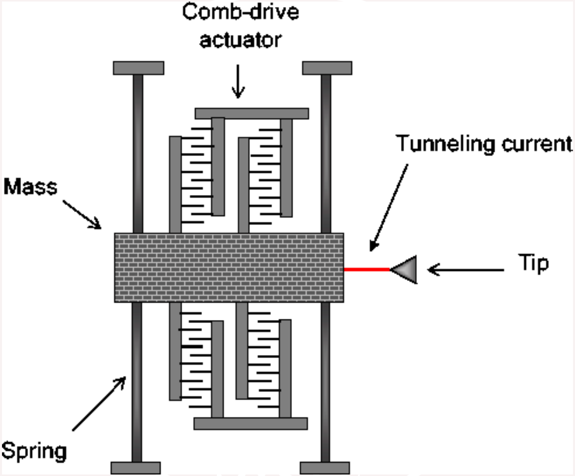
- Does not depend on feedback gains K_x and K_z!
- Does not depend on B
- Does depend on filter gains

Many design options:

- Optimize with respect to disturbances and uncertainty
- Shape the frequency response $G_{\hat{w}w}$ (automotive)

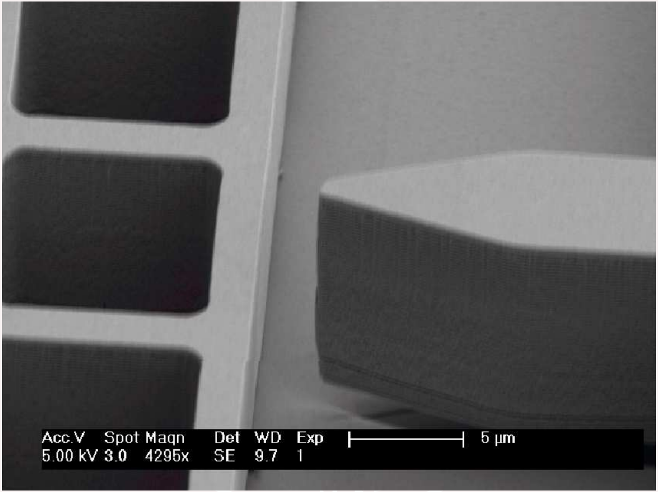
Outline

The Tunneling Accelerometer



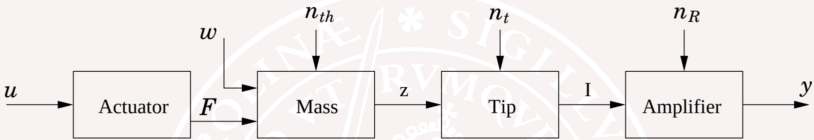
Courtesy of Laura Oropeza-Ramon

Tunneling Tip



Courtesy of Laura Oropeza-Ramon

Block Diagram



Actuator:

$$F = \frac{N\epsilon_0 h}{d}(V_0 + u)^2, \qquad \boxed{\delta F = k_a \delta u, \quad k_a = 2\frac{N\epsilon_0 h V_0}{d}}$$

Mass: $m\dfrac{d^2z}{dt^2} + c\dfrac{dz}{dt} + kz = F + mw + n_{th}$

Tunneling tip:

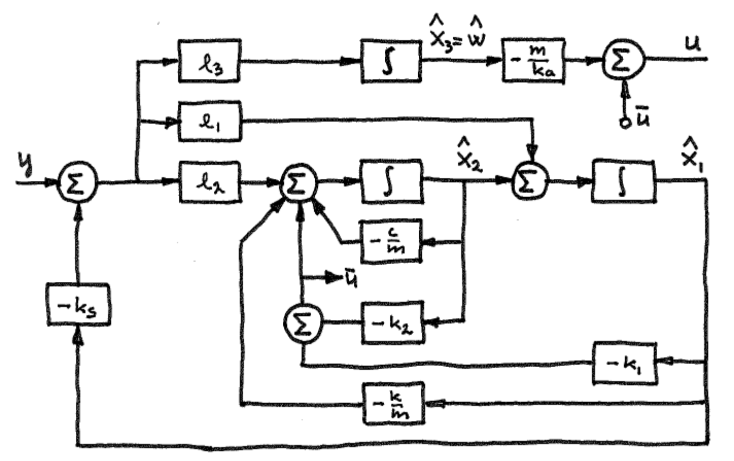
$$I = k_t^0 V_v e^{-\alpha x\sqrt{\phi}}, \qquad \boxed{\delta I = k_t I_e \delta x + n_t, \quad k_t = \alpha\sqrt{\phi}}$$

Amplifier: $V = k_v(RI + n_R)$ (2 nA, simplified)

Noise Sources

- Thermal noise white noise force with spectral density $4ck_BT$ (dissipation fluctuation theorem), c damping coefficient, $k_B = 1.38 \times 10^{-23}$ [J/Kelvin] Boltzmann's constant and T temperature
- Tunneling noise modeled as shot noise which is white noise with spectral density $q_0 2I$, where $q_0 = 1.6 \times 10^{-19}\ C$ is the charge of the electron and I is the current.
- Model resistors by an ideal resistor with a voltage source in series representing the Johnson-Nyquist noise which is white noise with spectral density $4k_BTR$
- Amplifier noise
- $1/f$ noise

Simplified Block Diagram

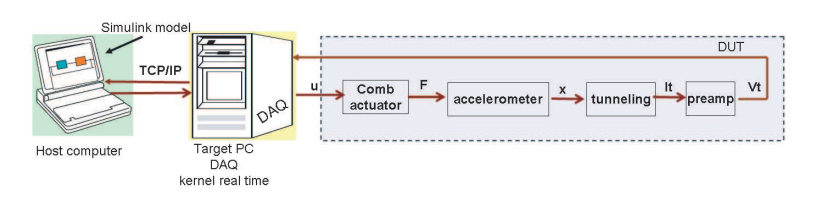


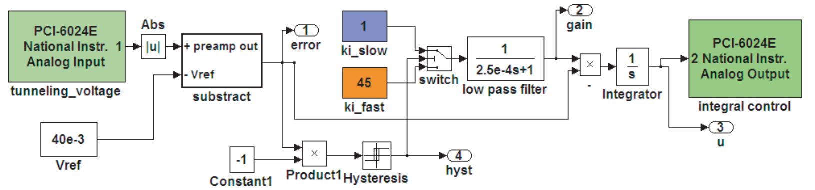
Physical interpretations!

Outline

First Attempt

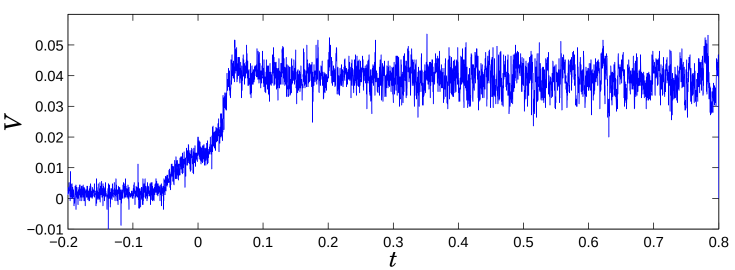
- Initialize - Initiate tunneling, get from 1 µm to 1 nm safely
- Switched integrating controller
- Regulate - maintain tunneling





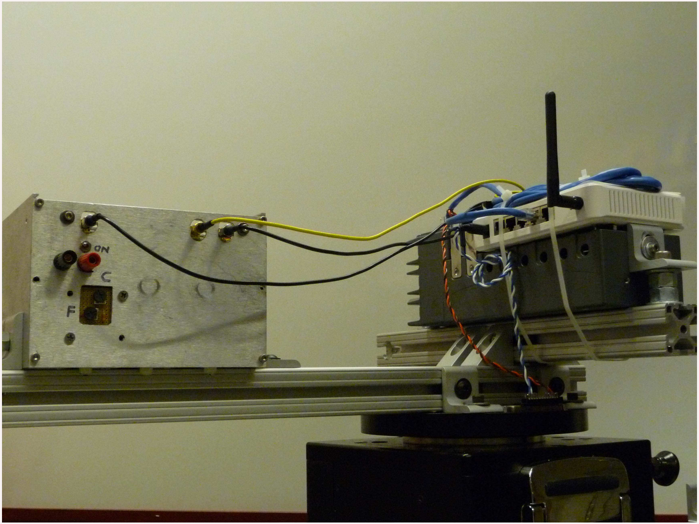
Hunt for Noise Sources

- Originally very high noise levels
- Guide-lines from physical modeling very useful



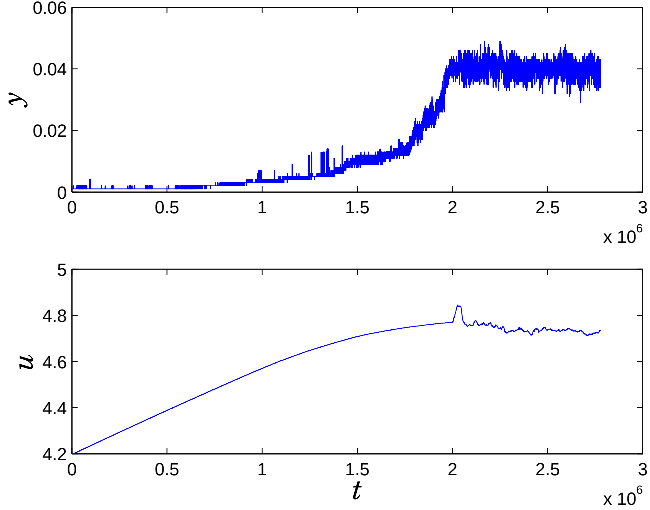
- Redesign electronics: preamplifier, DAC with better resolution
- Replace PC by National Instruments Compact Rio

Experimental Set-up

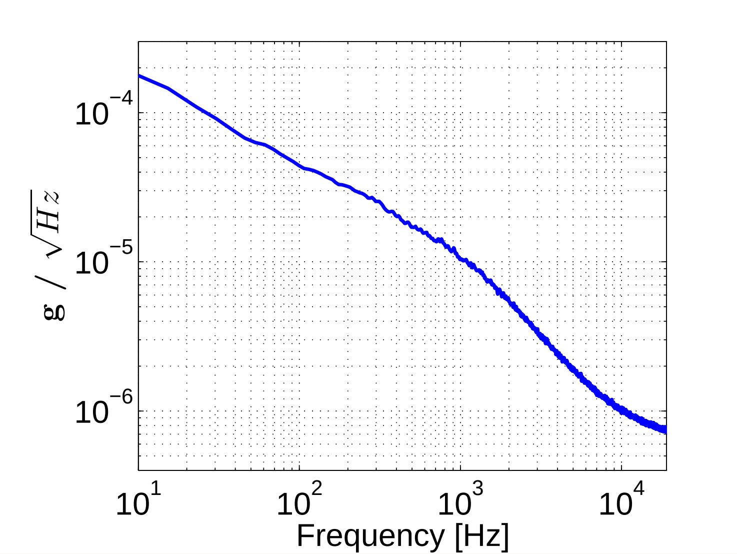


Courtesy of Chris Burgner

Improved Electronics



Control Signal has Long Term Drift $1/f$



Outline

Summary

- Interesting application area for control
- Systems with low damping $Q = \frac{1}{2\zeta}$ up to 1000

  Truxal 1961: The design of feedback systems to effect satisfactorily the control of *very lightly damped* physical systems is perhaps the most basic of the difficult control problems.
- Noise

  Thermal, Johnson-Nyquist, tunneling, $1/f$
- Integrated systems and control design
- A design framework

  Controller architecture
  Design trade-offs
  High sampling rates MHz, analog or FPGA
  High precision $\sigma = 0.3\,$Å

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Parameters

Boltzmann's constant	k_B	1.3807×10^{-23} J/K
Charge of electron	q_0	1.602×10^{-19} C
Tunneling constant	α	1.025 $1/\text{Å}\sqrt{\text{eV}}$
Tunneling barrier	ϕ	0.05 eV
Temperature	T	293 K
Mass	m	4.917 µg
Resonant frequency	f_0	4.2 kHz
Q-value	Q	10
Actuator gain	k_a	9.2×10^{-7} N/V
Tunneling gain	k_t	4 A/m
Preamp resistance	R	10.2 MΩ
Voltage gain	k_v	2
Sensor gain	$k_s = k_t k_v R$	21.6 MV/m