Cognitive Process Control

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CA4-120, Lam Research
March 13th, 2012. Tuesday 4:00-5:00

Outline

- **Introduction - CSOIS and Research Strength**
- Cognitive Process Control – A New Framework
- Potential Contributions from CSOIS to Lam Research
  - Jitter Margin Accommodation
  - Undistortion Technique
  - Iterative-Variant Uncertainties in R2R Controls
  - Fractional Order Modeling/Controls
  - **New Ideas in Virtual Metrology/Outlier Modeling**
  - MIMO Robust Control and Performance Monitoring

Utah State University

Located in Logan, Utah, USA
80 miles North of Salt Lake City

25,767 students study at USU nestled in the Rocky Mountains of the inter-mountain west

CSOIS is a research center in the Department of Electrical and Computer Engineering

CSOIS
CENTER FOR SELF-ORGANIZING AND INTELLIGENT SYSTEMS

CSRA Research:
Center for Self-Organizing and Intelligent Systems

- CSOIS is a research center in USU's Department of Electrical and Computer Engineering that coordinates most CSRA (Control Systems, Robotics and Automation) research
- Officially Organized 1992 - Funded for 7 (seven) years by the **State of Utah's Center of Excellence Program (COEP)**
- Horizontally-Integrated (multi-disciplinary)
  - Electrical and Computer Engineering (Home dept.)
  - Mechanical Engineering
  - Computer Science
- Vertically-integrated staff (20-40) of faculty, postdocs, engineers, grad students and undergrads
- Average over $2.0M in funding per year from 1998-2004
- Three spin-off companies from 1994-2004.

CSOIS Core Capabilities and Expertise

- Control System Engineering
  - Algorithms (Intelligent Control)
  - Actuators and Sensors
  - Hardware and Software Implementation
- Intelligent Planning and Optimization
- Real-Time Programming
- Electronics Design and Implementation
- Mechanical Engineering Design and Implementation
- System Integration

We make real systems that WORK

and others want them!

CSRA/CSOIS Courses

- **Undergraduate Courses**
  - MAE3340 (Instrumentation, Measurements); ECE3640 (Laplace, Fourier)
  - MAE5310/ECE4310 Control I (classical, state space, continuous time)
  - MAE5620 Manufacturing Automation
  - ECE/MAE5320 Mechatronics (4cr, lab intensive) (Sp2012) (Sp2013)
  - ECE/MAE5330 Mobile Robots (4cr, lab intensive) (Fall 2011) (Fall 2012)
- **Basic Graduate Courses**
  - MAE/ECE6340 Spacecraft attitude control
  - ECE/MAE6320 Linear multivariable control (Fall 2011) (Fall 2012)
  - ECE/MAE6350 Robotics (TOD)
- **Advanced Graduate Courses**
  - ECE/MAE7330 Nonlinear and Adaptive control (Spring 2012)
  - ECE/MAE7350 Intelligent Control Systems (TOD)
  - ECE/MAE7360 Robust and Optimal Control (Fall 2011) (Fall 2013)
  - ECE/MAE7750 Distributed Control Systems (Fall 2012)

Selected CSOIS Research Strengths

- ODV (omnidirectional vehicle) Autonomous Robotics
- Iterative Learning Control Techniques
- Currently:
  - MAS-net (mobile actuator and sensor networks) and Cyber-Physical Systems (CPS)
  - Smart Mechatronics, Multi-UAV-Based Collaborative Personal Remote Sensing, Multispectral Imager;
  - Cooperative Control; Formation Control; Information Consensus; Engineered Swarms
  - Fractional Dynamic Systems, Fractional Order Signal Processing and Fractional Order Control/Modeling
  - Crowd dynamics and evacuation control with IwDs

Current Research Sponsors (11/2011)

- **Samsung:** Fractional order control of HDDs
- **NSF:** Personal remote sensing – New Zealand
- **DOE:** Automatic Electrical Transportation
- **UWRL:** UAV PRS, payloads for precision ag.
- **NASA:** UAV Airworthiness for UAS2NAS
- **SDL:** MPPT for satellite PV solar panels
- **NIDRR**: Evacuation study of crowds with IwDs

(Total more than $1M for now. **2011 expenditure**: $367K)

CSOIS Members (=30, Spring 2012)

- **1 Faculty (Dr. YangQuan Chen)**
- **7 Ph.D. Students**
  - Cal Coopmans (S10) | Austin Jensen (S10) | Hadi Malek (F10) | Jinlu Han (F09) | Brandon Stark (F10) | Zhuo Robin Li (F11), Daniel Stuart (F09)
- **3 Master Students**
  - Pooja Kavathekar (F10); David Nathan Hoffer (MAE F11); David Cornelio (F11)
- **9 Undergraduate Students**
  - Aaron Dennis (EE); Aaron Quitberg (MAE); Joseph J. Montgomery (EE); Chris Coffin (CS, URCO) Jeremy Frint (MAE); Jacob Vanfleet (CS), Brandon Willis (MAE), Jarret Bone (MAE, URCO), Steven Morales (CS)
- **4 Visiting Professors**
  - Prof. Kecai Cao; Prof. Xuefeng Zhang; Prof. Igor Podlubny; Prof. Aiming Ge
- **6 Exchange Graduate Students**
  - 2 MS: Kaplanek, Johannes; Michal Podhradský
  - 4 PhD: Sara Dadras; Caibing Zeng; Chun Yin; Yaojin Xu;

Utah State University

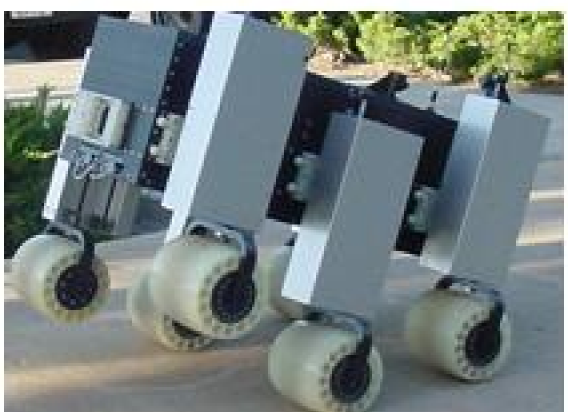
CSOIS
CENTER FOR SELF-ORGANIZING AND INTELLIGENT SYSTEMS

Some Robots Built At USU

T1

T2

ODIS



T3

CSOIS spinoff companies: ASI / VPI

ODIS On Duty in Baghdad

"Putting Robots in Harm's Way, So People Aren't"

OSAM UAV Team won 2nd @ AUVSI UAS Competition, June 2008

http://www.engr.usu.edu/wiki/index.php/OSAM

Utah State – Wins $8,000 for 2nd Place Overall, 2nd Place in Mission, Honorable Mention in both Orals and Journal, and Prize Barrels for Autonomous Mission Flight, Autonomous Landing, JAUS and Perfect Identification of the Off-Path Target.

- We won #1 in AUVSI 2009 UAS Competition!!
  - June 17-21, 2009. Maryland AFB.
  - $14000 cash award.
  - Other registered participants: UCSD, MIT, Cornell, NCSU etc.
  - We made some headlines including ESPN2!
  - We are the second time to participate this event!
  - UCSD, Embry Riddle,Cornell, U Alberta, UT Austin.

Watch us at

http://www.youtube.com/user/USUOSAM

Utah State University

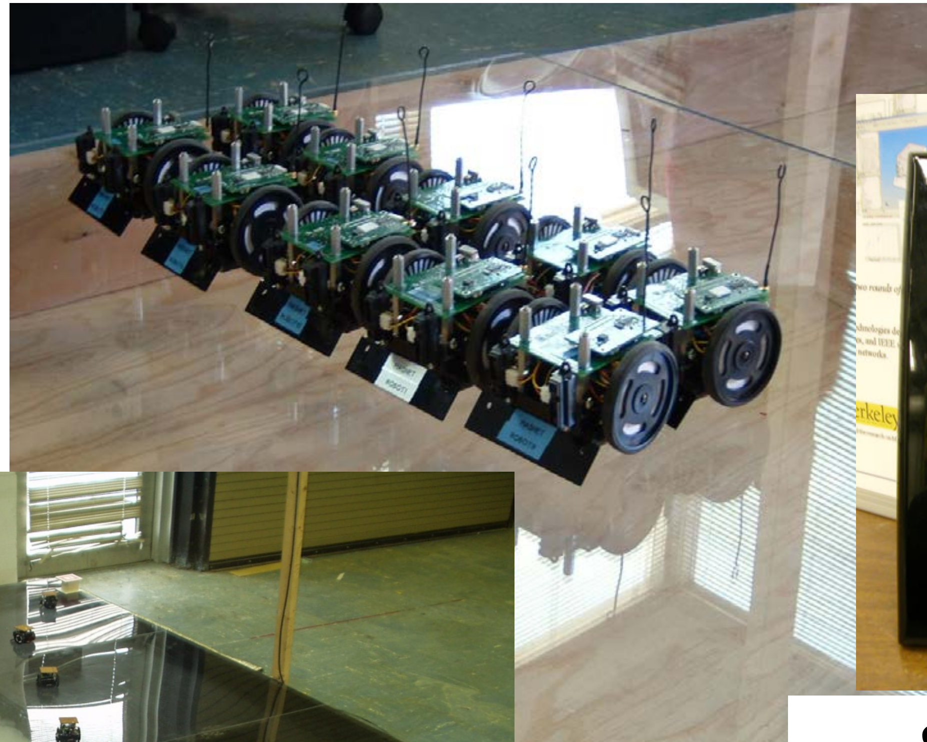
CSOIS CENTER FOR SELF-ORGANIZING AND INTELLIGENT SYSTEMS

- We won #1 again in AUVSI'11 UAS Competition!!
  - June 15-19, 2011. Maryland AFB.
  - $13400 cash award. Swept all three categories.
  - Other registered participants: UCSD, NCSU, UT Austin etc.
  - First time in the competition history to win 1st place twice.
  - VTOL team made history too by flying waypoints autonomously

Watch our UAV-based real world applications (not just for fun!) at **http://aggieair.usu.edu**

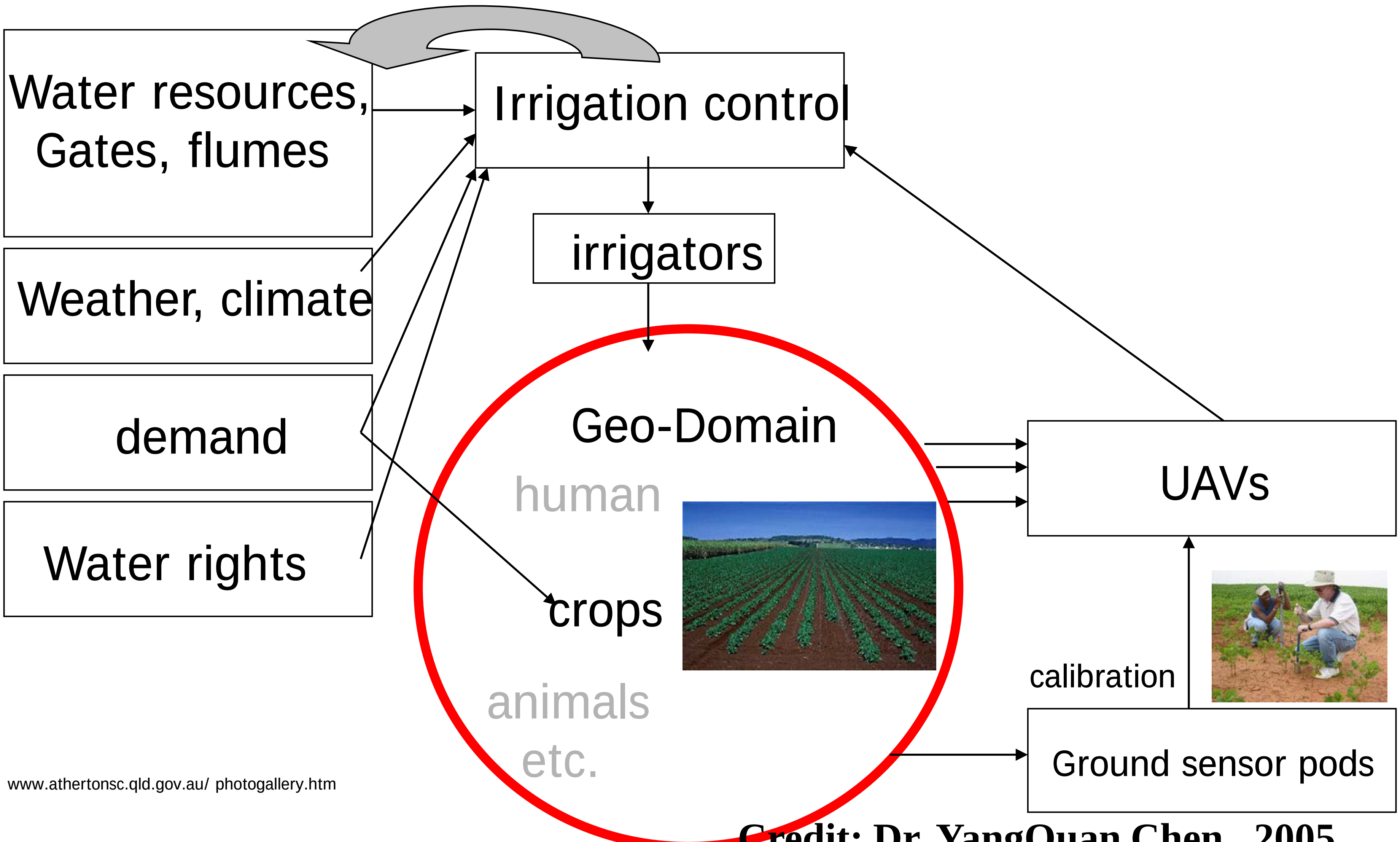
Mote-Based Distributed Robots

Prototype plume-tracking testbed - 2004



$2000 2nd Place Prize in 2005 Crossbow Smart-Dust Challenge

WaterWatch?



www.athertonsc.qld.gov.au/ photogallery.htm

Credit: Dr. YangQuan Chen, 2005

Some “bragging rights” of CSOIS

- http://www.hub.sciverse.com/action/search/results?st=%22fractional+order%22
- http://www.hub.sciverse.com/action/search/results?st=uav+remote+sensing
- http://www.hub.sciverse.com/action/search/results?st=iterative+learning+control
- http://www.hub.sciverse.com/action/search/results?st=fractional (over 1.1M docs, #5)
- http://www.hub.sciverse.com/action/search/results?st=%22fractional+processes%22
- http://www.hub.sciverse.com/action/search/results?st=mobile+actuator+network

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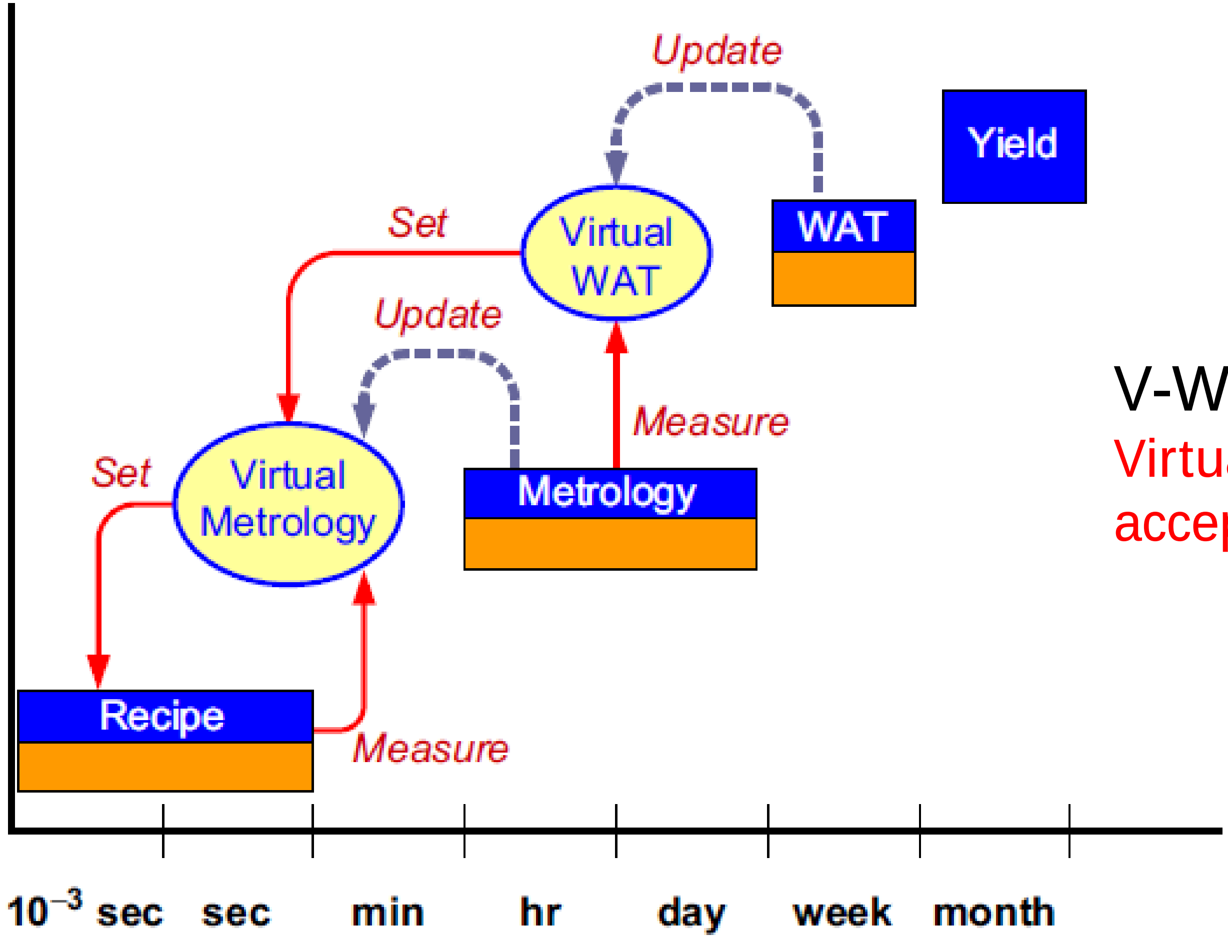
Process Control

From "Supervisory Control (SC)" to "Statistic Process Control (SPC)" to "Cognitive Process Control"

- Enablers
  - Cheaper embedded wireless radio communication
  - Large memory/storage at low cost
  - Larger processing power of microprocessors
  - Richer model-based derived information

What are considered as “Cognitive”?

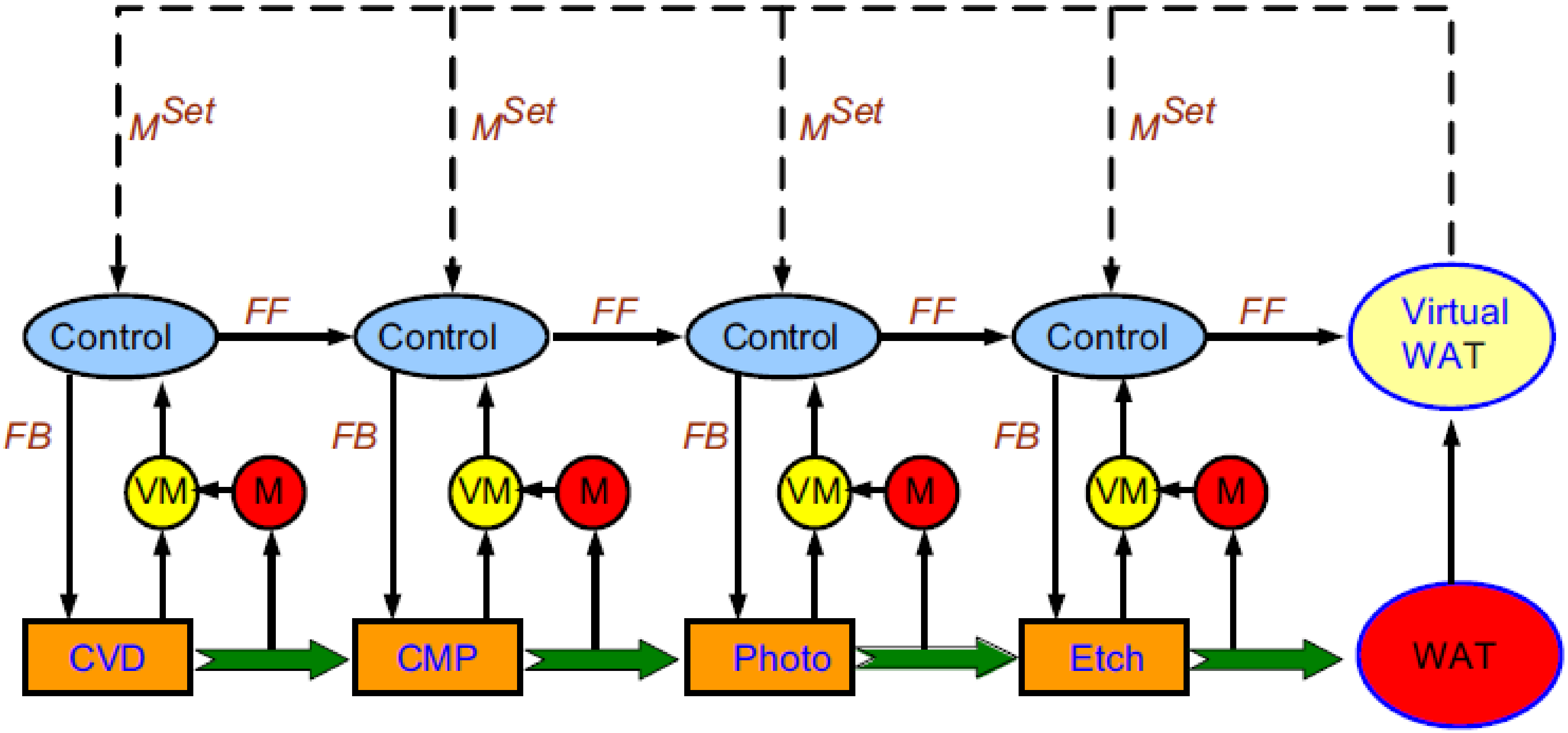
- Aware of process vital signs for healthy runs
  – Not only in process level, but also in component level
- Decision making and health issues alerting using multiple information sources
- Learning from past actions and induced errors
  – R2R, RC, ILC
- Pattern discovery and anomalous behavior detection at multiple time scales
- Virtual metrology for “Cognitive Process Control”



V-WAT:
Virtual wafer acceptance test

Su etal. “Control relevant issues in semiconductor manufacturing: Overview with some new results.” Control Engineering Practice 15 (2007) 1268–1279

Cognitive Process Control: Where? When?



Keys:

M:metrology, VM:virtual metrology, MSet:metrology setpoint
FB:feedback, FF:feedforward

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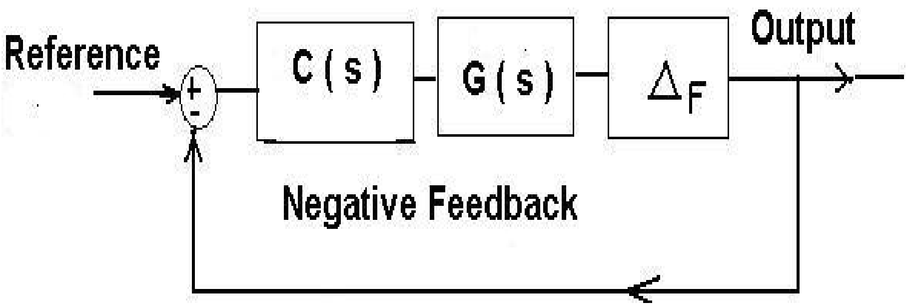
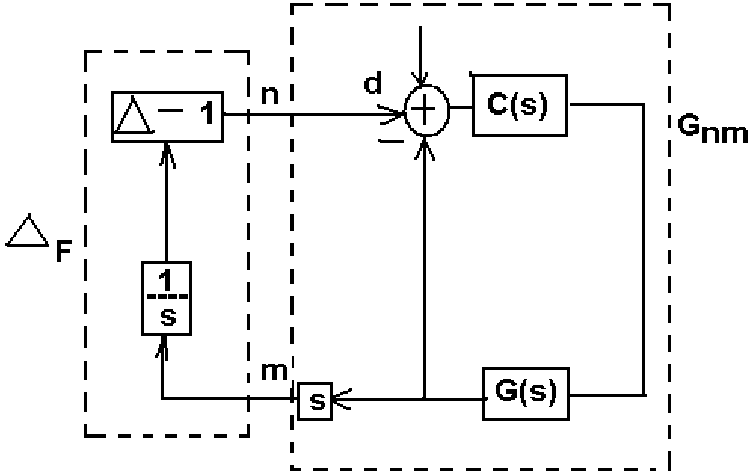
Jitter Margin





$$\Delta m(t) = m(t - \delta(t)) \text{ s.t. } 0 \le \delta(t) \le \delta_{max},$$

$$\| G_{nm} \|_{L_2} = \sup_{\omega \epsilon [0,\infty]} \left| \frac{G(j\omega)C(j\omega)}{1 + G(j\omega)C(j\omega)} \right| < \frac{1}{\delta_{max}\omega}.$$

Related works

- Varsha Bhambhani+, YangQuan Chen*, Dingyu Xue. Optimal Fractional Order Proportional Integral Controller for Varying Time-Delay Systems. *In Proceedings of the IFAC World Congress*, Seoul, Korea, July 2008,
- Varsha Bhambhani+, Yiding Han+, Shayok Mukhopadhyay+, Ying Luo+ and YangQuan Chen*. Random delay effect minimization on a hardware-in-the-loop networked control system using optimal fractional order PI controllers. *In Proc. of the 3rd IFAC Workshop on Fractional Derivative and Applications (FDA08)*, Ankara, Turkey, Nov. 2008.
- Varsha Bhambhani*. "Optimal Fractional Order Proportional and Integral Controller for Processes with Random Time Delays." Master of Science Thesis of Utah State University, 2008. http://digitalcommons.usu.edu/etd/246

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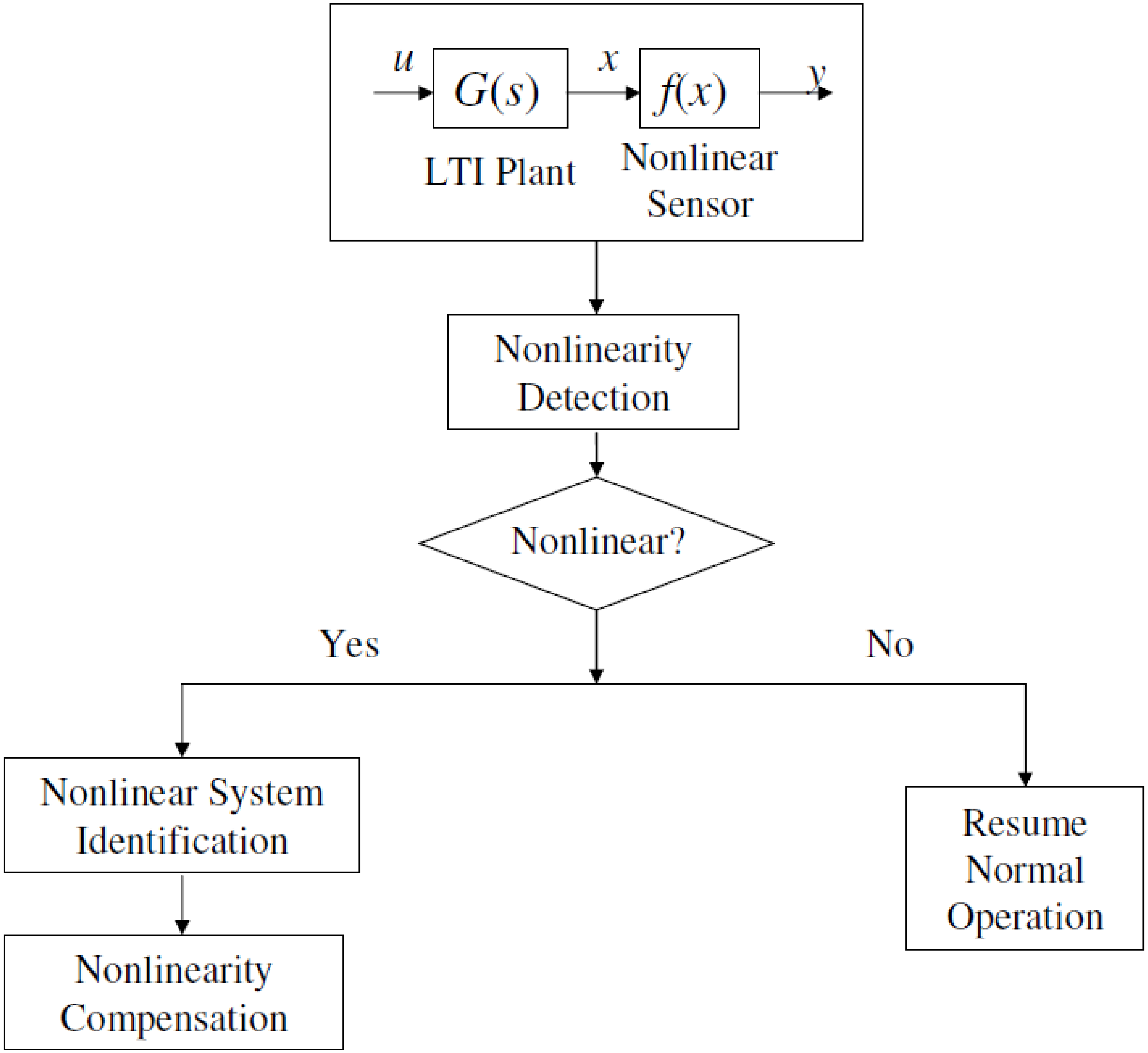
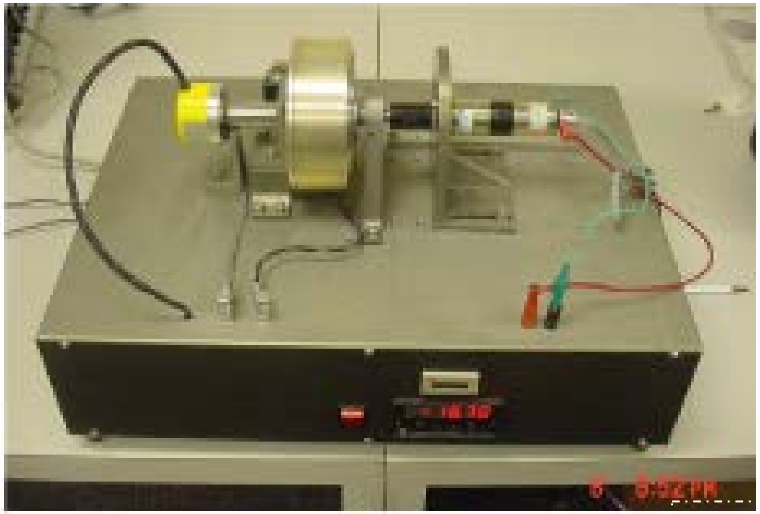
Undistortion Technique

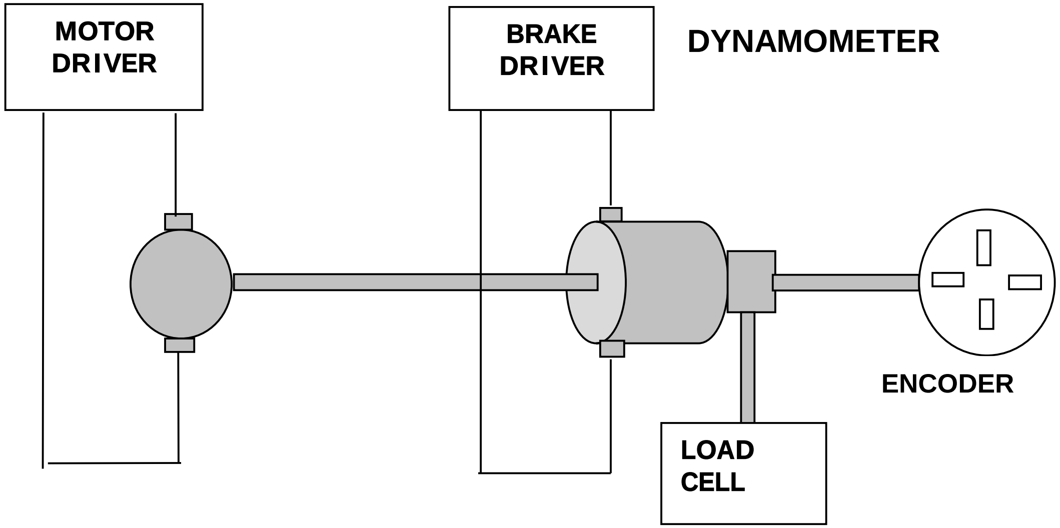
- Detection, Identification and Compensation of Nonlinearities



The Fractional Horsepower Dynamometer



Rapid Testing and Prototyping of Nonlinear Controllers

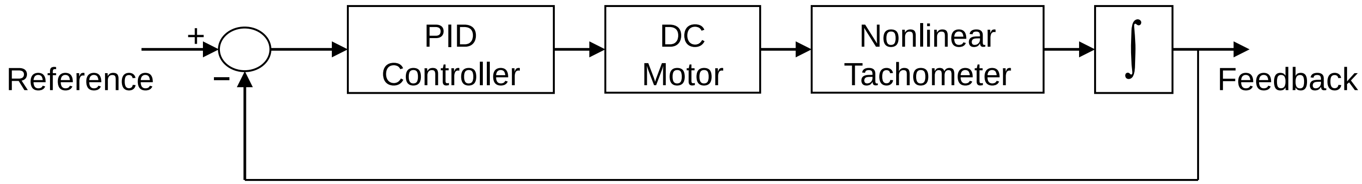


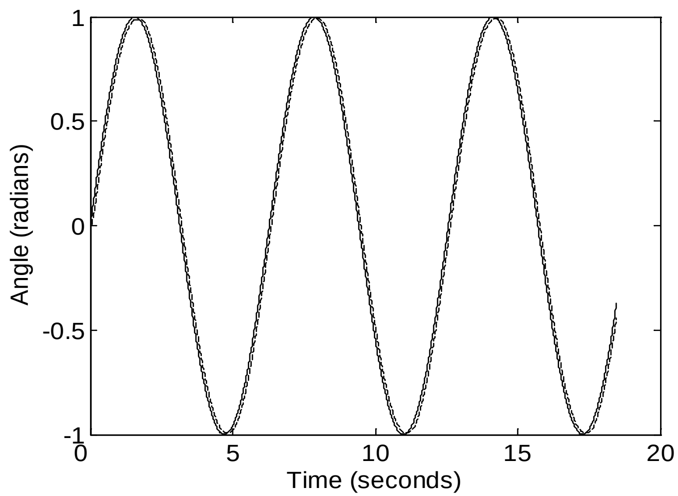
$$\dot{x}(t) = v(t)$$

$$\dot{v}(t) = -f(t,x) + u(t)$$

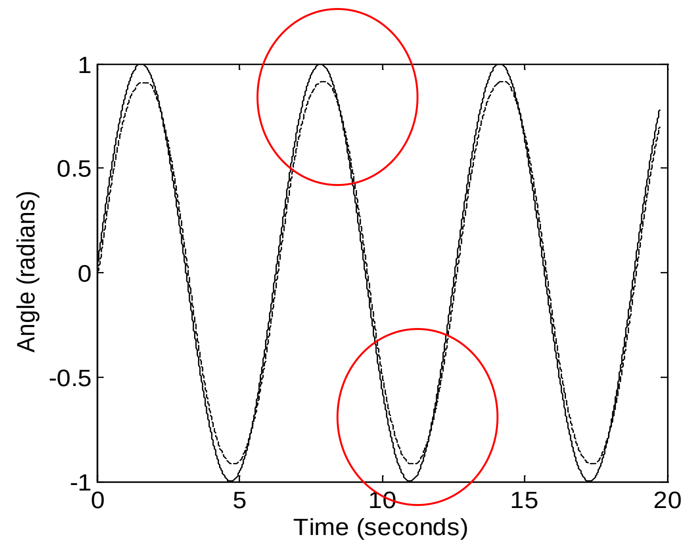
Nonlinearity Detection: Motivation

Consider a position control system with nonlinear sensor ($y=x+\alpha x^3$).





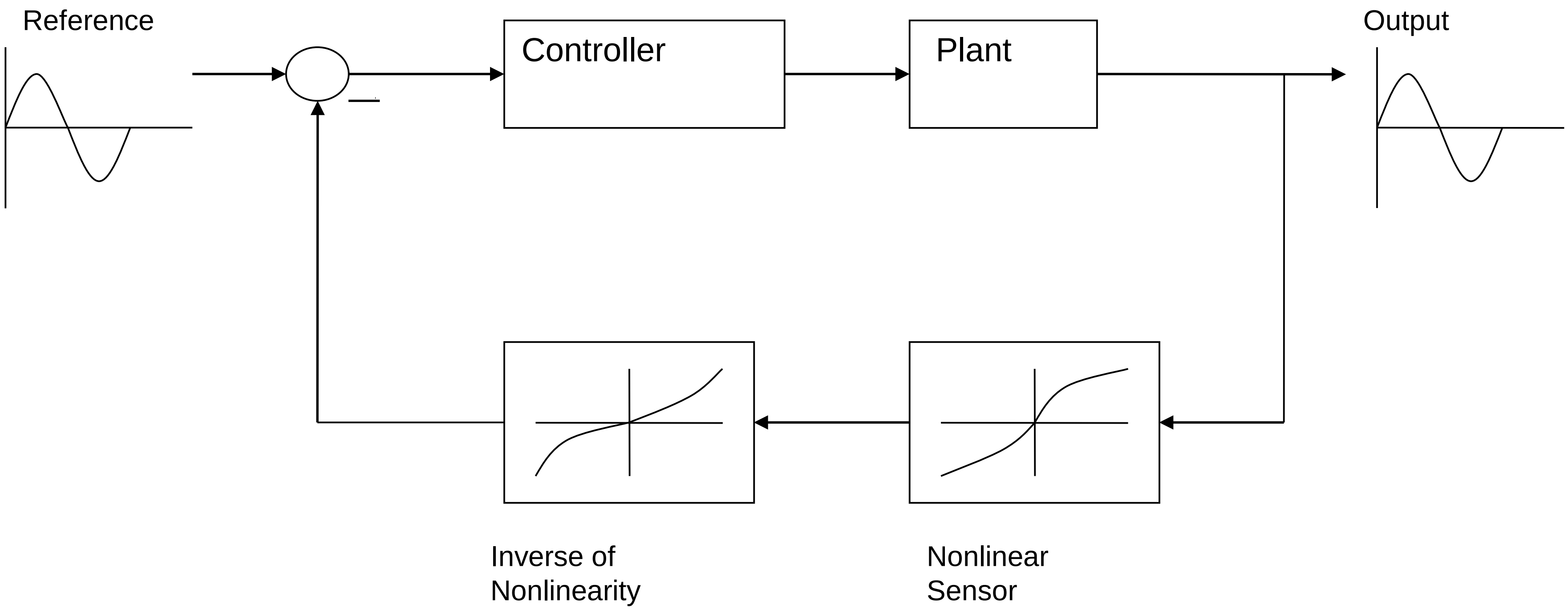
$\alpha=0$



$\alpha=0.1$

Nonlinearity Detection: Motivation

The basic idea of static nonlinearity compensation:



Nonlinearity Detection Method

Higher-Order Statistics (HOS)

- First and second order statistics (mean, autocorrelation, power spectrum) are useful in describing linear process only.
- Presence of nonlinearity in system causes interaction of different frequencies [Fackrell 1996].
- HOS tools like bispectrum and bicoherence can be used to analyze nonlinear process data.
- HOS can be used for:

1. detecting deviations due to Gaussianity,
2. identifying true phase character of the signals,
3. detecting and identifying nonlinearities in time series. [NikiasPetropulu93]

Nonlinearity Detection Method

Higher-Order Statistics (HOS)

- Bispectrum:

$$B(f_1, f_2) \equiv E[X(f_1)X(f_2)X^*(f_1 + f_2)]$$

Indicates the interaction between frequencies f_1 and f_2.

- Bicoherence:

$$bic^2(f_1, f_2) \equiv \frac{|B(f_1, f_2)|^2}{E[|X(f_1)X(f_2)|^2]E[|X(f_1 + f_2)|^2]}$$

Describes the phase and power coherence at the coupled frequency (f_1,f_2). [ChoudhuryShahThornhill2004]

Nonlinearity Detection Method

Nonlinearity Index (*NLI*)

- For linear signals, the squared bicoherence is a constant in the bifrequency plane. The flatness of squared bicoherence plot can be checked by

$$NLI \equiv \left| \hat{bic}^2_{\max} - \left(\overline{\hat{bic}^2} + 2\sigma_{\hat{bic}^2} \right) \right| .$$

NLI should ideally be zero for linear signals.

For practical purposes signals with *NLI* value less than 0.01 can be considered linear. [ChoudhuryShahThornhill2004]

Related publications

- 2006. Yashodhan Tarte. “Detection, Identification, and Compensation of Nonlinearities and an Experimental Verification Platform for Nonlinear Controllers”, Master of Science Thesis.
- Tarte, Yashodhan+ and YangQuan Chen*. “Wiener System Identification with Four-Segment and Analytically Invertible Nonlinearity Model”. *Proc. of the 2007 American Control Conference*, July 11-13, 2007, Marriott Marquis Hotel at Times Square, New York City, USA.
- YangQuan Chen*, Yashodhan Tarte+. "Sensor Undistortion Using Hyperbolic Splines in Least Squares Sense," June 14-16, 2006, Minneapolis, Minnesota, *American Control Conf*., pp. 2987-2988.
- Yashodhan Tarte+, YangQuan Chen*, Wei Ren, Kevin L. Moore. “Fractional Horsepower Dynamometer - A General Purpose Hardware-In-The-Loop Real-Time Simulation Platform for Nonlinear Control Research and Education”. December 13-15, 2006. San Diego. *IEEE Int*, *Conference on Decision and Control*.

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ILC – Iterative Learning Control

- Y. Chen, J.-X. Xu, T.H. Lee and S. Yamamoto, ``Comparative Studies of Iterative Learning Control Schemes for A Batch Chemical Process'', Presented at the IEEE Singapore Int. Symposium on Control Theory and Applications, Singapore, pp. 166-70, 1997.
- J.-X. Xu, Y. Q. Chen*, T.H. Lee and S. Yamamoto, 1999, ``Terminal Iterative Learning Control with an Application to RTPCVD Thickness Control,'' ***Automatica***, vol. 35, no. 9, pp. 1535-1542, 1999.

Also first in ILC+HDD servo

- US06,437,936. 08/20/2002. “Repeatable runout compensation using a learning algorithm with scheduled parameters”
- US06,563,663. 05/13/2003. “Repeatable runout compensation using iterative learning control in a disc storage system”
- US06,574,067. 06/03/2003. “Optimally designed parsimonious repetitive learning compensator for HDDs having high track density”
- US06,654,198. 11/25/2003. “Repeatable run-out error compensation method for a disc drive”

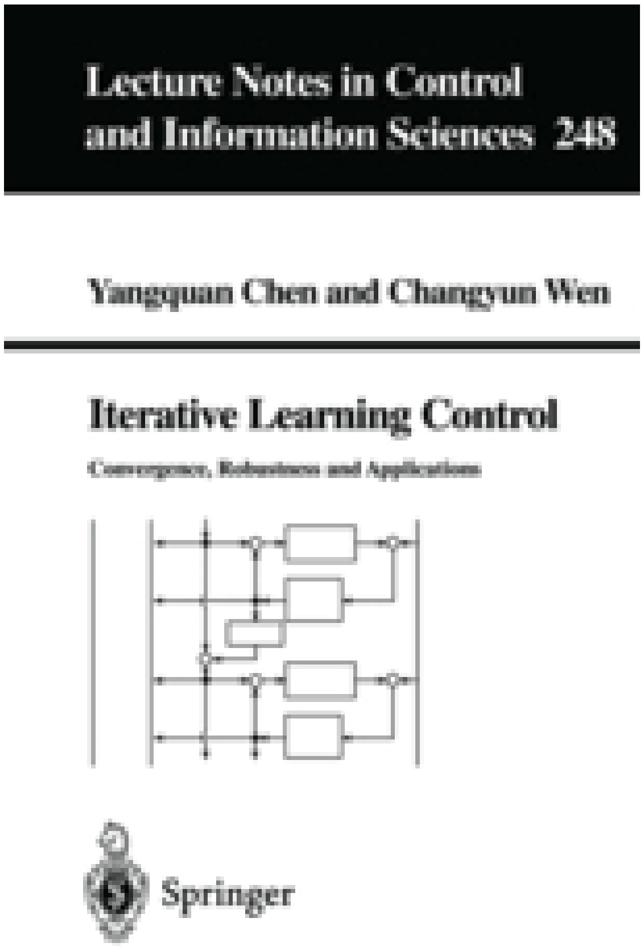
ILC linked to "Real-time SPC"

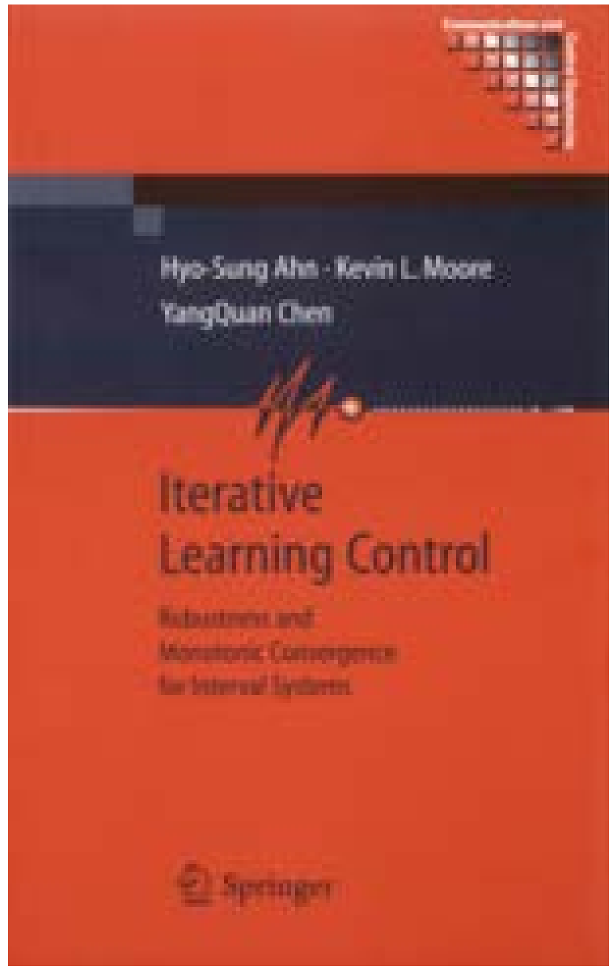
- http://www.neng.usu.edu/ece/csois/ilc/ILC/ilcref.html (1997) RT SPC
- R2R is a type of ILC, see
  - Youqing Wang, Furong Gao, Francis J. Doyle III. "Survey on iterative learning control, repetitive control, and run-to-run control" Journal of Process Control 19 (2009) 1589–1600

More information

- YangQuan Chen, Kevin Moore, Jie Yu, Tao Zhang. "Iterative learning control and repetitive control in harddisk drive industry - a tutorial". Int. J. of Adaptive Control and Signal Processing, 22(4), 2008, pp. 325-343.
- **"Iterative Learning Control" entry for "Encyclopedia of the Sciences of Learning"** Seel, Norbert M. (Ed.) 2012, 4300 p. 100 illus. In 7 volumes.

Our ILC books



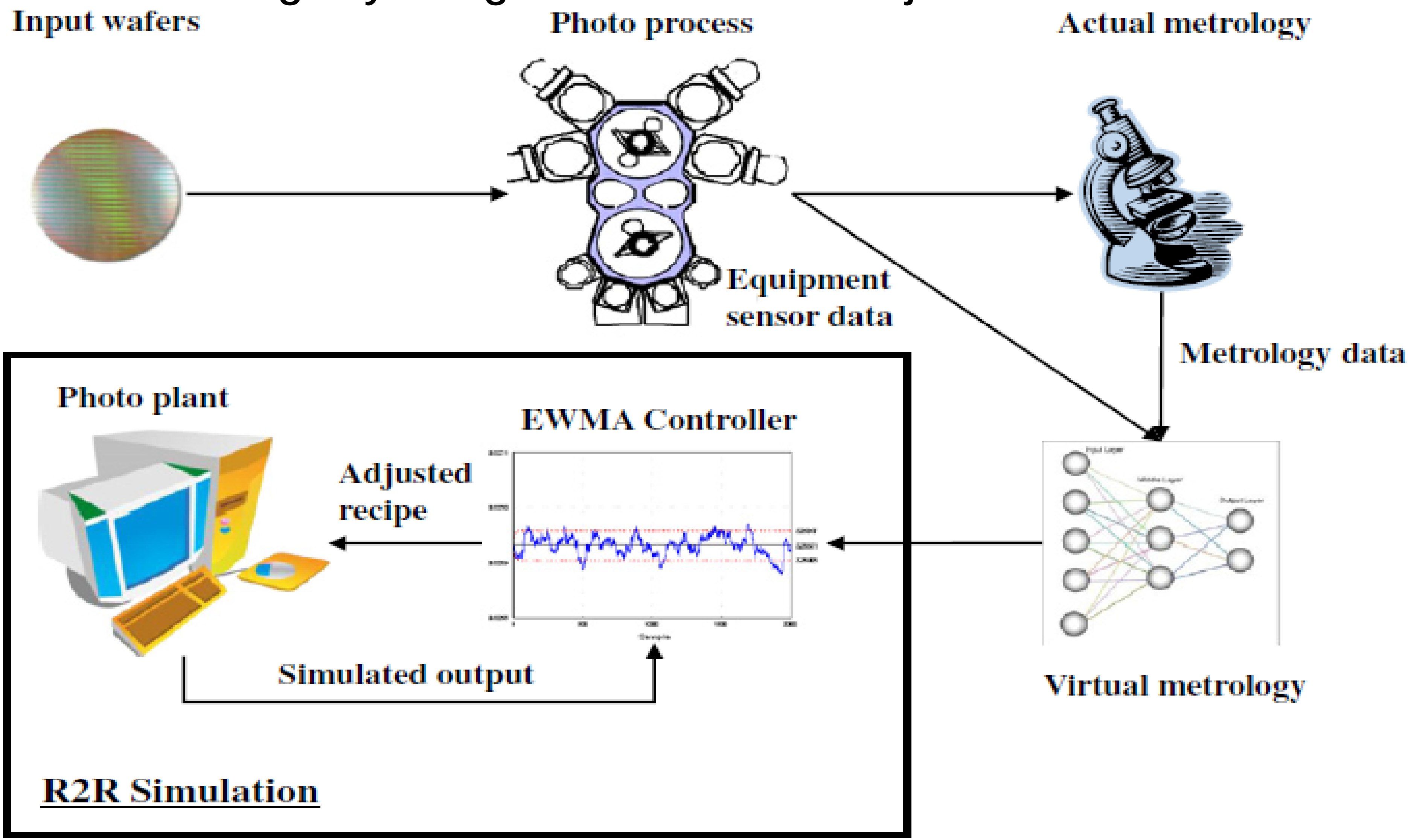


Iteration-Domain Robustness Designs

- Robustness with respect to batch-to-batch or **run-to-run variability** was first investigated by Moore-Chen-Ahn school.
- So are
  - Monotonic ILC
  - Interval ILC
  - Intermittent ILC
  - Multi-agent ILC

Kevin L. Moore*, Hyo-Sung Ahn+, and YangQuan Chen. "Iteration Domain H_∞-Optimal Iterative Learning Controller Design". (Wiley) International Journal of Nonlinear and Robust Control. Volume 18, Issue 10, Date: 10 July 2008, Pages: 1001-1017

"Virtual metrology for run-to-run control in semiconductor manufacturing" by Kang et al doi:10.1016/j.eswa.2010.08.040



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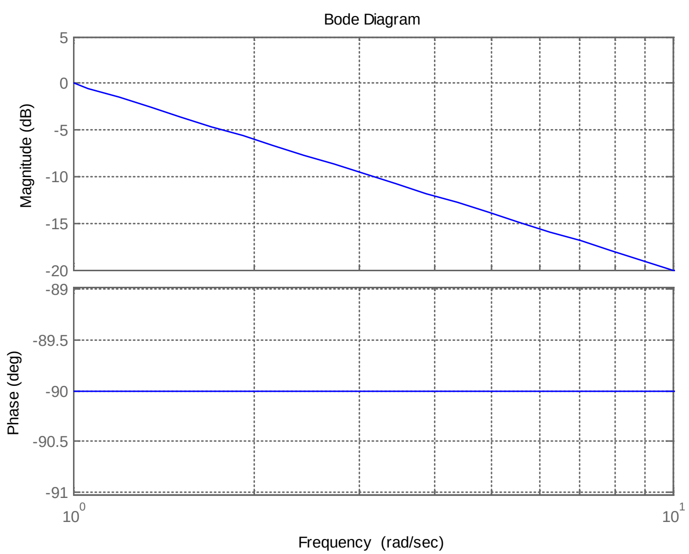
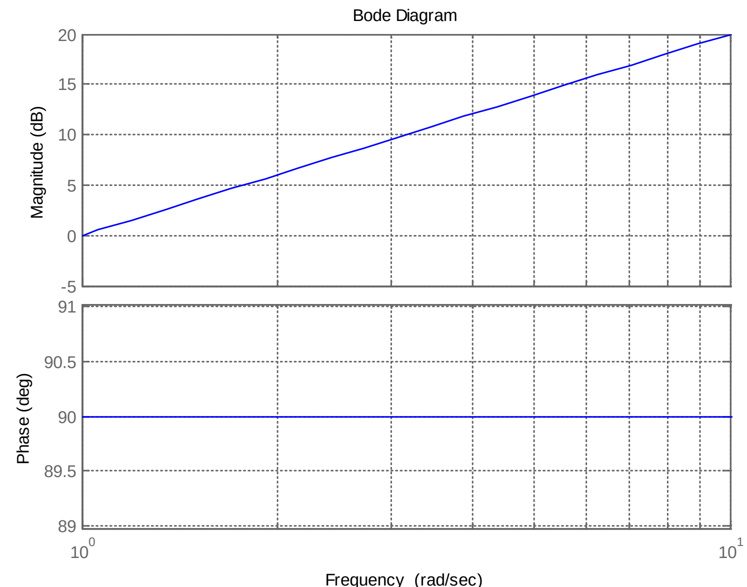
Fractional Order Modeling/Control/Signal Processing

- Fractional Calculus and Fractional Order Thinking
- From Fractional Order Signal Processing, Modeling to Control

Fractional (Noninteger)(order) operator

- First order differentiator: s
- First order integrator: $1/s$





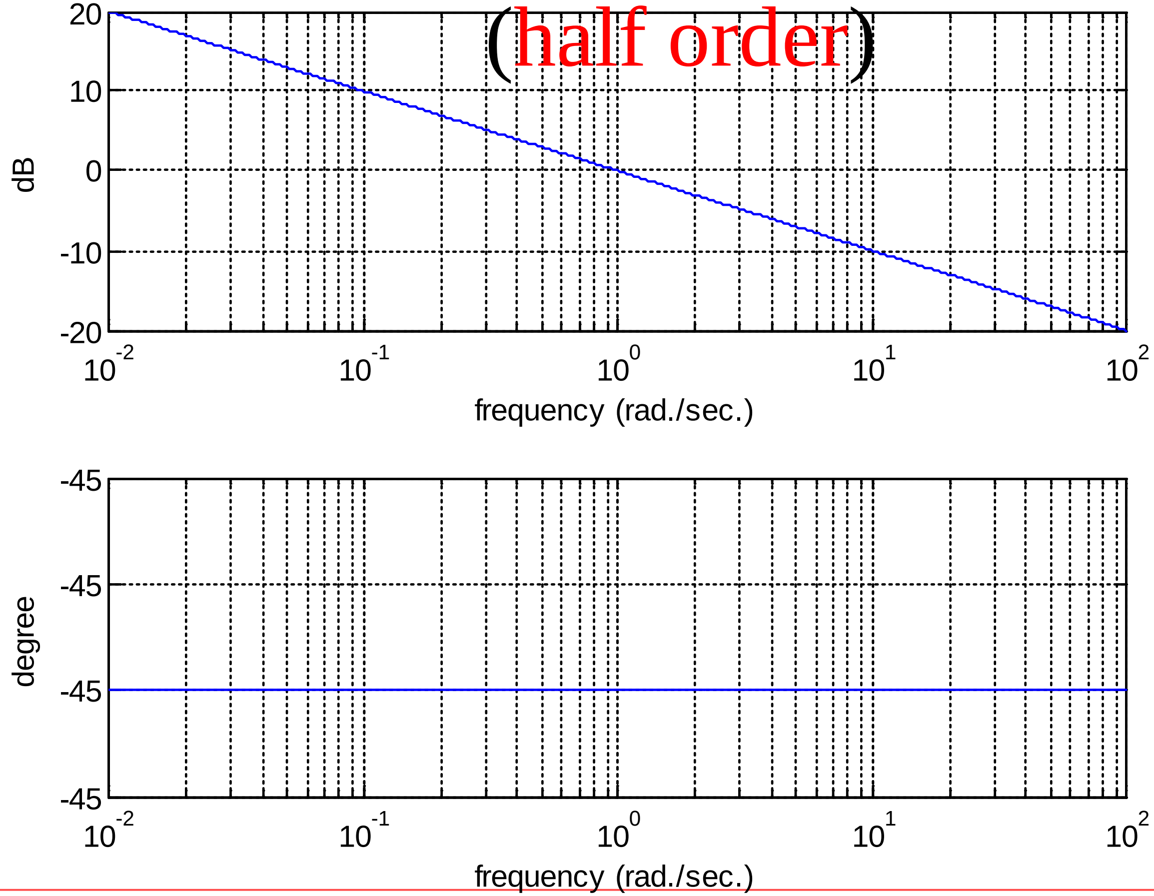

```
sys1=tf([1],[1,0]);figure;bode(sys1);grid on;
```

```
sys1=tf([1],[1,0]);figure;bode(1/sys1);grid on;
```

What is s^{α} when α is a *non-integer*?

Fractional Order Integrator (half order)

$$G(s) = \frac{1}{\sqrt{s}}$$

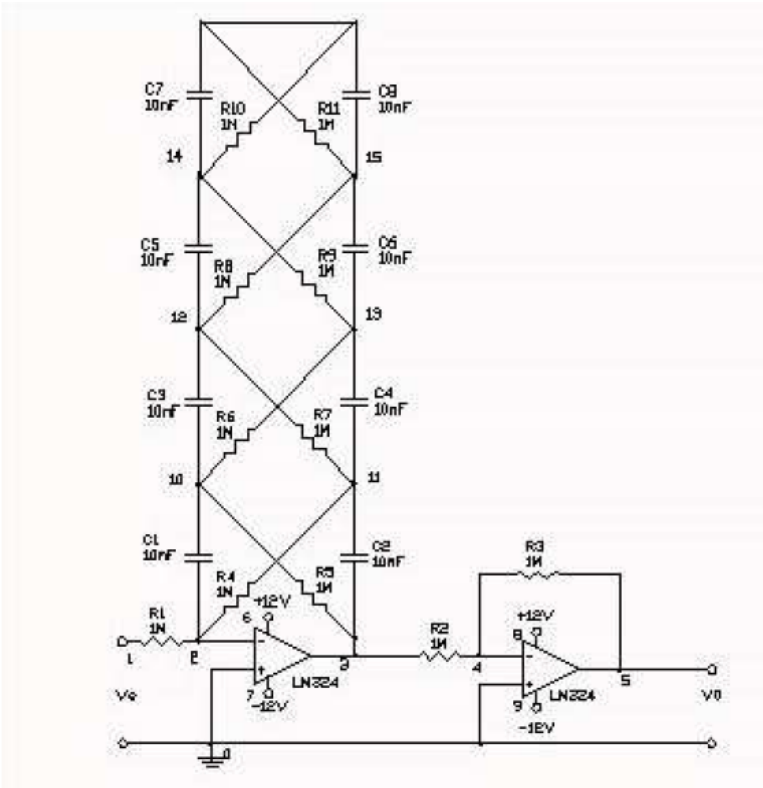


Legal in MATLAB

and everywhere?

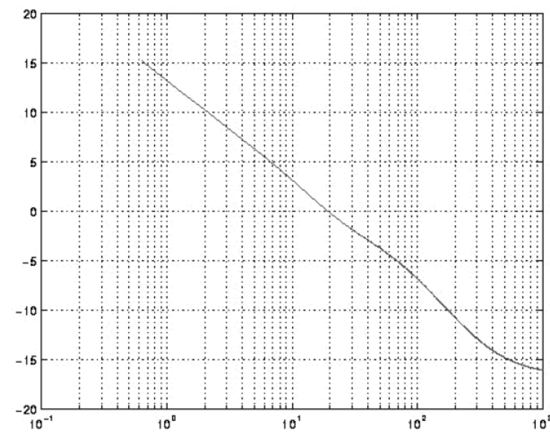
```
a=-0.5;w=logspace(-2,2,1000);fi=(j.*w).^a;
figure;subplot(2,1,1);semilogx(w,20*log10(abs(fi)));
xlabel('frequency (rad./sec.)');ylabel('dB');grid on
subplot(2,1,2);semilogx(w,180*angle(fi)/pi);
xlabel('frequency (rad./sec.)');ylabel('degree');grid on
```

Possible? Possible! Legal!!

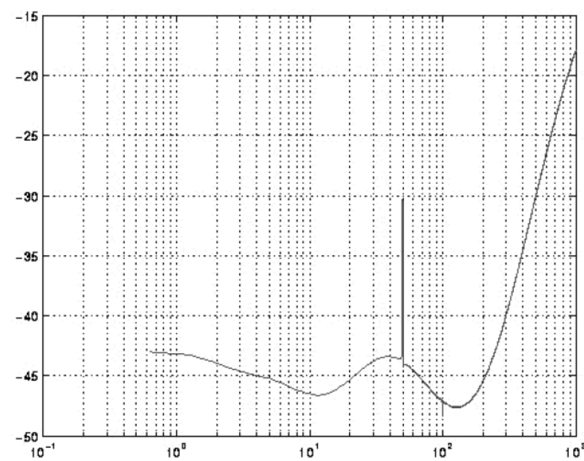


Analog $1/\sqrt{s}$ using op-amps.

Magnitude plot (dB vs. rad./sec.)



Phase plot (deg. vs. rad./sec.

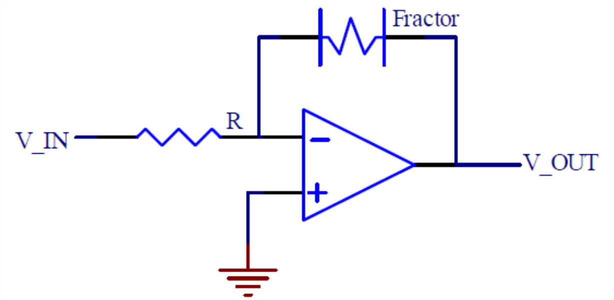


I. Petras, I. Podlubny, P. O'Leary, L. Dorcak, and Vinagre B. "**Analogue Realization of Fractional Order Controllers**". FBERG, Technical University of Kosice, Kosice, Slovak, **ISBN 8070996277** edition, 2002.

Fractor: Analogue device

NSF SBIR 0538866

Fractional Calculus Day at USU, April 19, 2005



$$G(s) = -\frac{K}{R(s\tau)^{\lambda}}$$

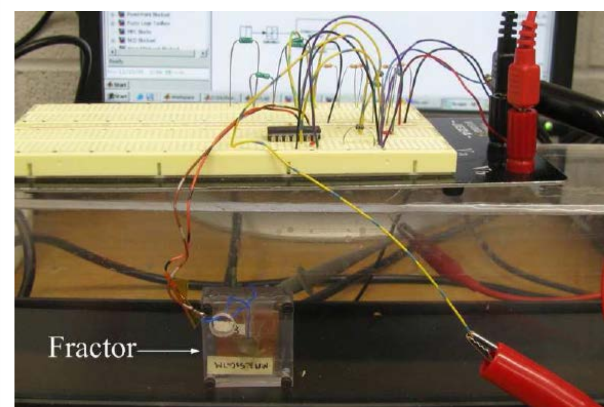
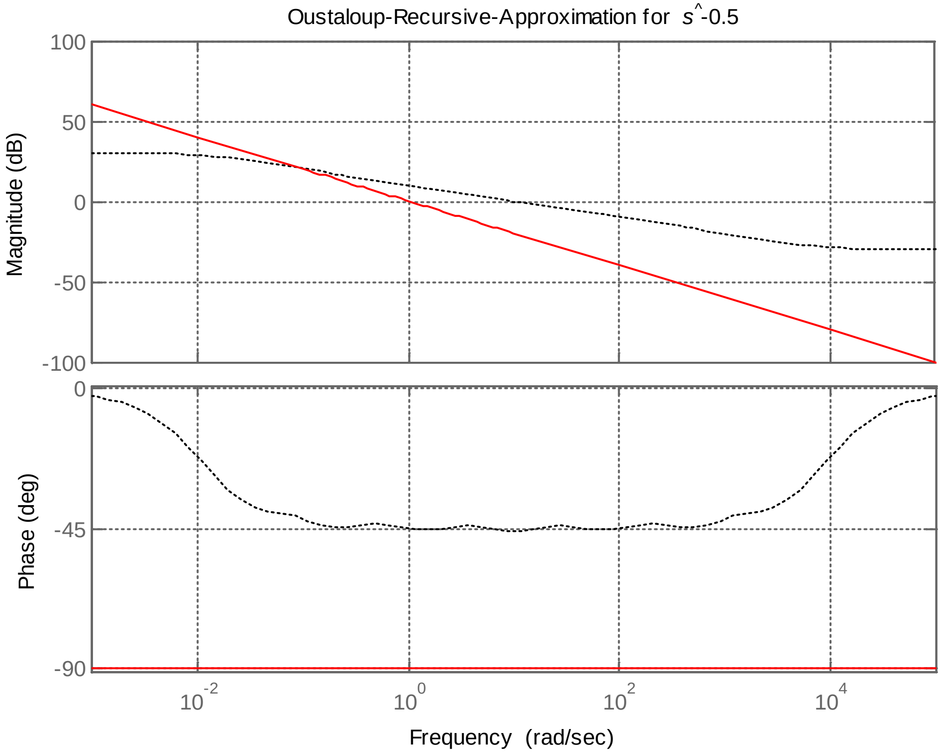


Photo credit: Igor Podlubny

Oustaloup's Recursive Approximation for fractional order differentiators/integrator

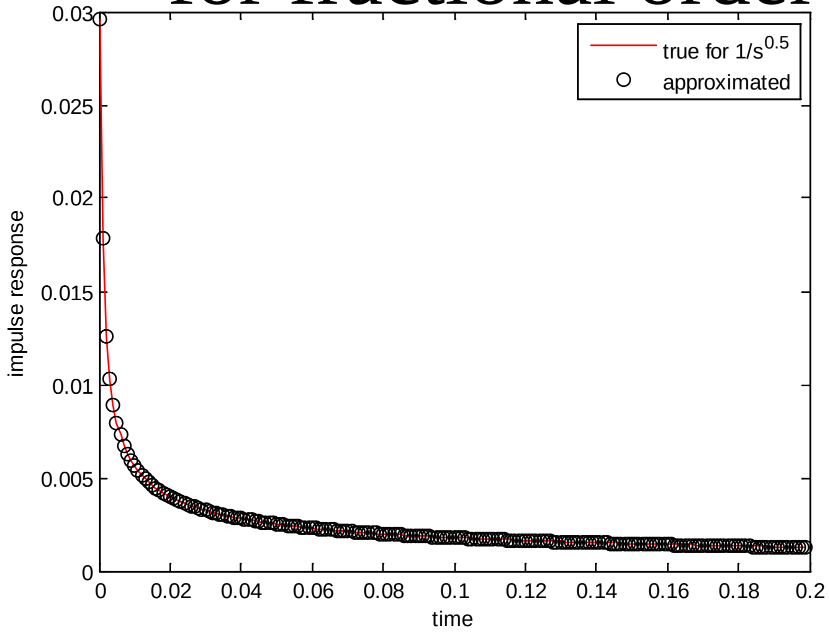


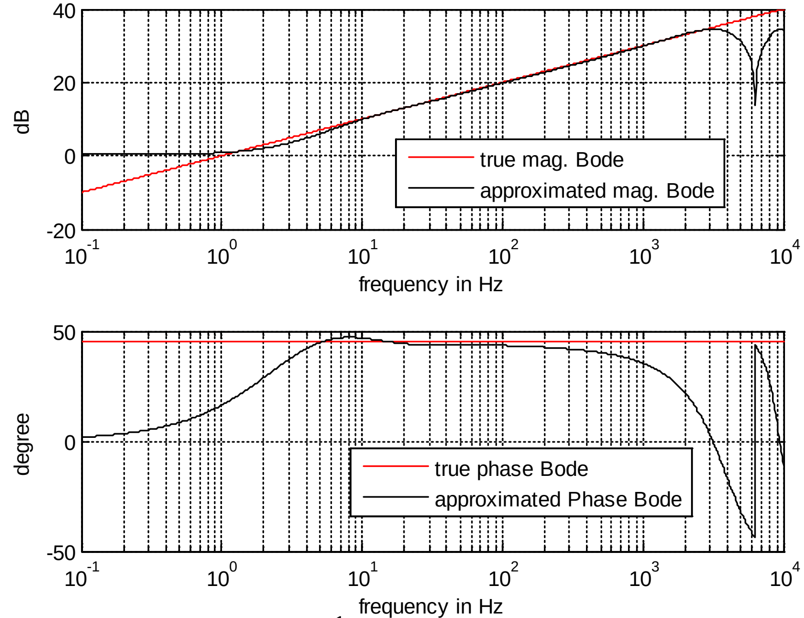

```
w_L=0.1;w_H=1000; r=-0.5; figure; N=3; sys1=tf(1,[1,0]);
sys_N_tf=ora_foc(r,N,w_L,w_H);bode(sys_N_tf,'k:',sys1,'r-');grid on;
title(['Oustaloup-Recursive-Approximation for {\it s}^{\^}',num2str(r)]);
```

$$G(s) = \frac{1}{s^{\gamma}} \approx \frac{B(s)}{A(s)}$$

http://www.mathworks.com/matlabcentral/fileexchange/3802-oustaloup-recursive-approximation-for-fractional-order-differentiators

Chen's impulse response invariant discretization for fractional order differentiators/integrator





irid_fod(0.5,.001,7)

$$G(s)=\frac{1}{s^{\gamma}}\approx\frac{B(z^{-1})}{A(z^{-1})}$$

http://www.mathworks.com/matlabcentral/fileexchange/21342-impulse-response-invariant-discretization-of-fractional-order-integratorsdifferentiators

What is s^α when α is a *non-integer* ?

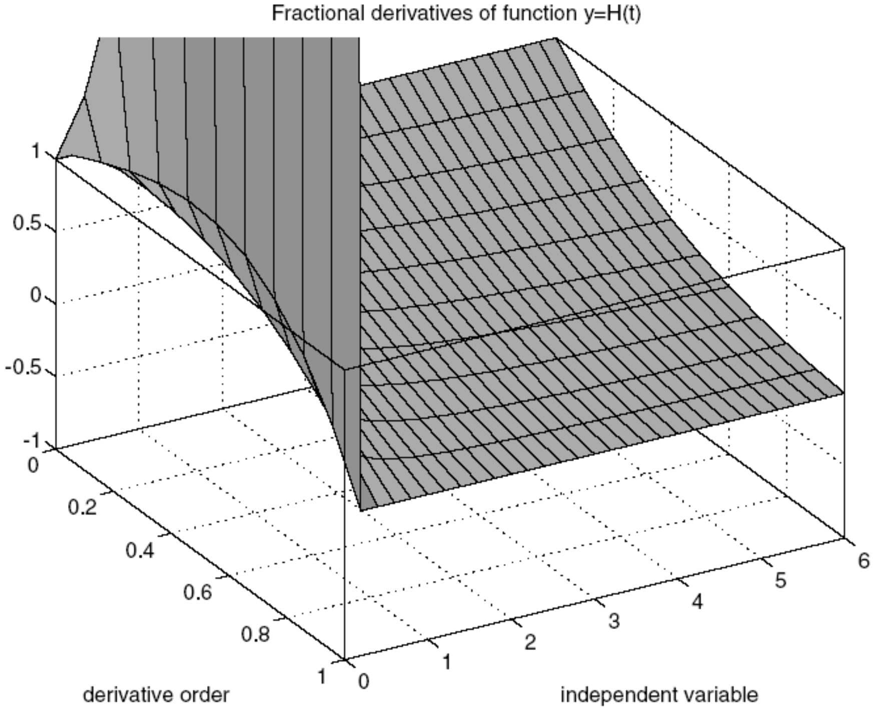
Operator ${}_a\mathrm{D}_t^\alpha$

A generalization of differential and integral operators:

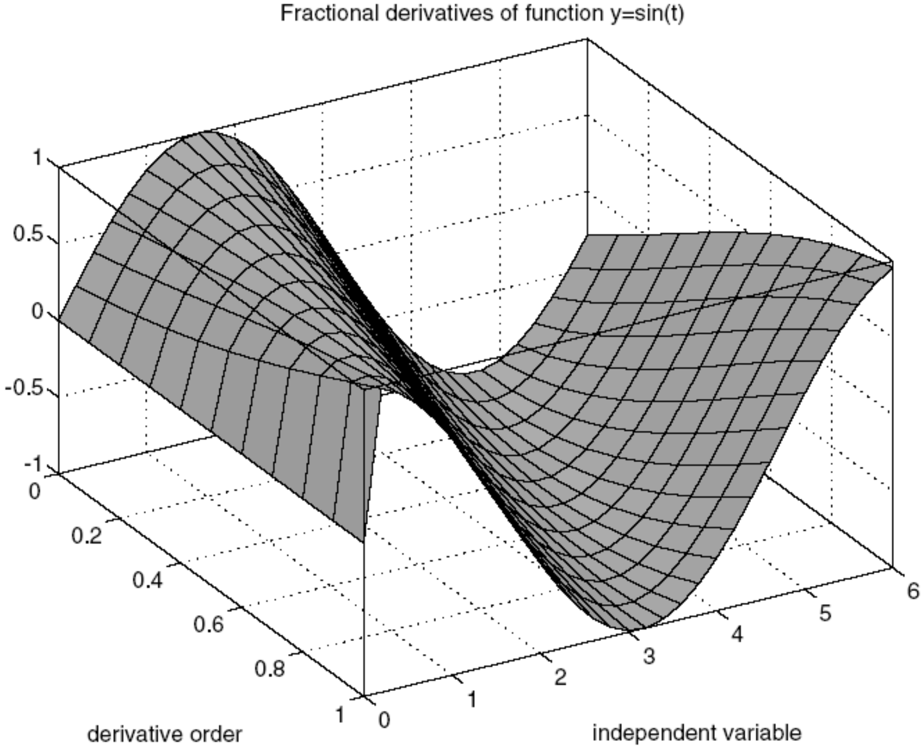
$$ {}_a\mathrm{D}_t^\alpha = \begin{cases} \mathrm{d}^\alpha/\mathrm{d}t^\alpha & \mathbb{R}(\alpha) > 0, \\ 1 & \mathbb{R}(\alpha) = 0, \\ \int_a^t (\mathrm{d}\tau)^{-\alpha} & \mathbb{R}(\alpha) < 0. \end{cases} \quad (7) $$

There are two commonly used definitions for the general fractional order differentiation and integral, i.e., the **Grünwald-Letnikov definition** and the **Riemann-Liouville definition**.

Example: Heaviside's unit step

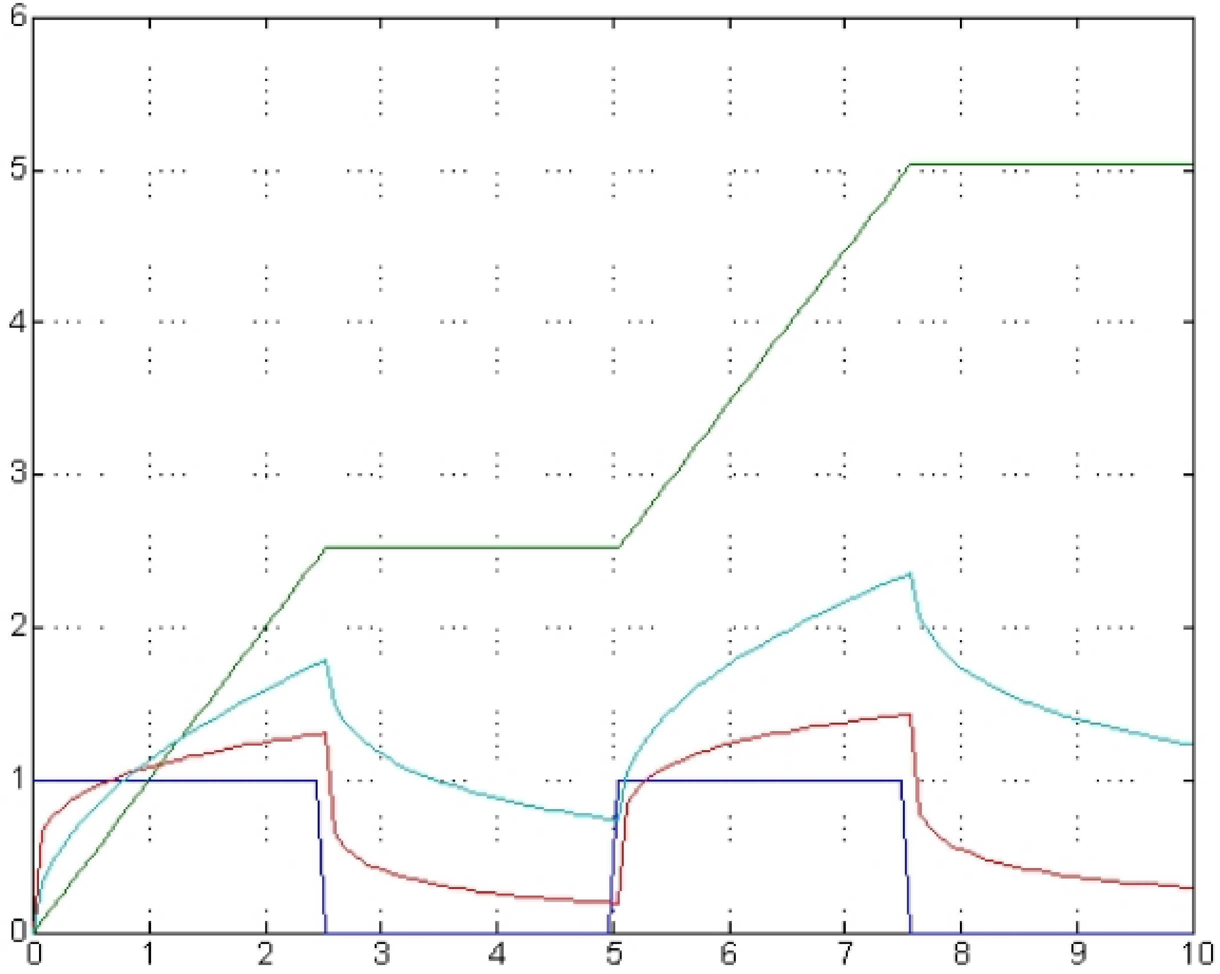


Example: $\sin(t)$



Slide credit: Igor Podlubny

Fractional derivatives of ramp function.

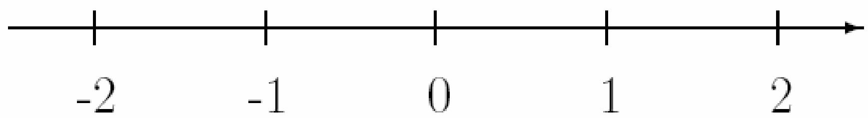


Nothing surprising so far.

Quite intuitive in fact.

For example,

… from integer to non-integer …



$$x^n = \underbrace{x \cdot x \cdot \ldots \cdot x}_{n}$$

$$x^n = e^{n \ln x}$$

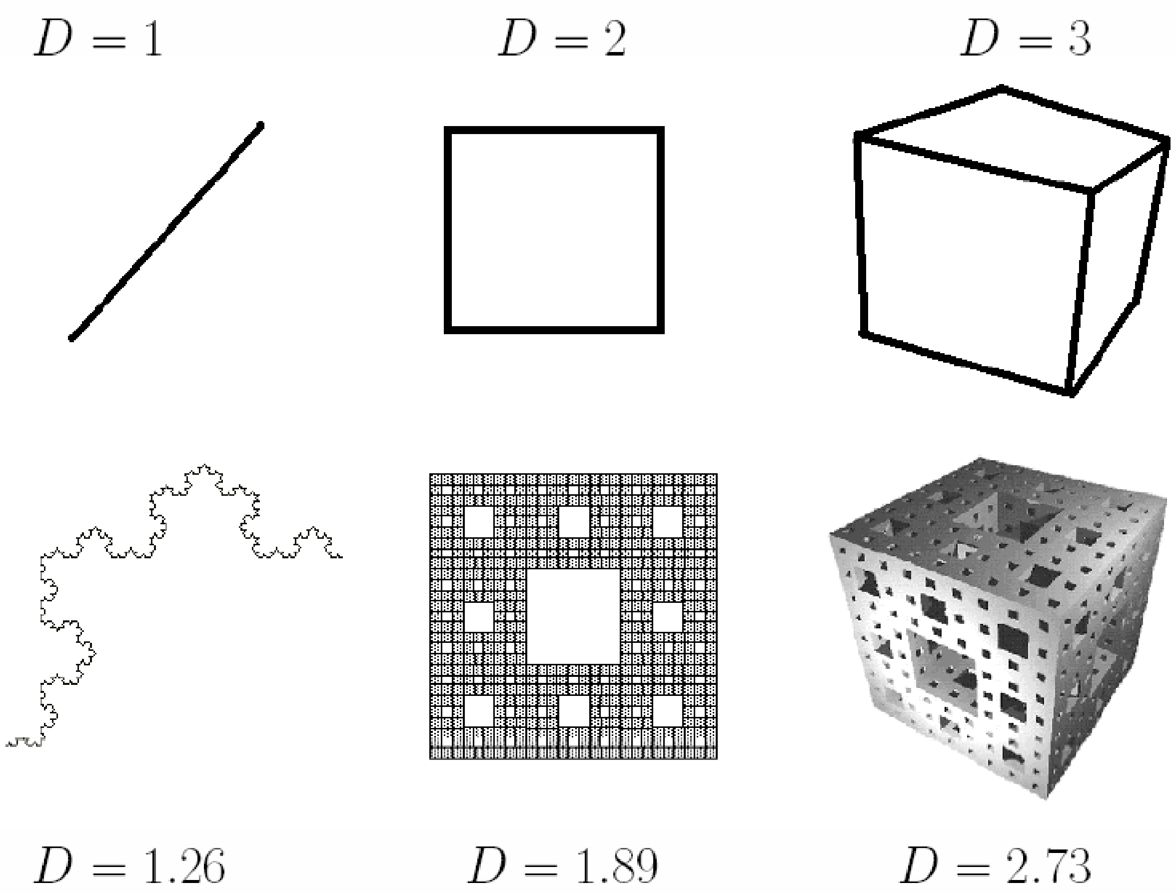
$$n! = 1 \cdot 2 \cdot 3 \cdot \ \ldots \cdot (n-1) \cdot n,$$

$$\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dt, \qquad x > 0,$$

$$\Gamma(n+1) = 1 \cdot 2 \cdot 3 \cdot \ \ldots \cdot n = n!$$

Slide credit: Igor Podlubny

. . . from integer to non-integer . . .



Slide credit: Igor Podlubny

Interpolation of operations

$$f, \quad \frac{df}{dt}, \quad \frac{d^2 f}{dt^2}, \quad \frac{d^3 f}{dt^3}, \quad \ldots$$

$$f, \quad \int f(t)dt, \quad \int dt \int f(t)dt, \quad \int dt \int dt \int f(t)dt, \quad \ldots$$

$$\ldots, \quad \frac{d^{-2} f}{dt^{-2}}, \quad \frac{d^{-1} f}{dt^{-1}}, \quad f, \quad \frac{df}{dt}, \quad \frac{d^2 f}{dt^2}, \quad \ldots$$

Slide credit: Igor Podlubny

"Fractional Order Thinking" or, "In Between Thinking"

- For example
  - Between integers there are non-integers;
  - Between logic 0 and logic 1, there is the "**fuzzy logic**";
  - Between integer order splines, there are "**fractional order splines**"
  - Between integer high order moments, there are **noninteger order moments (e.g. FLOS)**
  - Between "integer dimensions", there are **fractal dimensions**
  - Fractional Fourier transform (FrFT) – in-between time-n-freq.
  - Non-Integer order calculus (fractional order calculus – abuse of terminology.) (FOC)

Fractional Calculus was born in 1695

$$\frac{d^n f}{dt^n}$$

What if the order will be $n = ½$?

It will lead to a paradox, from which one day useful consequences will be drawn.

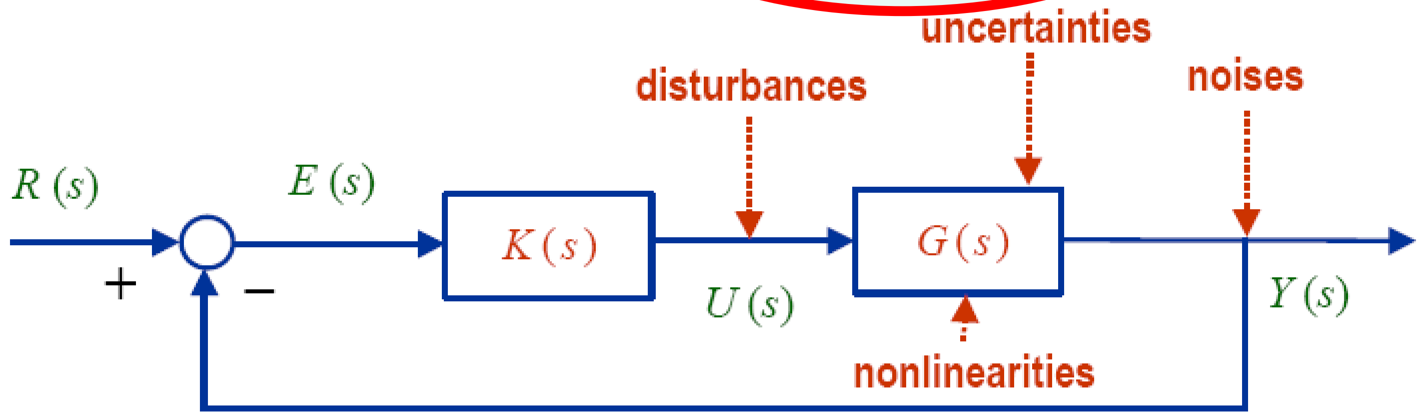
G.F.A. de L'Hôpital
(1661–1704)

G.W. Leibniz
(1646–1716)

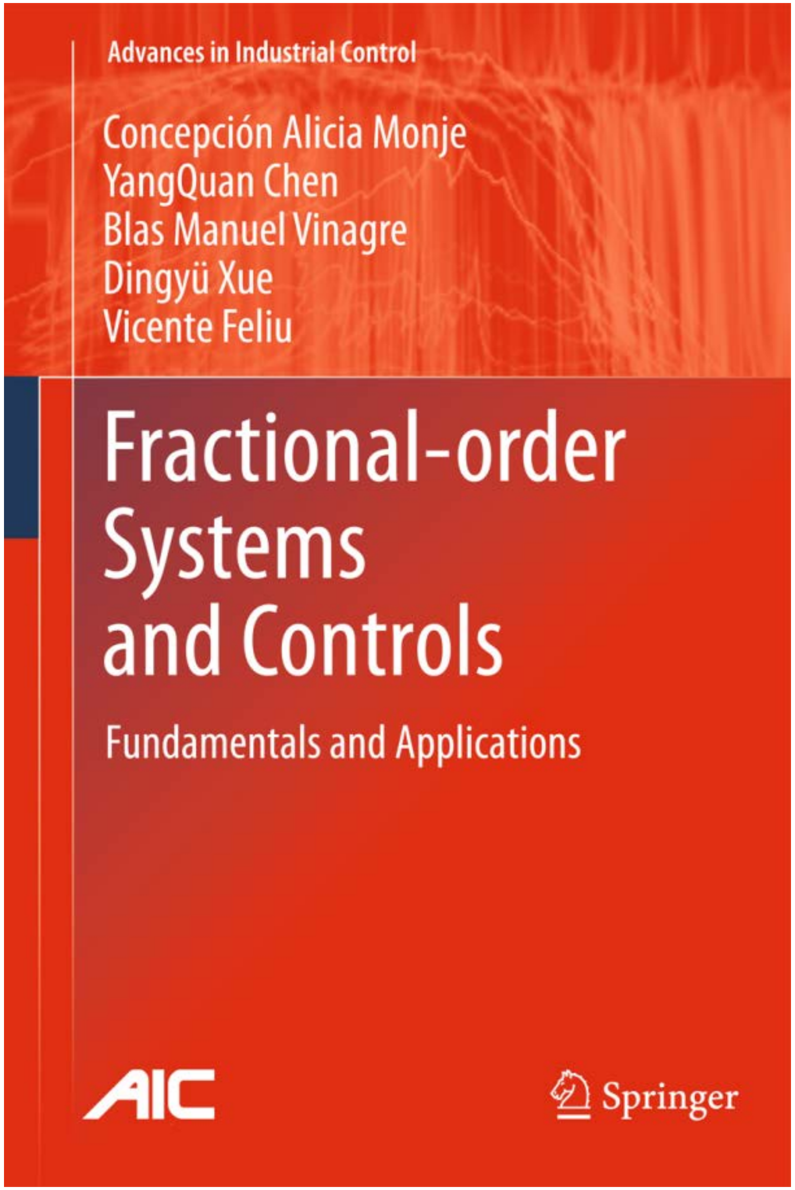
Slide credit: Igor Podlubny

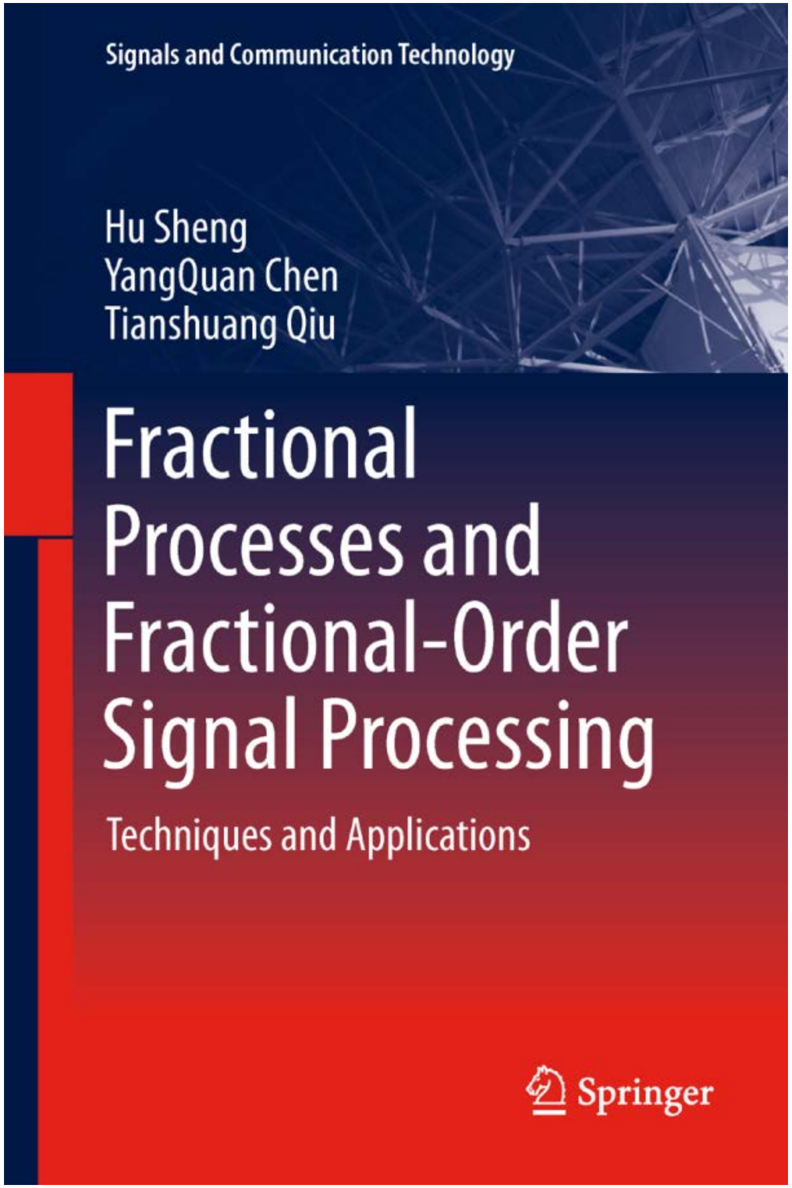
FOMs and Fractional Order Controls

- **IO Controller + IO Plant**
- **FO Controller + IO Plant**
- **FO Controller + FO Plant**
- **IO Controller + FO Plant**



Concepcin A. Monje, YangQuan Chen, Blas Vinagre, Dingyu Xue and Vicente Feliu (2010). "Fractional Order Systems and Controls - Fundamentals and Applications." Advanced Industrial Control Series, Springer-Verlag, www.springer.com/engineering/book/978-1-84996-334-3 (2010), 415 p. 223 ill.19 in color.



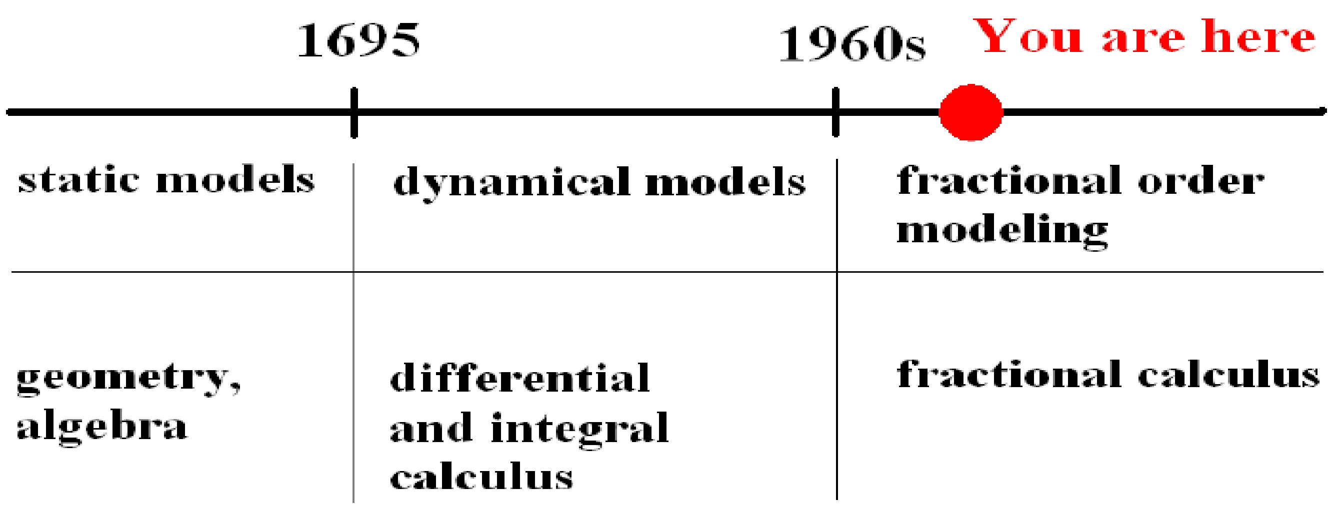


2001-2010

2005-2011

Why and How and When

- Why – Many reasons. Dynamic systems modeling and controls. Better characterization, better control performance
How – Analog versus digital realization methods. Many.
When – **Now**. Ubiquitous. Take a try since we have the new tool. **The beginning of a new stage**

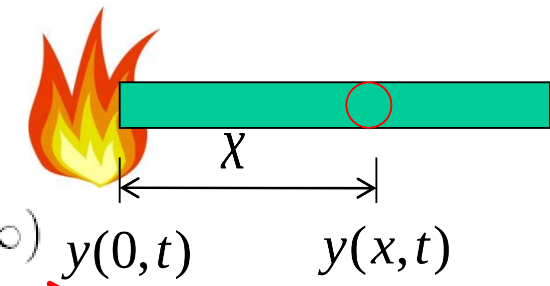


Slide credit: Igor Podlubny

Modeling: heat transfer

$$\frac{\partial^2 y(x,t)}{\partial x^2} = k^2 \frac{\partial y(x,t)}{\partial t},$$

$$(t > 0, \quad 0 < x < \infty)$$



Boundary condition: $y(0,t) = m(t)$

$y(x,0) = 0$ initial condition

$\left|\lim_{x\to\infty} y(x,t)\right| < \infty$ Physical limit

Transfer function:

$$\frac{\mathrm{d}^2 Y(x,s)}{\mathrm{d}x^2} = k^2 s Y(x,s)$$

$$Q(0,s) = M(s)$$

$$\left|\lim_{x\to\infty} Y(x,s)\right| < \infty$$

$$Y(x,s) = A(s)e^{-kx\sqrt{s}} + B(s)e^{kx\sqrt{s}}$$

$$\begin{aligned} A(s) &= Y(0,s) = M(s) \\ B(s) &= 0 \end{aligned}$$

$$Y(x,s) = M(s)e^{-kx\sqrt{s}}$$

$$G(s) = \frac{Y(x,s)}{M(s)} = e^{-kx\sqrt{s}}$$

think about transfer function $e^{-\sqrt{s}}$!

Irrational Transfer Function.

Taylor series expansion: polynomial of half order integrators!!

Ideal physical plant model:

$$G_p(s) = e^{-\sqrt{s}}$$

First Order Plus Time Delay (FOPTD) Model:

$$G_{IO}(s) = \frac{K_1}{T_1 s + 1} e^{-L_1 s}$$

Time Delay with Single Fractional Pole Model:

$$G_{FO}(s) = \frac{K_2}{T_2 s^{0.5} + 1} e^{-L_2 s}$$

All models are wrong but some are useful.

George E. P. Box

All models are wrong but some are dangerous ...

Leonard A. Smith

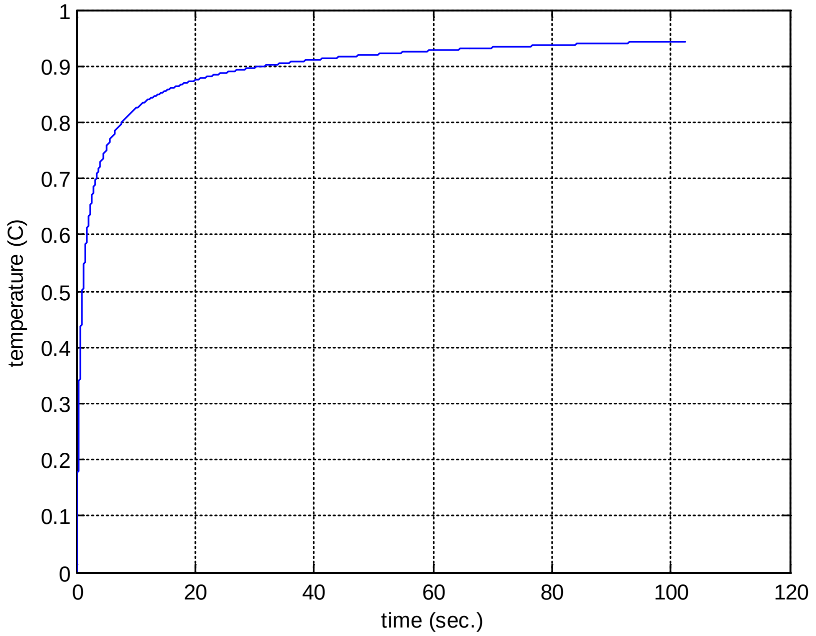
Step response of the "Ideal Plant"

$$y(0,t) = m(t) = 1u(t), M(s) = \frac{1}{s}$$

$$Y(x,s)\Big|_{x=1} = G(x,s)\Big|_{x=1} M(s) = G_p(s)M(s) = \frac{1}{s}e^{-\sqrt{s}}$$

So, "Reaction-Curve" or Step response of the "Ideal Plant"

$$y(t) = L^{-1}[\frac{1}{s}e^{-\sqrt{s}}]$$



Magic code to do $y(t) = L^{-1}[\frac{1}{s} e^{-\sqrt{s}}]$

```
% step response of normalized 1D heat equation when x=1
clear all;close all; alpha=.5; Ts=0.1;
F= @(s)  exp(-s.^alpha)./s;
%----------------------------------------------------------------
alfa=0; M=1024; P=20; Er=1e-10; tm=M*Ts; wmax0=2*pi/Ts/2; L = M;
Taxis=[0:L-1]*Ts;  n=1:L-1; n=n*Ts ;
N=2*M; qd=2*P+1; t=linspace(0,tm,M); NT=2*tm*N/(N-2); omega=2*pi/NT;
c=alfa-log(Er)/NT; s=c-i*omega*(0:N+qd-1);
Fsc=feval(F,s); ft=fft(Fsc(1:N)); ft=ft(1:M);
q=Fsc(N+2:N+qd)./Fsc(N+1:N+qd-1); d=zeros(1,qd); e=d;
   d(1)=Fsc(N+1); d(2)=-q(1); z=exp(-i*omega*t);
   for r=2:2:qd-1; w=qd-r; e(1:w)=q(2:w+1)-q(1:w)+e(2:w+1); d(r+1)=e(1);
      if r>2; q(1:w-1)=q(2:w).*e(2:w)./e(1:w-1); d(r)=-q(1);
      end
   end
   A2=zeros(1,M); B2=ones(1,M); A1=d(1)*B2; B1=B2;
   for n=2:qd
   A=A1+d(n)*z.*A2; B=B1+d(n)*z.*B2;A2=A1; B2=B1; A1=A; B1=B;
   end
ht=exp(c*t)/NT.*(2*real(ft+A./B)-Fsc(1));
%----------------------------------------------------------------
figure;tt=0:(length(ht)-1);tt=tt*Ts;plot(tt,ht);
xlabel('time (sec.)');ylabel('temperature (C)');grid on
```

Application of numerical inverse Laplace transform algorithms in fractional calculus
Journal of the Franklin Institute, *Volume 348, Issue 2*, *March 2011*, *Pages 315-330*
Hu Sheng, Yan Li, YangQuan Chen http://dx.doi.org/10.1016/j.jfranklin.2010.11.009 (Check ref [8])

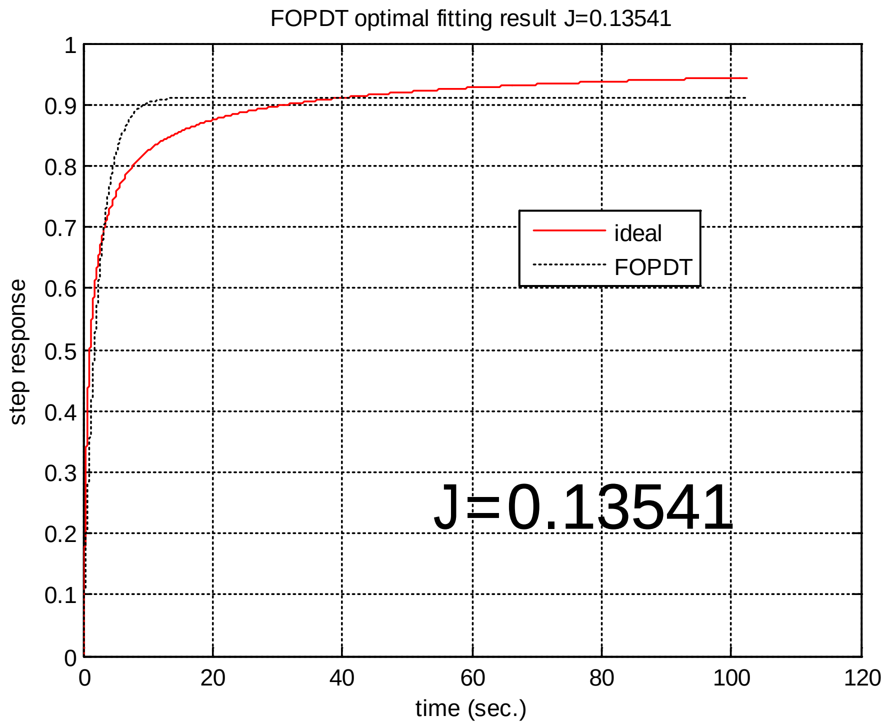
So, let us do fitting!

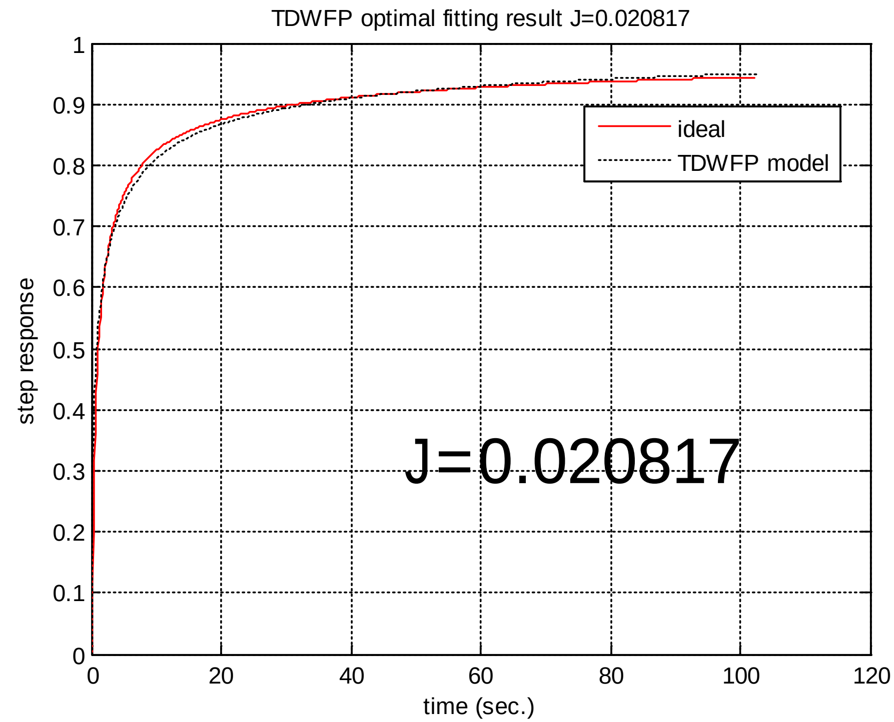
Ideal physical plant model: $$G_p(s) = e^{-\sqrt{s}}$$

First Order Plus Time Delay (FOPTD) Model: $$G_{IO}(s) = \frac{K_1}{T_1 s + 1} e^{-L_1 s}$$

Time Delay with Single Fractional Pole Model: $$G_{FO}(s) = \frac{K_2}{T_2 s^{0.5} + 1} e^{-L_2 s}$$

All models are wrong but some are useful. **George E. P. Box**





K1	T1	L1
0.9120	2.2393	0

K2	T2	L2
1.0197	1.2312	0.0001

Fitting code for $G_{IO}(s) = \dfrac{K_1}{T_1 s + 1} e^{-L_1 s}$

```
% Ts: sampling period; ht: step response (from NILT numerical inverse
% Laplace transform)
% previously we got Ts and ht array (reaction curve)
options=optimset('TolX',1e-10,'TolFun',1e-10);
Tic;[x,FVAL,EXITFLAG] =fminsearch(@(x) fopdtfit(x,ht,Ts),[1,1,0],options);toc
% May need to wait half minute
K1=x(1);T1=x(2);L1=x(3);T=(0:length(ht)-1)*Ts;if L1<0; L1=0; end
sysfoptd=tf([K1],[T1,1],'iodelay',L1);
y=step(sysfoptd,T);plot(T,ht,'r',t,y,'k:');grid on;
title(['FOPDT optimal fitting result J=',num2str(FVAL)]);
xlabel('time (sec.)');ylabel('step response'); legend('ideal', 'FOPDT')
```

```
% fitting using FOPTD model - integral of error square (ISE)
function [J]=foptdfit(x,y0,Ts);
K1=x(1);T1=x(2);L1=x(3);T=(0:length(y0)-1)*Ts;if L1<0; L1=0; end
sysfoptd=tf([K1],[T1,1],'iodelay',L1);
y=step(sysfoptd,T);
J=(y'-y0)*(y-y0')*Ts;
```

Fitting code for $G_{FO}(s) = \frac{K_2}{T_2 s^{0.5} + 1} e^{-L_2 s}$

```
options=optimset('TolX',1e-10,'TolFun',1e-10);
Tic;[x,FVAL,EXITFLAG] =fminsearch(@(x) tdwfpfit(x,ht,Ts),[1,2,0],options);toc
% May need to wait 1000+ seconds!
K1=x(1);T1=x(2);L1=x(3);Np=length(ht);T=(0:Np-1)*Ts;if L1<0; L1=0; end
y=mlf(0.5,1.5,-T.^0.5/T1);y=(K1/T1)*(T.^0.5) .* y;
Nstep=floor(L1/Ts);
y1=zeros(size(y));y1(Nstep+1:Np)=y(1:Np-Nstep);
y=y1;plot(T,ht,'r',t,y,'k:');grid on;
title(['TDWFP optimal fitting result J=',num2str(FVAL)]);
xlabel('time (sec.)');ylabel('step response'); legend('ideal', 'TDWFP model')
```

```
% fitting using TDWFP model - integral of error square (ISE)
function [J]=tdwfpfit(x,y0,Ts);
K1=x(1);T1=x(2);L1=x(3);Np=length(y0);T=(0:Np-1)*Ts;if L1<0; L1=0; end
y=mlf(0.5,1.5,-T.^0.5/T1);y=(K1/T1)*(T.^0.5) .* y;
Nstep=floor(L1/Ts);y1=zeros(size(y));y1(Nstep+1:Np)=y(1:Np-Nstep);
J=(y1-y0)*(y1-y0)'*Ts;
% get MLF.m from
% www.mathworks.com/matlabcentral/fileexchange/8738-mittag-leffler-function
```

Benefits of FOM

- Captures (more) physics $G_p(s) = e^{-\sqrt{s}} \rightarrow G_{FO}(s) = \frac{K_2}{T_2 s^{0.5} + 1} e^{-L_2 s}$
- Reaction curve fitting: **Better than the best** FOPDT model $G_{IO}(s) = \frac{K_1}{T_1 s + 1} e^{-L_1 s}$
- Could be a nice starting point for better controller design?

FO Controller + IO Plant

Fractional order speed control of DC motor

System transfer function $G(s) = \frac{k}{Js(Ts+1)}$ J being the payload inertia. Phase margin of controlled system:

$$\Phi_m = \arg\left[C(j\omega_g)G(j\omega_g)\right] + \pi$$

Controller: $C(s) = k_1 \frac{k_2 s+1}{s^\alpha}$, $k_2 = T$ giving a **constant phase margin:**

$$\begin{aligned} \Phi_m &= \arg\left[C(j\omega)G(j\omega)\right] + \pi = \arg\left[\frac{k_1 k}{(j\omega)^{(1+\alpha)}}\right] + \pi \\ &= \arg\left[(j\omega)^{-(1+\alpha)}\right] + \pi = \pi - (1+\alpha)\frac{\pi}{2} \end{aligned}$$

Step response:

$$y(t) = \pounds^{-1}\left\{\frac{kk_1/J}{s\left(s^{1+\alpha} + kk_1/J\right)}\right\} = \left(\frac{kk_1}{J}\right) t^{1+\alpha} E_{1+\alpha,2+\alpha}\left(-\frac{kk_1}{J} t^{1+\alpha}\right) \quad (63)$$

Mittag-Leffler function: definition

$$E_{\alpha,\beta}(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(\alpha k + \beta)}, \quad (\alpha > 0, \quad \beta > 0)$$

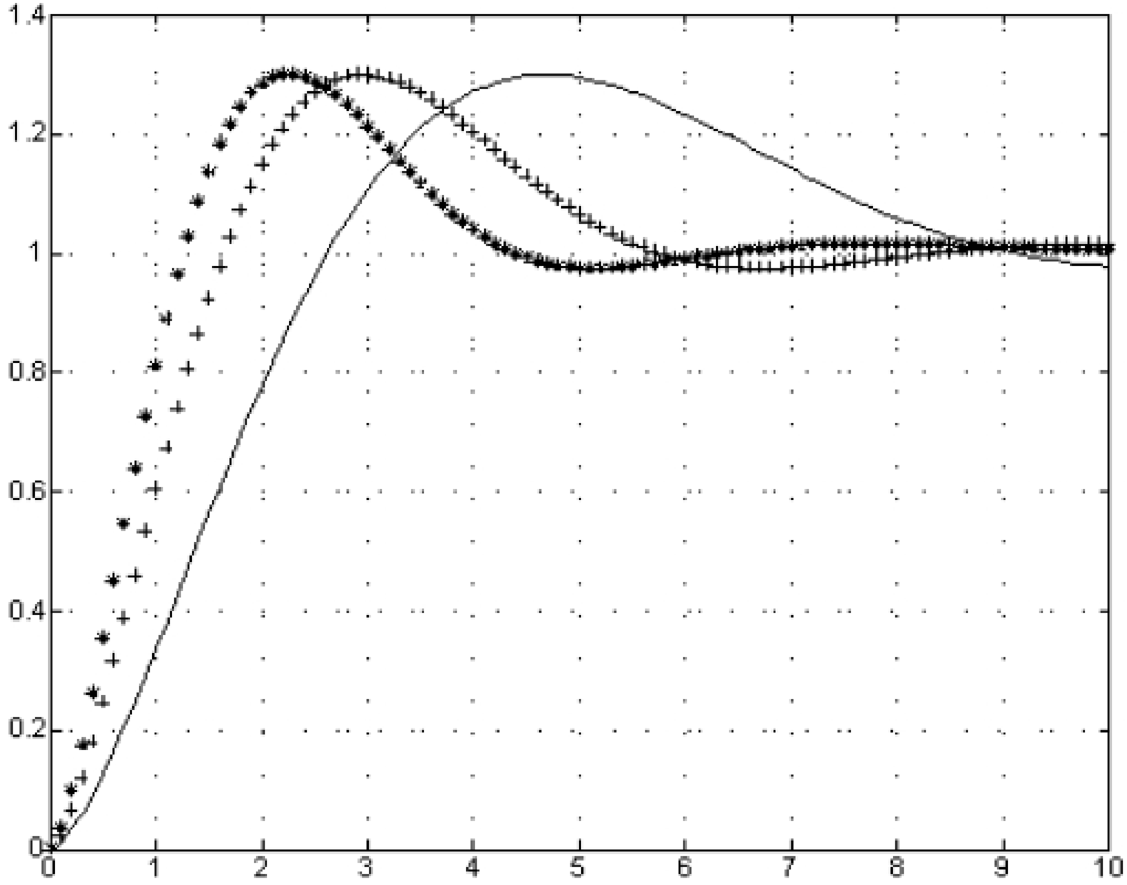
$$E_{1,1}(z) = e^z,$$

$$E_{2,1}(z^2) = \cosh(z), \quad E_{2,2}(z^2) = \frac{\sinh(z)}{z}.$$

$$E_{1/2,1}(z) = e^{z^2}\mathrm{erfc}(-z);$$

$$\mathrm{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} e^{-t^2} dt.$$

Slide credit: Igor Podlubny

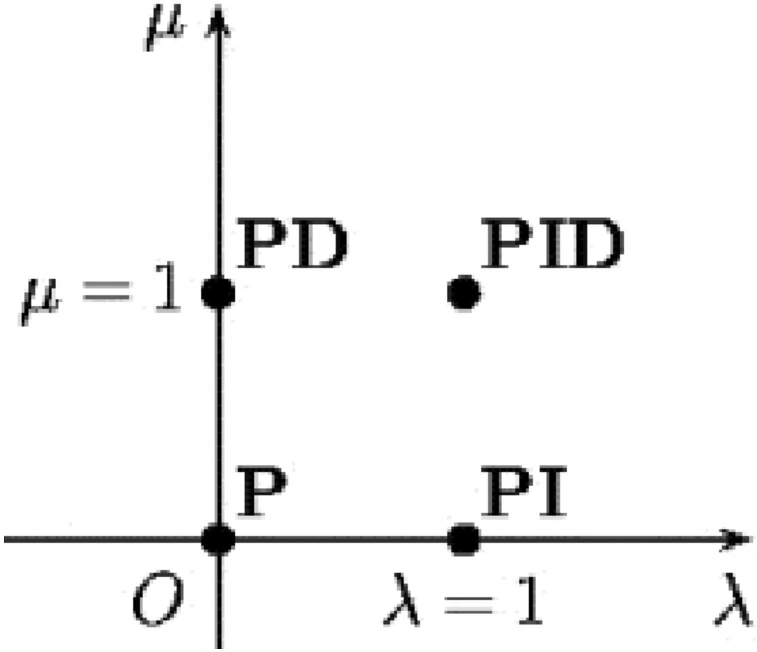


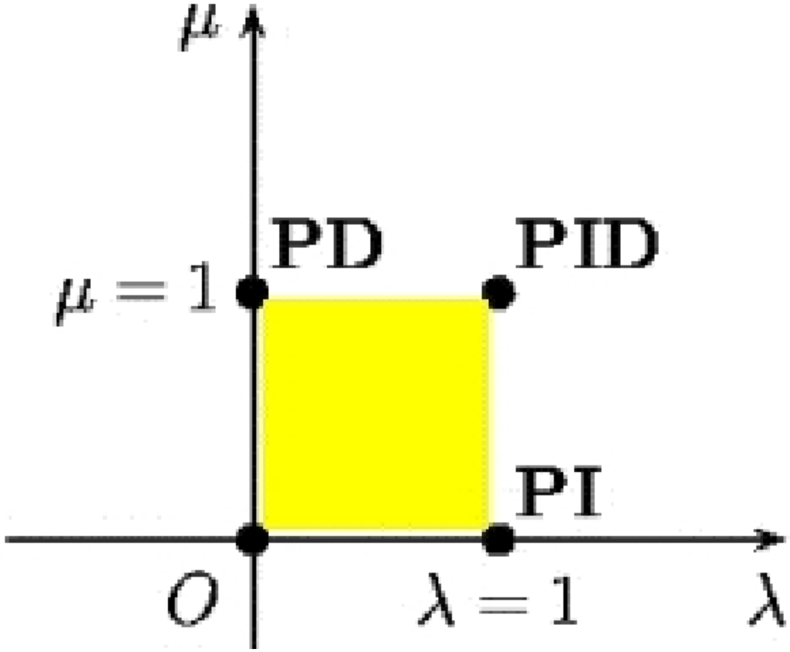
Note the iso-damping (similar overshoot!)

Fractional order PID control

- 90% are PI/PID type in industry. (**Ubiquitous**)

$$u(t) = K_p(e(t) + T_i \mathrm{D}_t^{-\lambda} e(t) + \frac{1}{T_d} \mathrm{D}_t^{\mu} e(t)). \qquad (\mathrm{D}_t^{(*)} \equiv {}_0\mathrm{D}_t^{(*)}).$$





Igor Podlubny. "Fractional-order systems and $PI^{l}D^{\mu}$-controllers". IEEE Trans. Automatic Control,44(1): 208–214, 1999.

*YangQuan Chen, Dingyu Xue, and Huifang Dou. "**Fractional Calculus and Biomimetic Control**". IEEE Int. Conf. on Robotics and Biomimetics (RoBio04), August 22-25, 2004, Shengyang, China.*

IFAC

ELSEVIER

Control Engineering Practice
Best Paper Prize

Awarded jointly by Elsevier Ltd and the International Federation of Automatic Control (IFAC)
for the best paper published in the period 2008-2011

Awarded to

Y. Chen

for the paper

Tuning and auto-tuning of fractional order controllers for industry applications

(Vol. 16, No. 7, pp. 798-812)

Christopher Greenwell, Publisher
Elsevier Ltd.

Prof. Andreas Kugi, Editor-in-Chief
Control Engineering Practice

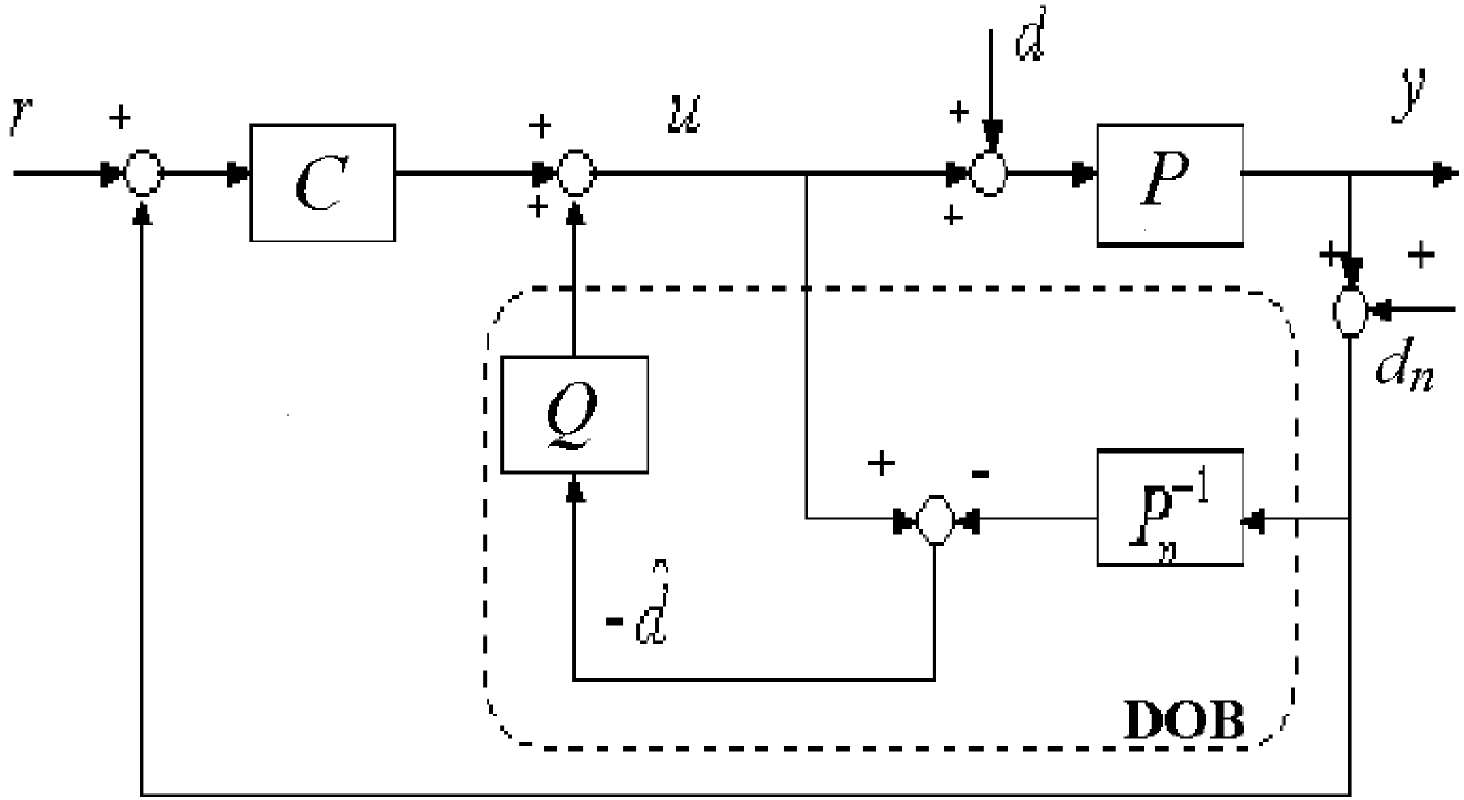
- Fractional Order System – official keyword of IFAC
- pid12.ing.unibs.it/

Attacked topics @ CSOIS

http://mechatronics.ece.usu.edu/foc/afc/

- Fractional order disturbance observer
- Fractional order adaptive control
- Fractional order PI/D control
- Most recently
  - Fractional order conditional integrator (e.g. Clegg integrator) (JPC 2011)
  - Fractional order consensus seeking (IEEE SMC-B 10)
  - Fractional order optimal control (MATLAB Toolbox)
  - Fractional order model predictive control (??)

YangQuan Chen*, Blas M. Vinagre and Igor Podlubny. "Fractional order disturbance observer for vibration suppression", (Kluwer) Nonlinear Dynamics , Vol. 38, Nos. 1-4, December 2004, pp. 355-367.



How to design/tune FOC for motion control?

$$C(s) = K_p(1 + K_d s^{\mu})$$

$$P(s) = \frac{1}{s(Ts+1)}$$

(i) Phase margin specification

$$\text{Arg}[G(j\omega_c)] = \text{Arg}[C(j\omega_c)P(j\omega_c)] = -\pi + \phi_m,$$

(ii) Robustness to variation in the gain of the plant

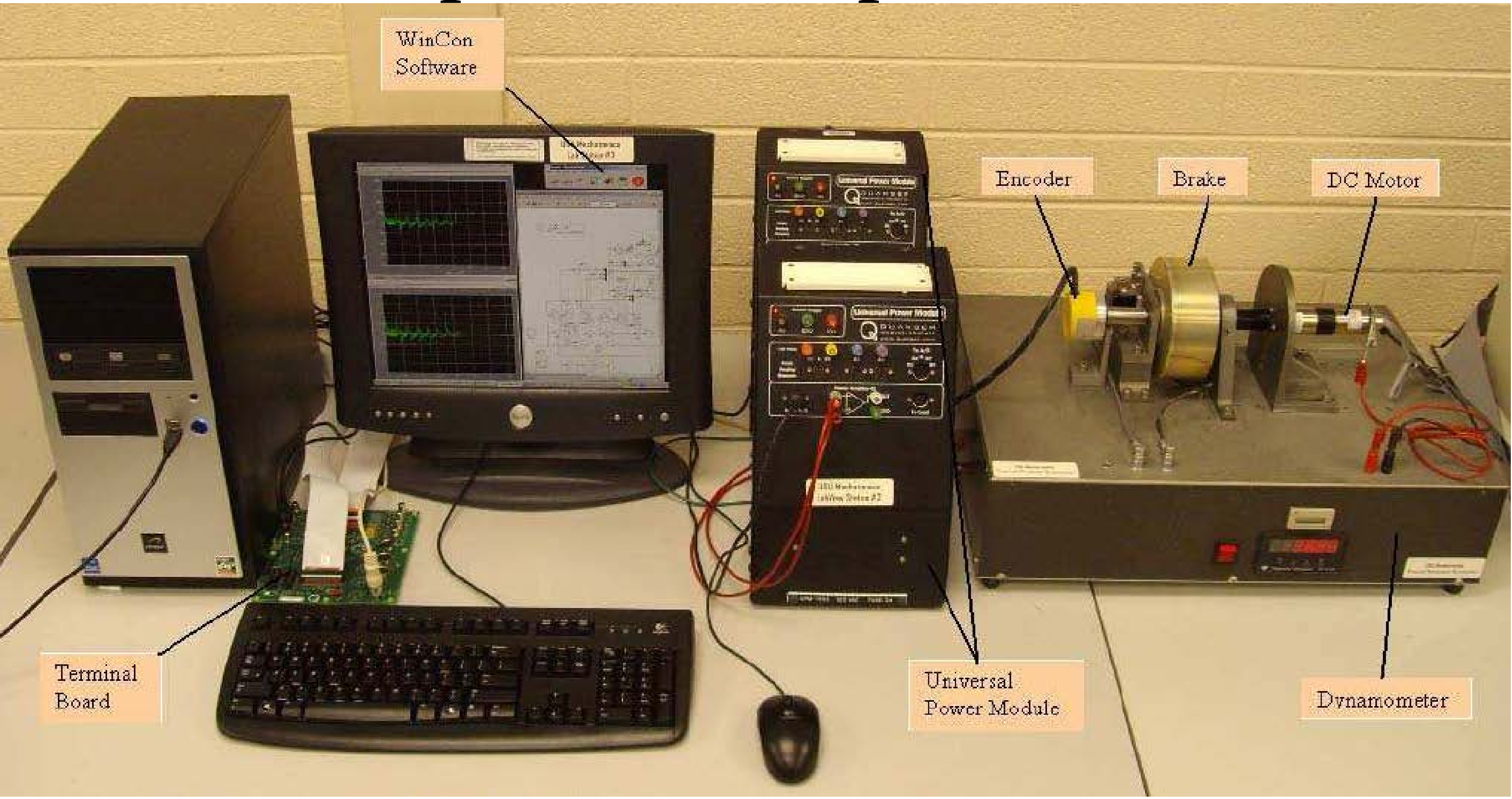
$$\left(\frac{\text{d}(\text{Arg}(C(j\omega)P(j\omega)))}{\text{d}\omega}\right)_{\omega=\omega_c} = 0,$$

with the condition that the phase derivative w. r. t. the frequency is zero, i.e., the phase Bode plot is flat, at the gain crossover frequency. It means that the system is more robust to gain changes and the overshoots of the response are almost the same.

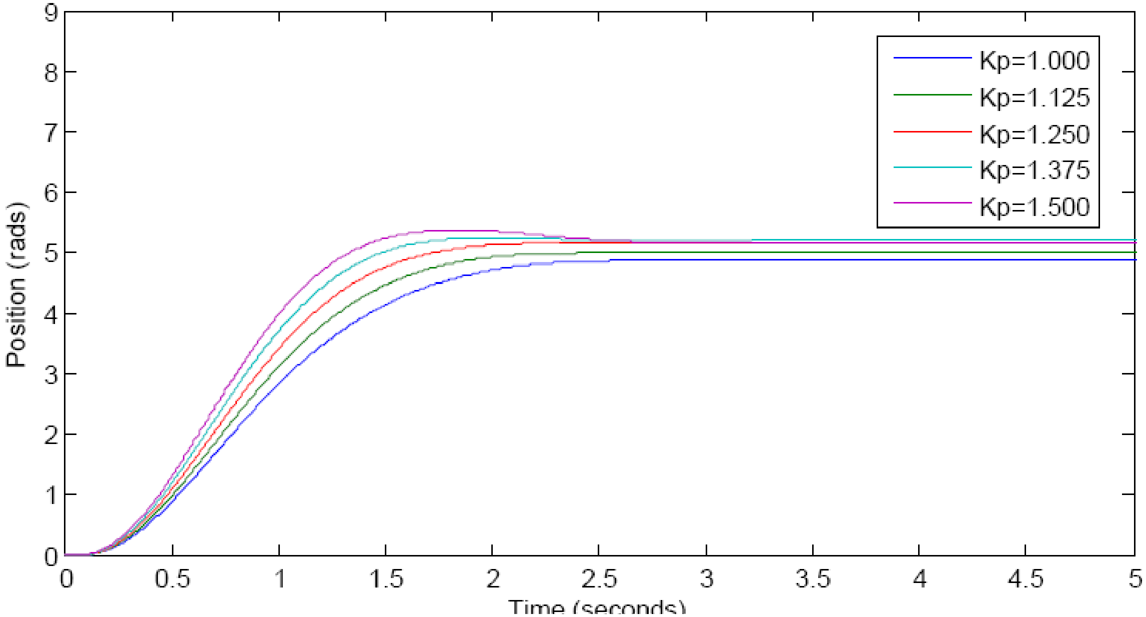
(iii) Gain crossover frequency specification

$$|G(j\omega_c)|_{dB} = |C(j\omega_c)P(j\omega_c)|_{dB} = 0.$$

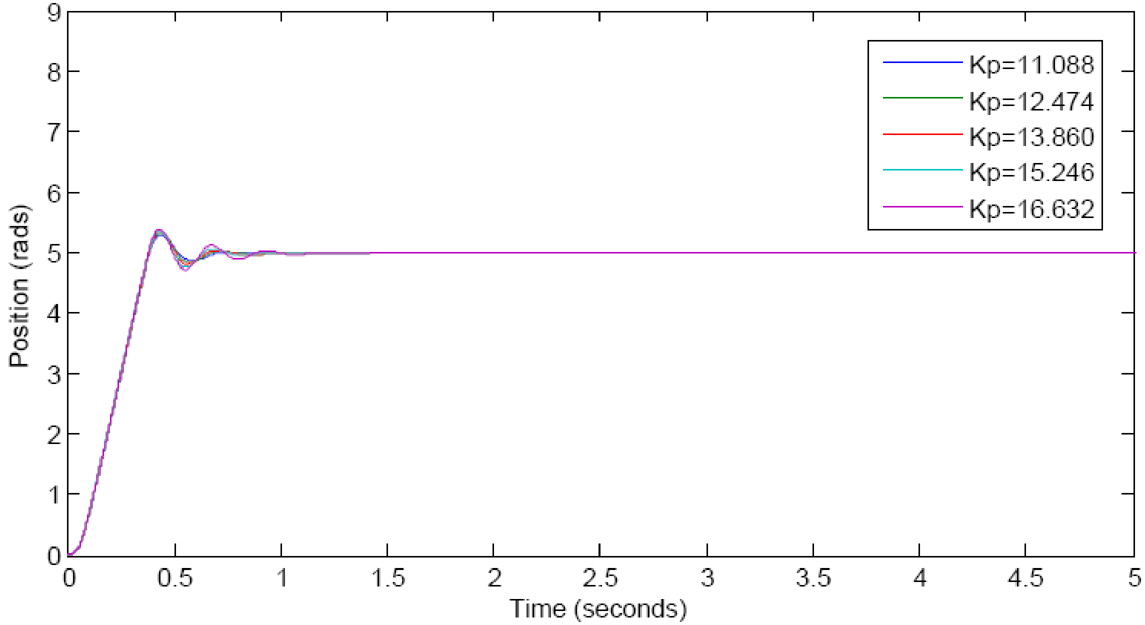
Experimental platform

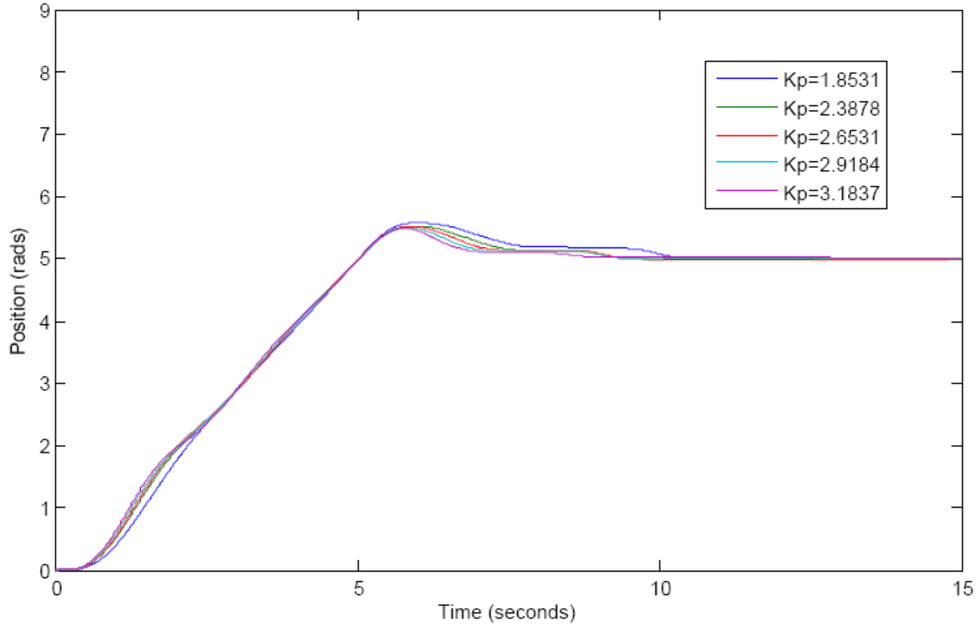


ITAE optimal P controller

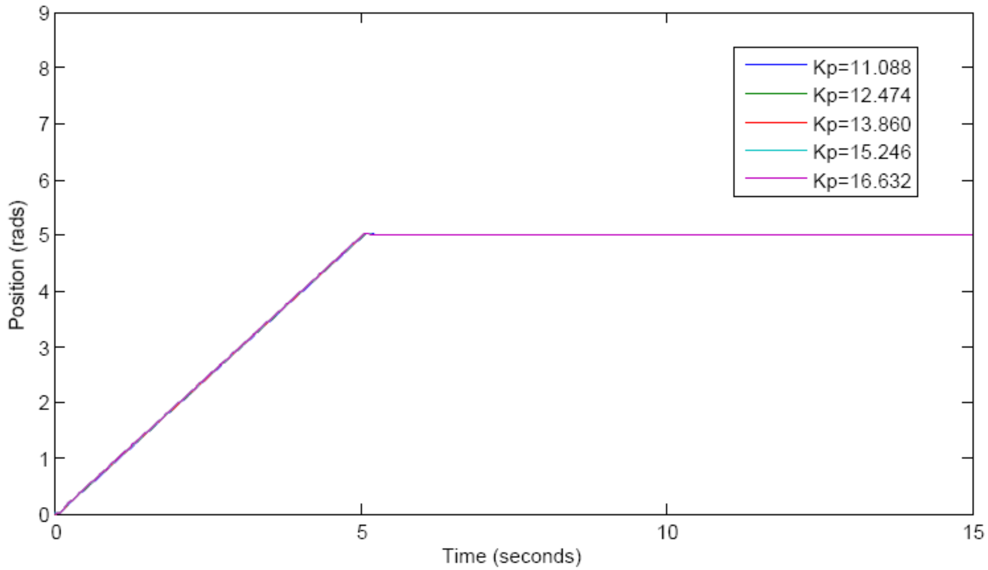


FOPD controller.





ITAE optimal PI controller



FOPD controller.

IEEE Trans. Control Systems Technology, 2010 18(2):516-520

DOI:10.1109/TCST.2009.2019120

Impressive Performance!

- How about FO[PD]?

$$C_3(s) = K_{p3}[1 + K_{d3}s]^{\mu}$$

- Note: FOPD shown previously is:

$$C_2(s) = K_{p2}(1 + K_{d2}s^{\lambda})$$

Ying Luo, Y. Q. Chen "Fractional order [proportional derivative] controller for a class of fractional order systems" *Automatica*, 45(10) 2009, pp 2446-2450.

Fractional Order Signal Processing

- Additional characterization
- Infinite variance issue (2^{nd} order moment)
- Long range dependence
- Time-frequency approach (FrFT)

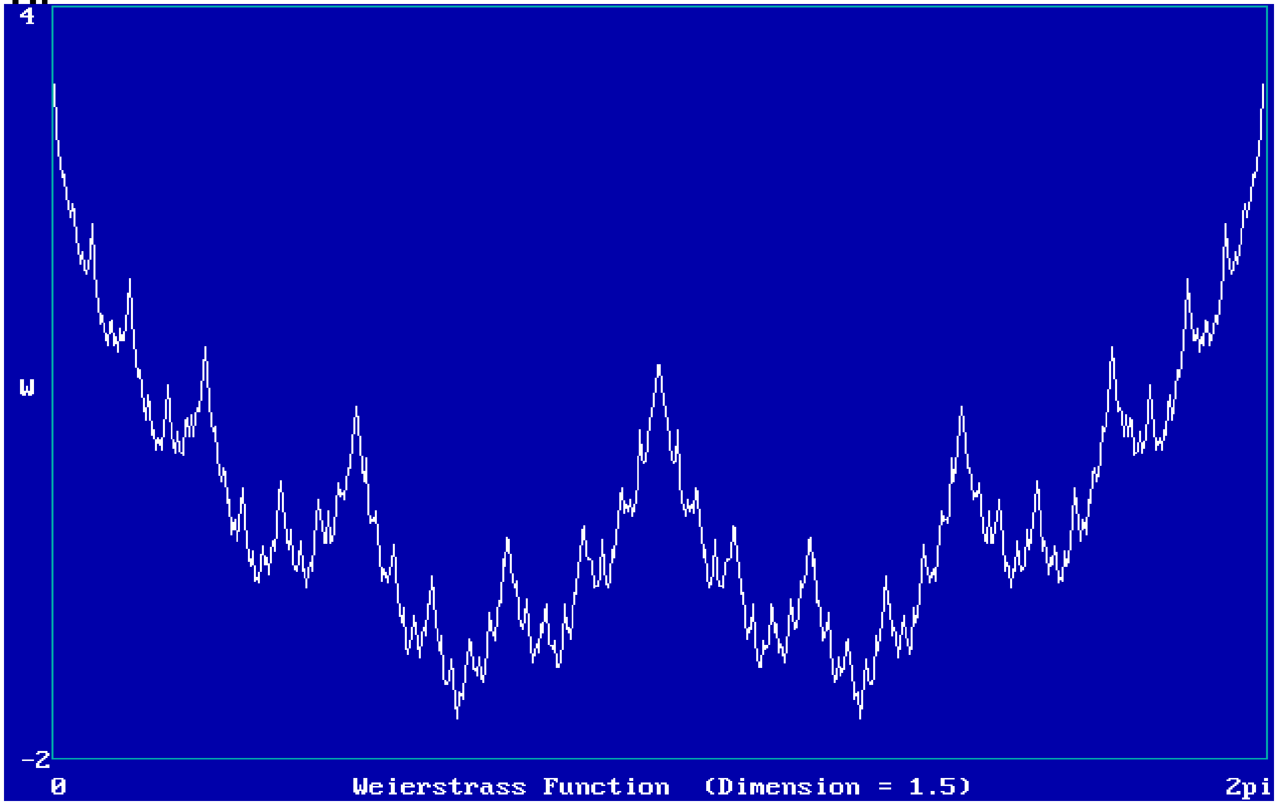
Example-1: Weierstrass function

$$f_a(x) = \sum_{k=1}^{\infty} \frac{\sin(\pi k^a x)}{\pi k^a}$$

- Nowhere differentiable!

Fractional order derivative exists

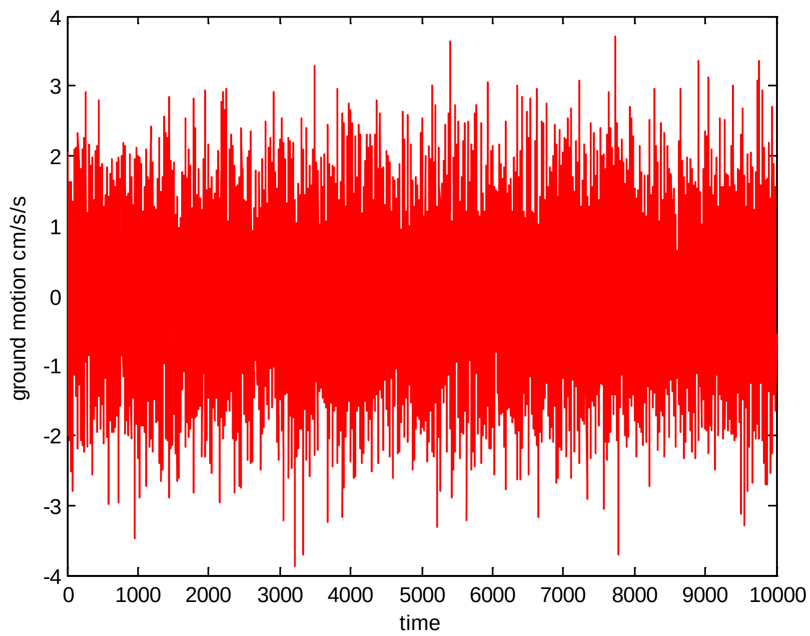
differentiability order 0.5 or less

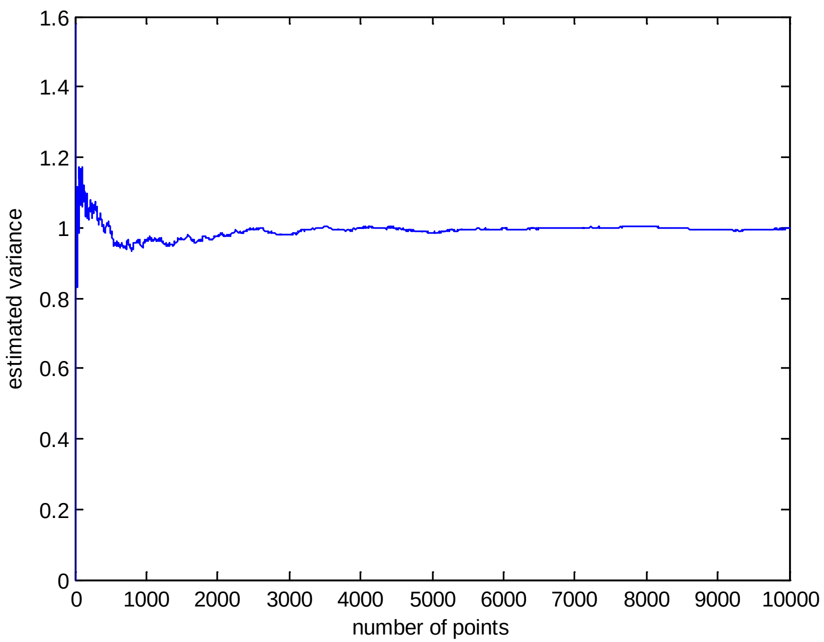


sprott.physics.wisc.edu/phys505/lect11.htm

Wen Chen. “Soft matters”. Slides presented at 2007 FOC_Day @ USU.

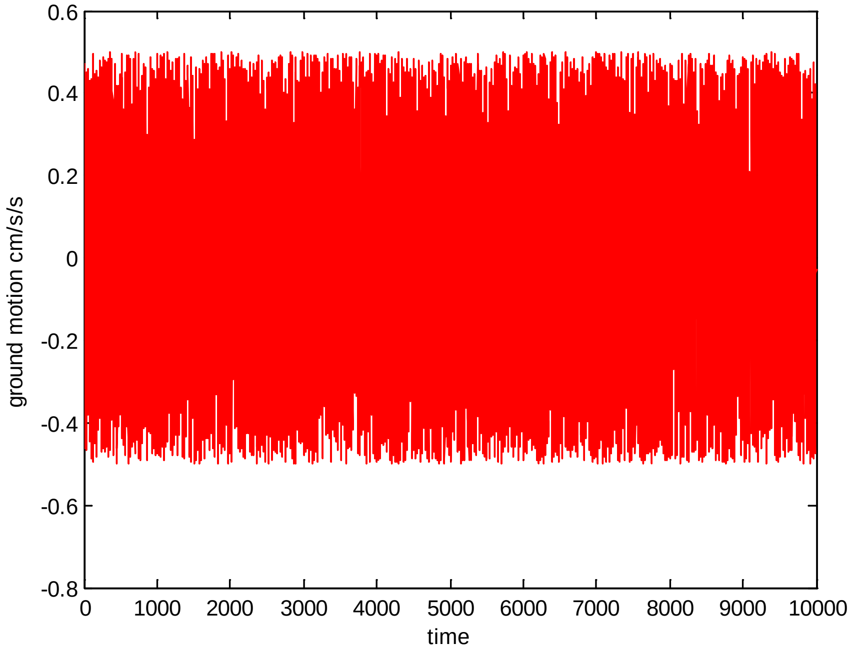
Noise - 1

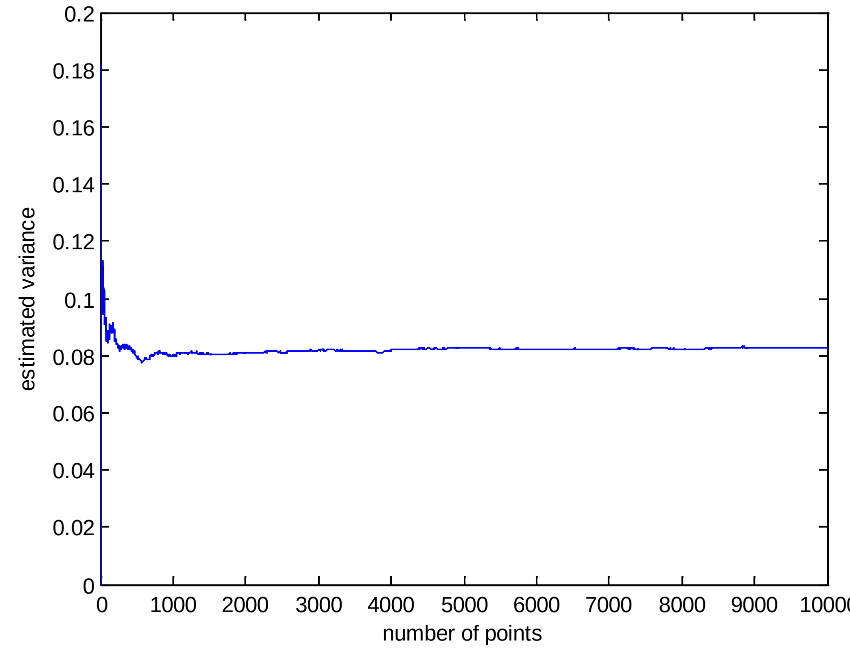




Normal distribution N(0,1) Sample Variance

Noise - 2





Uniformly distributed Sample Variance

Fractional Lower Order Statistics (FLOS) or Fractional Lower Order Moments (FLOM)

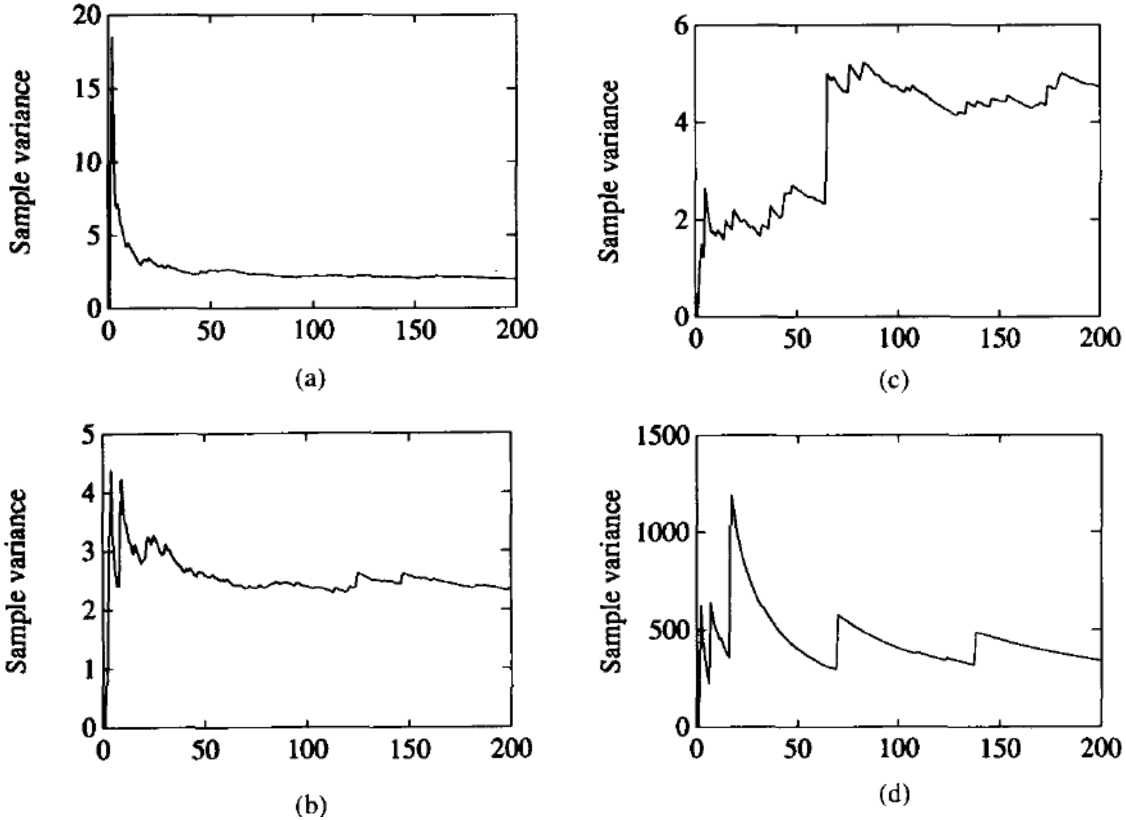


Fig. 2. Running sample variances for four different values of α: (a) $\alpha = 2.0$; (b) $\alpha = 1.9$; (c) $\alpha = 1.5$; (d) $\alpha = 1.1$.

Shao, M., and Nikias, C. L., 1993. “Signal processing with fractional lower order moments: stable processes and their applications”. Proceedings of the IEEE, 81 (7) , pp. 986 – 1010.

Important Remarks

A simple test of infinite variance is to plot the running sample variance estimate S_n with respect to number of points n where $S_n^2 = (\sum_{k=1}^{n}(x_k - \bar{x}_n)^2)/(n-1)$ and $\bar{x}_n = \sum_{k=1}^{n} x_k/n$. For finite variance processes x_k, S_n will converge to a constant value as n increases. If S_n does not converge to a constant value, x_k is a non-Gaussian infinite-variance process with fractional lower order $\alpha < 2$.

In fact, for a non-Gaussian stable distribution with characteristic exponent α, only the moments of orders less than α are finite. Therefore, variance can no longer be used as a measure of dispersion and in turn, many standard signal processing techniques such as spectral analysis and all least squares (LS) based methods may give misleading results.

Long-range dependence

- History: The first model for long range dependence was introduced by Mandelbrot and Van Ness (1968)
- Value: financial data

  communications networks data

  video traffic, biocorrosion data, …

  signals from nature and man-made systems

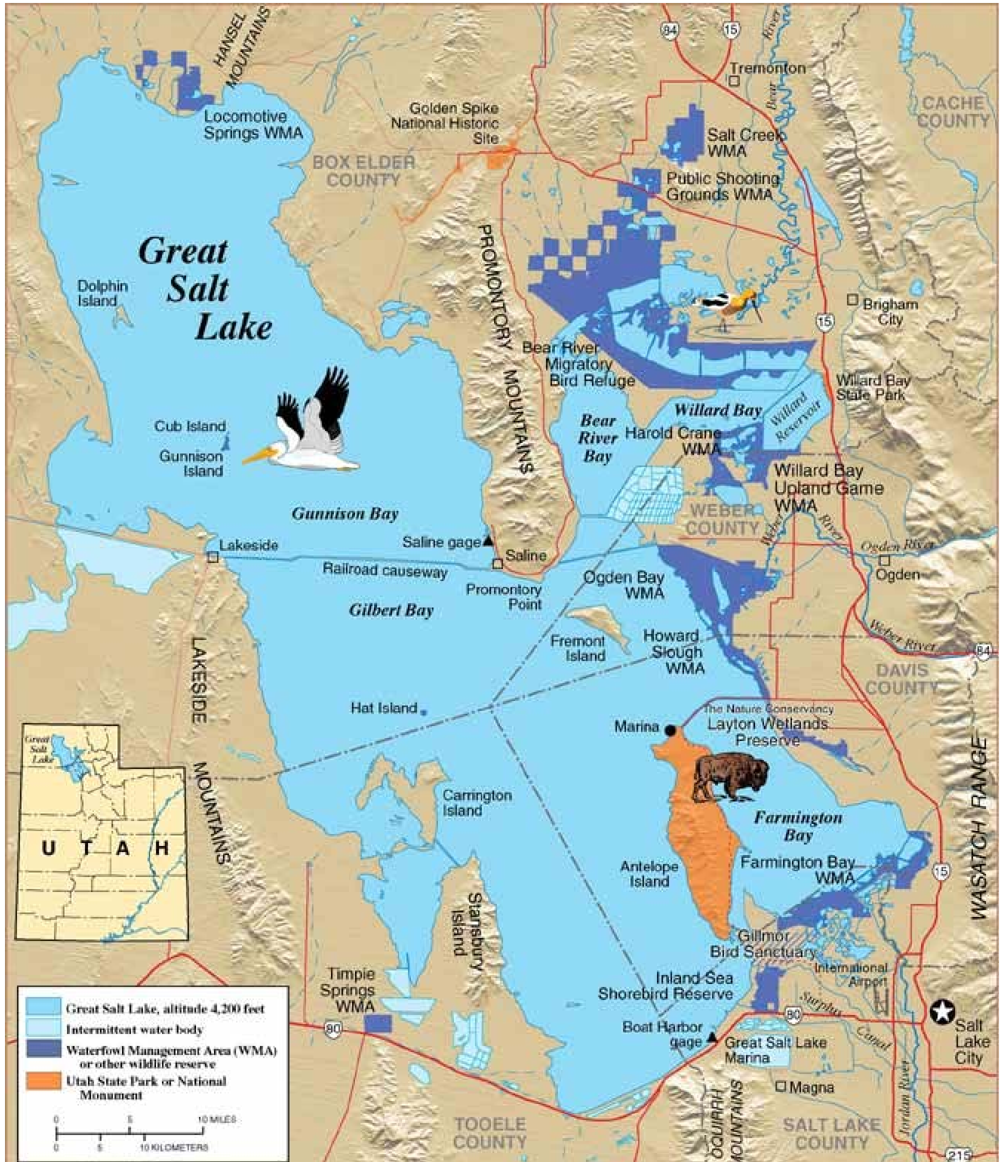
Long-range dependence

- Consider a second order stationary time series $Y = \{Y(k)\}$ with mean zero. The time series Y is said to be long-range dependent if

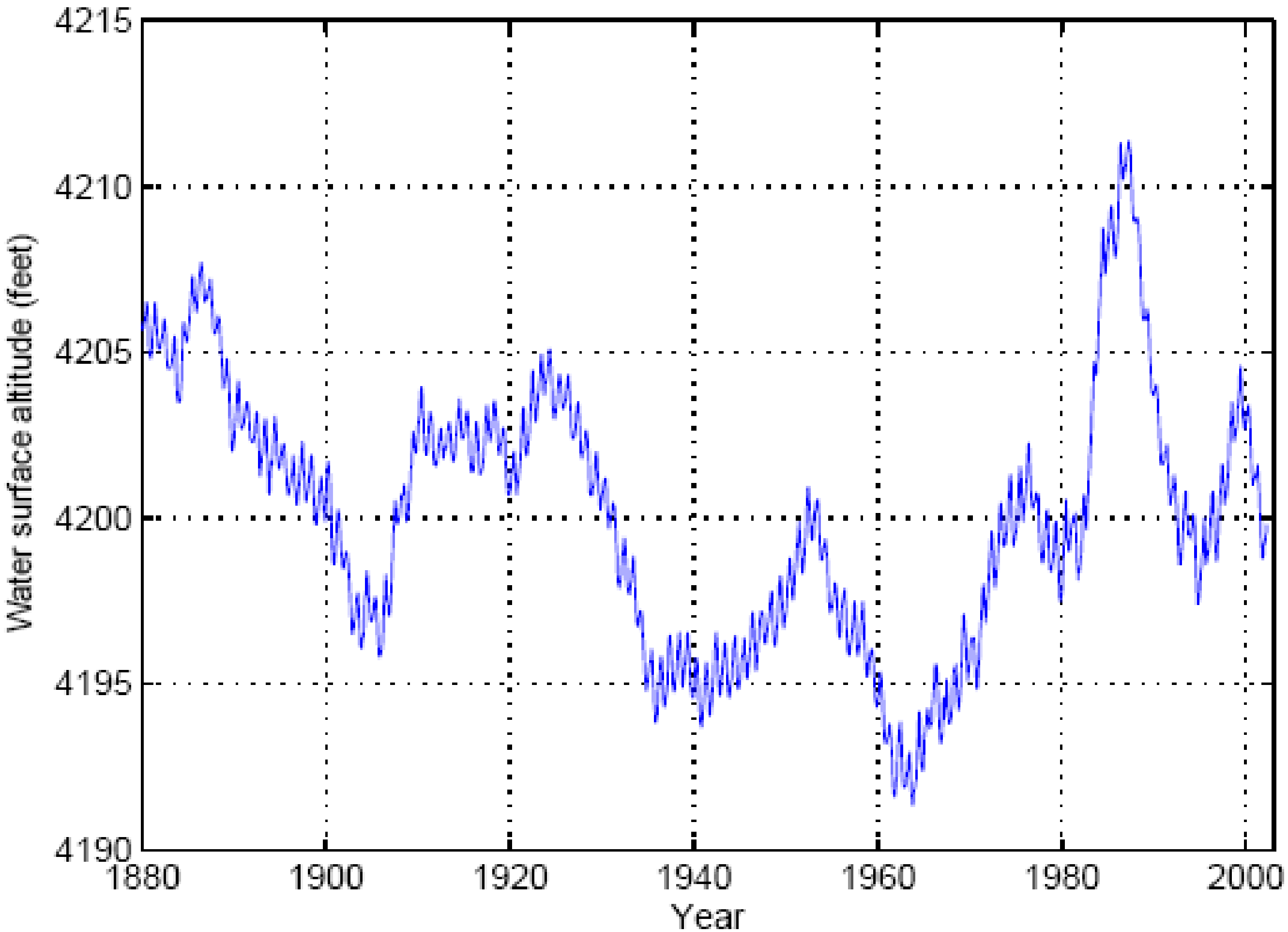
$$r_Y(k) = EY(k)Y(0) \sim c_Y |k|^{-\gamma}, k \to \infty, 0 < \gamma < 1$$

$$s_Y(\xi) \sim c_s |\xi|^{-\alpha}, 0 < \alpha < 1,$$

GSL: Do you care about it?



Long-term water-surface elevation graphs of the Great Salt Lake



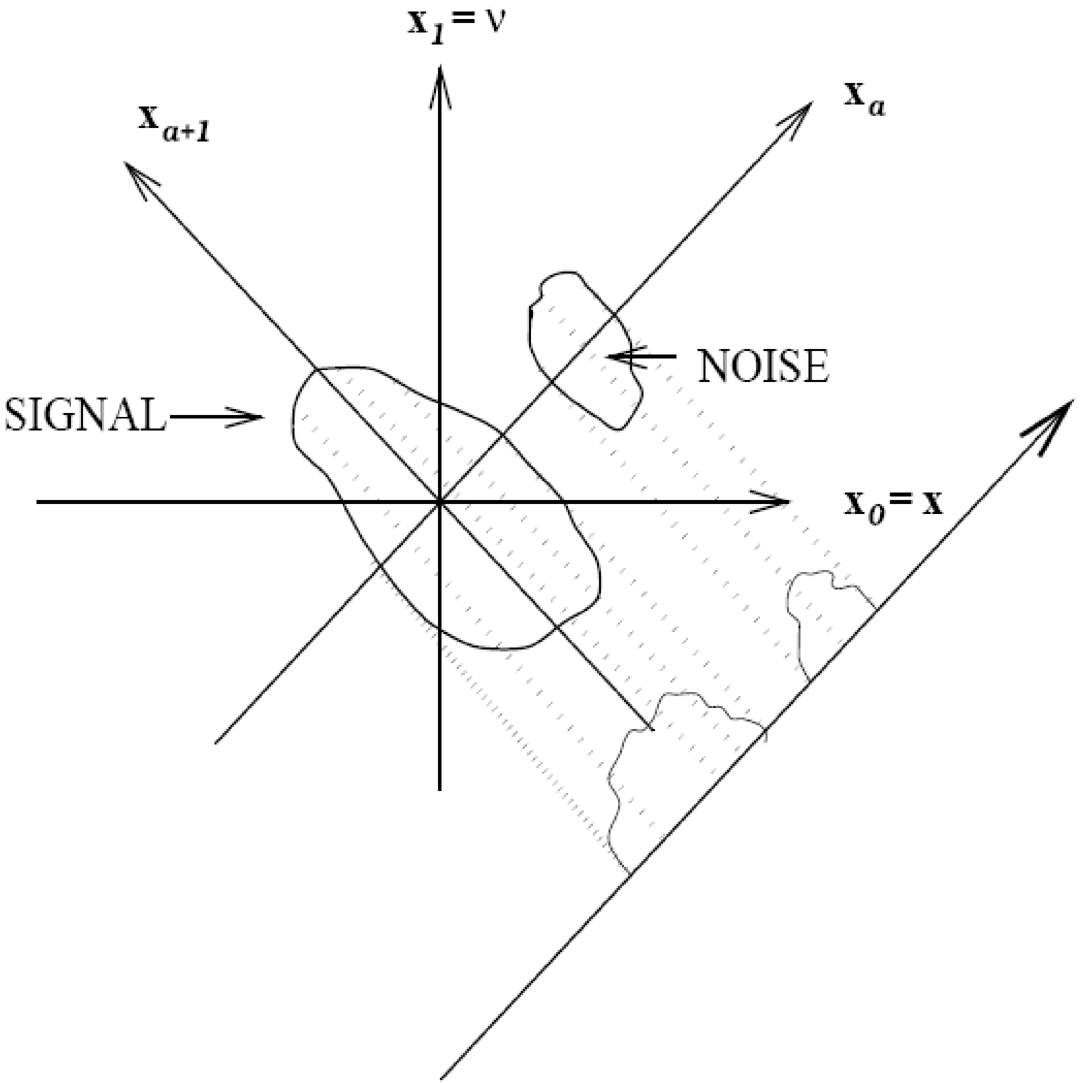
Elevation Records of Great Salt Lake

- The Great Salt Lake, located in Utah, U.S.A, is the fourth largest terminal lake in the world with drainage area of 90,000 km^2.
- The United States Geological Survey (USGS) has been collecting water-surface-elevation data from Great Salt Lake since 1875.
- The modern era record-breaking rise of GSL level between 1982 and 1986 resulted in severe economic impact. The lake levels rose to a new historic high level of 4211:85 ft in 1986, 12.2 ft of this increase occurring after 1982.
- The rise in the lake since 1982 had caused 285 million U.S. dollars worth of damage to lakeside.
- According to the research in recent years, traditional time series analysis methods and models were found to be insufficient to describe adequately this dramatic rise and fall of GSL levels.
- This opened up the possibility of investigating whether there is long-range dependence in GSL water-surface-elevation data so that we can apply FOSP to it.

A recent paper

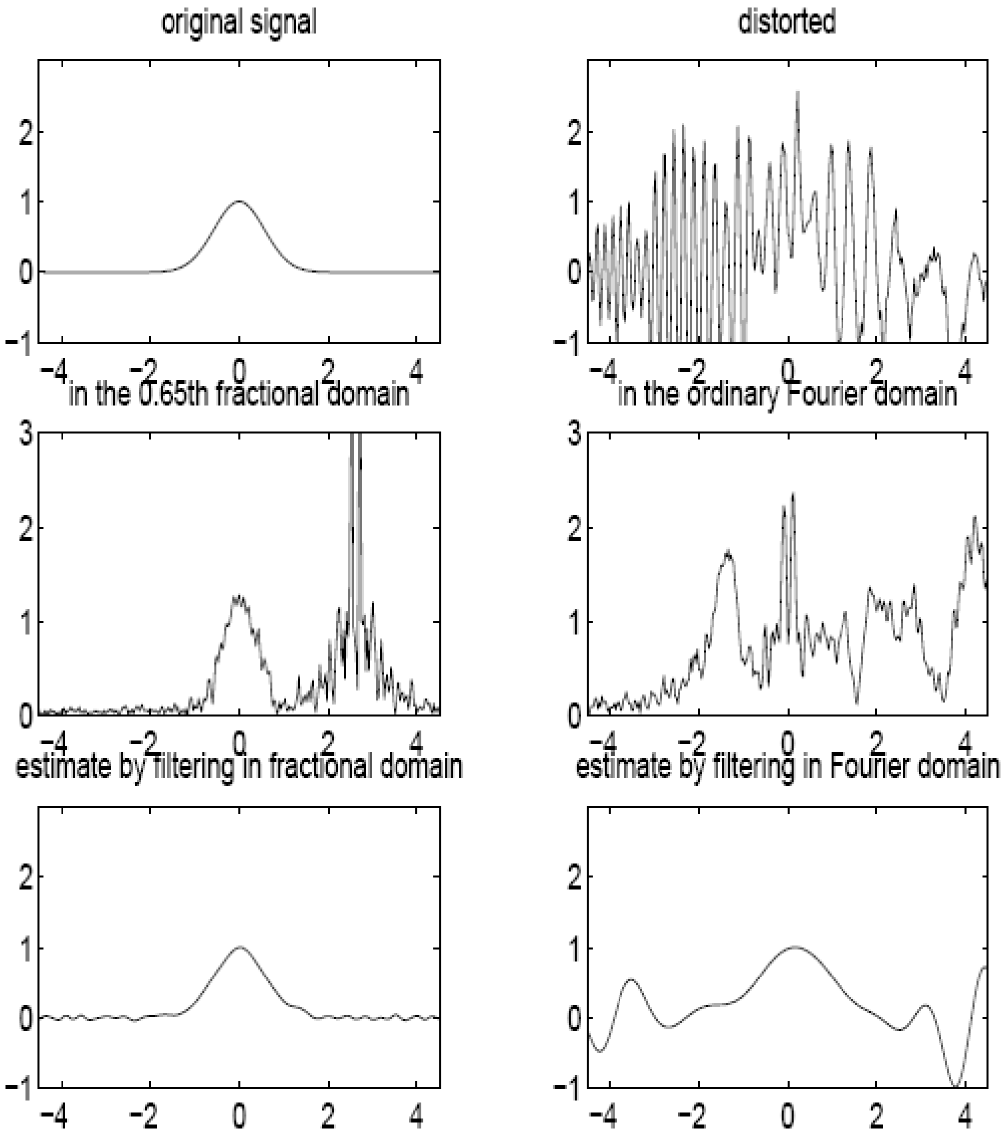
- Hu Sheng, YangQuan Chen "**FARIMA with stable innovations model of Great Salt Lake elevation time series**" Signal Processing, Volume 91, Issue 3, March 2011, Pages 553-561

Optimal filtering in fractional Fourier domain



Slide credit: HALDUN M. OZAKTAS

Optimal filtering in fractional order Fourier domain



Slide credit: HALDUN M. OZAKTAS

Summary of FOSP Techniques

- Fractional derivative and integral
- Fractional linear system
- Autoregressive fractional integral moving average
- 1/f noise
- Hurst parameter estimation
- Fractional Fourier Transform
- Fractional Cosine, Sine and Hartley transform
- Fractals
- Fractional Splines
- Fractional Lower Order Moments (FLOM) and Fractional Lower Order Statistics (FLOS)

Fractional Calculus, LRD, Power Law,

$u(t)$ → $H(s) = \dfrac{1}{s^{\alpha}}$ → $y(t)$

White Noise

$$h(t) = \frac{t^{\alpha-1}}{\Gamma(\alpha)}$$

$$Ryy(\tau) = \sigma^2 \frac{|\tau|^{2\alpha-1}}{2\Gamma(2\alpha)\cos\alpha\pi}$$

y(t) is a Brownian motion when α=1, i.e., $1/f^2$ process.

$1/f^{2\alpha}$ noise (signal) generation via fractional dynamic system

Power laws in

- Signal/Systems
- Probability distribution
- Random processes (correlation functions)

Rule of thumb for Fractional Order Thinking

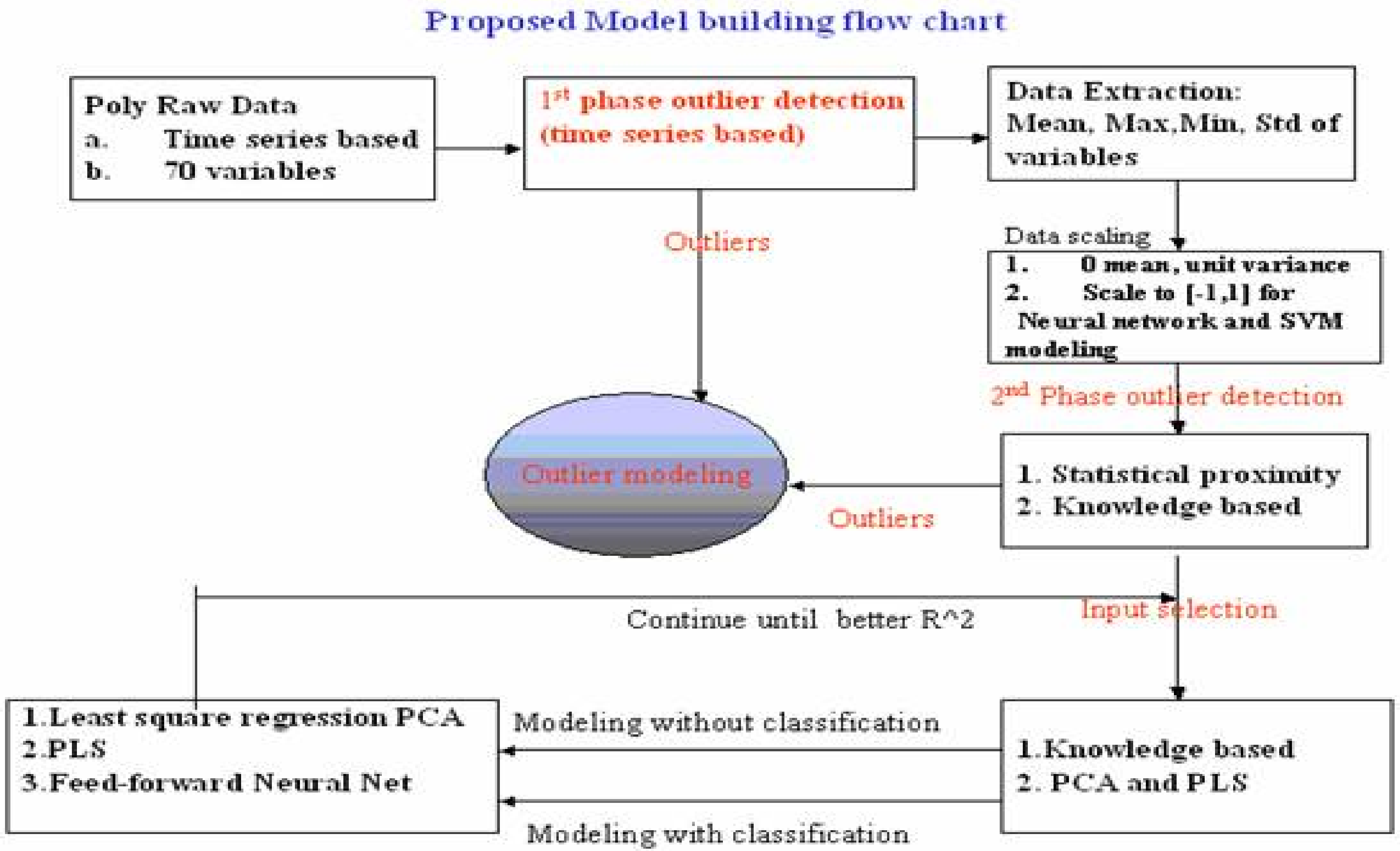
- Self-similar
- Scale-free/Scale-invariant
- Power law
- Long range dependence (LRD)
- $1/f^{a}$ noise

- Porous media
- Particulate
- Granular
- Lossy
- Anomaly
- Disorder
- Soil, tissue, electrodes, bio, nano, network, transport, diffusion, soft matters (**bio**x) …

Outline

- **Introduction - CSOIS and Research Strength**
- **Cognitive Process Control – A New Framework**
- **Potential Contributions from CSOIS to Lam Research**
  - Jitter Margin Accommodation
  - Undistortion Technique
  - Iterative-Variant Uncertainties in R2R Controls
  - Fractional Order Modeling/Controls
  - **New Ideas in Virtual Metrology/Outlier Modeling**
  - MIMO Robust Control and Performance Monitoring

Dynamic Virtual Metrology in Semiconductor Manufacturing



http://bcam.berkeley.edu/research/new_researchframes.html

New Ideas

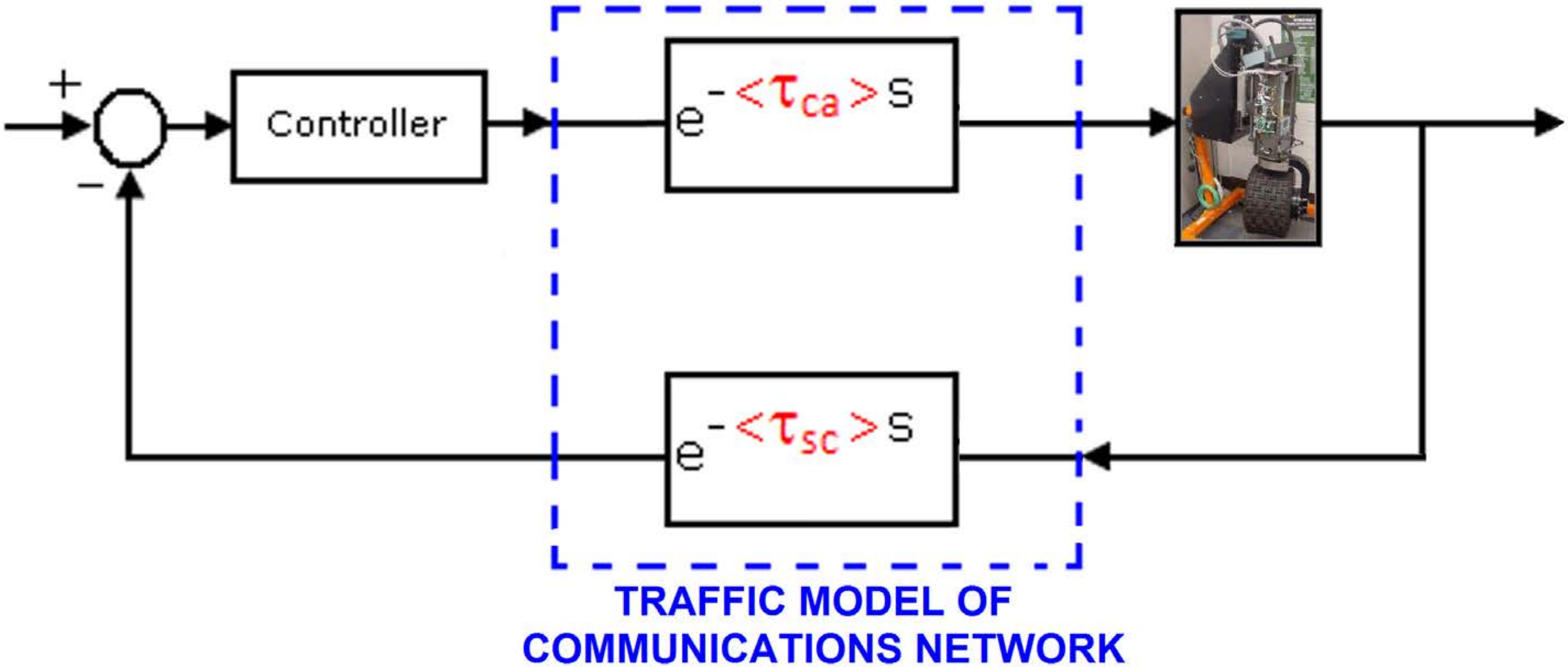
- Other efficient "learning machines"
  - RVM
- Other fitting methods
  - TLS fitting for "data boxes" (not point)
  - Interval computation tools (IntLab)
- Dynamic VM – R2R VM
- Fractional Order ANN based VM
  - Neuronal dynamics is inherently "fractional order"

"Outlier modeling" – A New Fractional Order Statistic Point of View

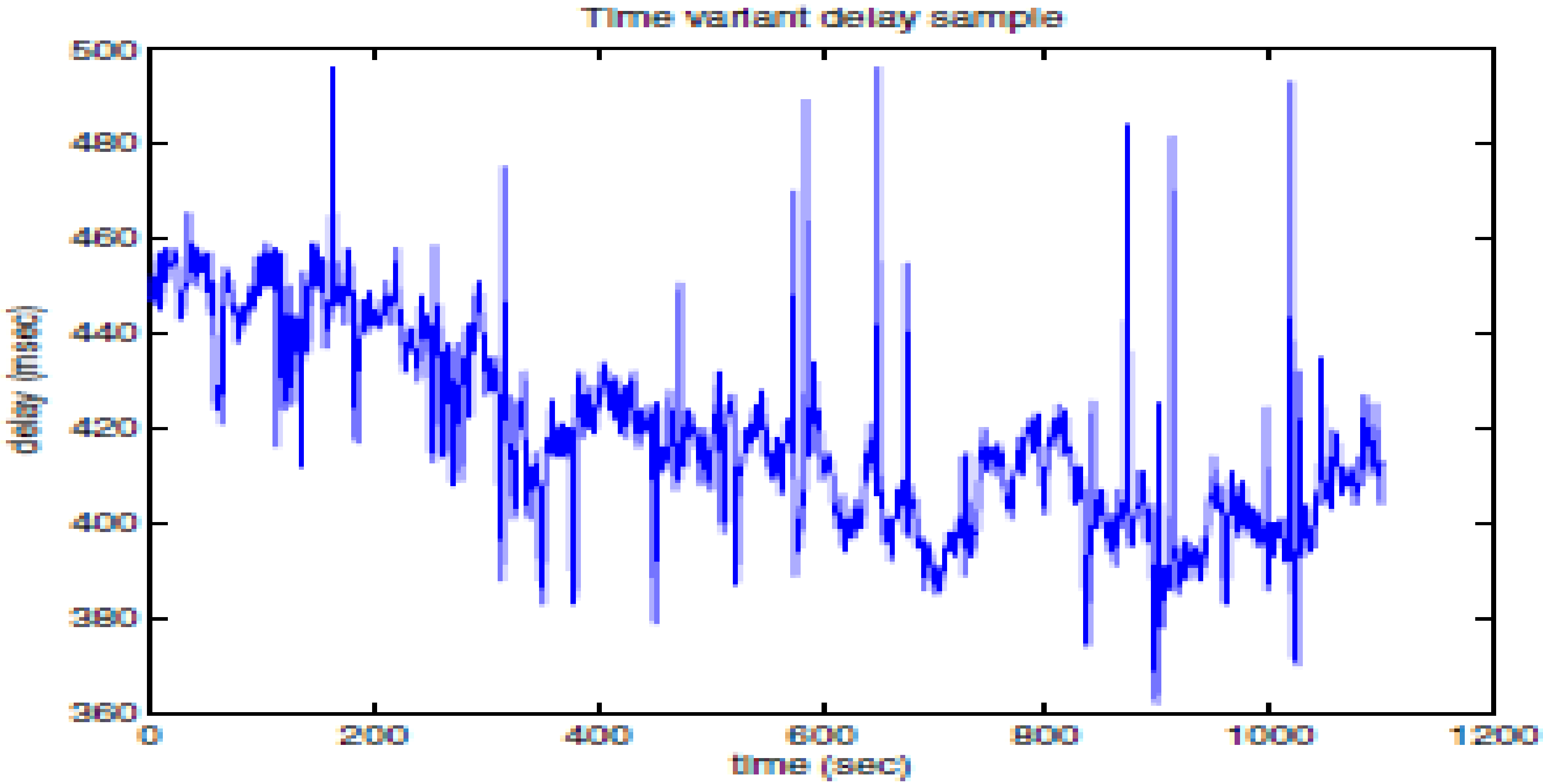
- Paradigm shift
- "How do you know outlier is not part of the dynamic system's behavior?" – YangQuan Chen
- Data has "equal rights"

- Outliers are of "spiky nature"
- "Event of low probability can still happen often"
  - Hint of "heavy-tailedness" of PDF

NCS – delay is random, time-varying

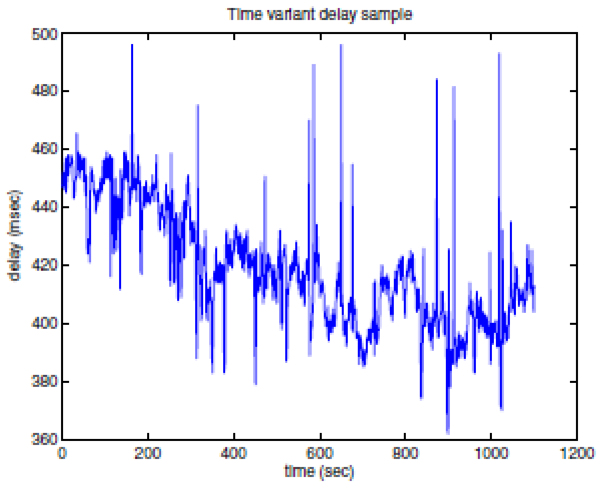


… and spiky

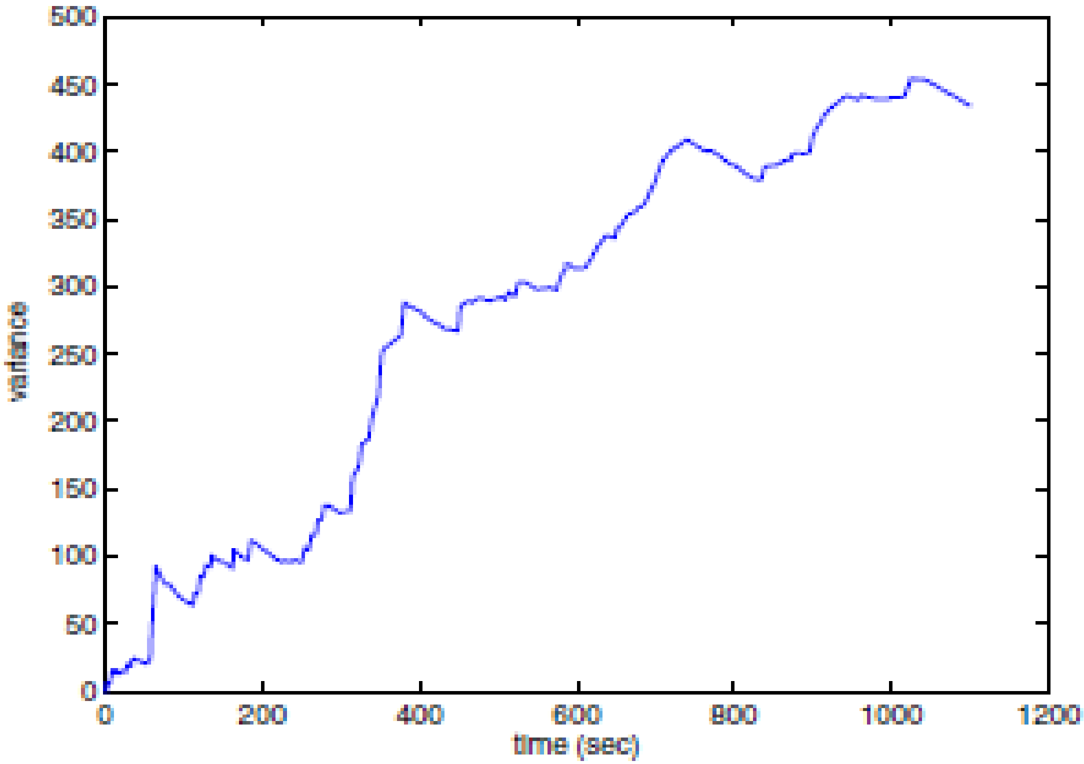


(a) Network delay samples

PROBLEM? running variance estimate is not convergent

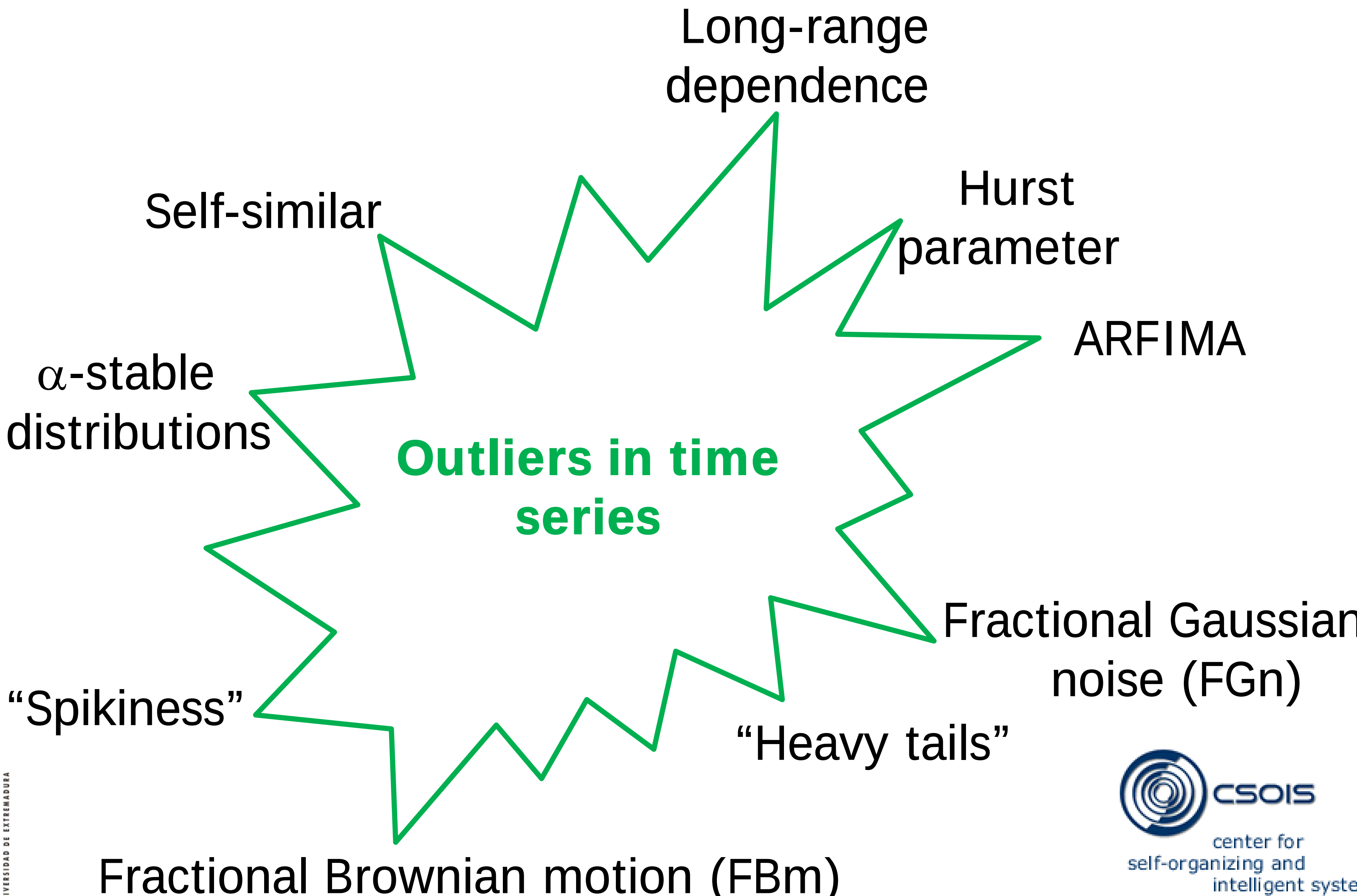


(a) Network delay samples



(b) infinite or divergent variance

CONCEPTS RELATED TO OUTLIER MODELING AND PREDICTION



MODELS IN LITERATURE

Outlier MODELS?

Fractional Brownian motion (FBm)

[1] O.I. Sheludin, S.M. Smolskiy, and A.V. Osin, *Self-Similar Processes in Telecommunications*. John Wile & Sons, Ltd, England, 2007.

α-stable distributions

[10] S. Mukhopadhyay, Y. Han, and Y.Q. Chen, "Fractional Order Networked Control Systems and Random Delay Dynamics: a Hardware-in-the-Loop Simulation Study". In: *Proceedings of the 2009 American Control Conference*, pp. 1418-1423, USA, 2009.

[11] W. Qin, Q. Wang, and A. Sivasubramiam, "An α-stable Model-based Linear-parameter-varying Control for Managing Server Performance Under Self-similar Workloads". *IEEE Transactions on Control Systems Technology*, Vol. 17, No. 1, pp. 123-134, January 2009.

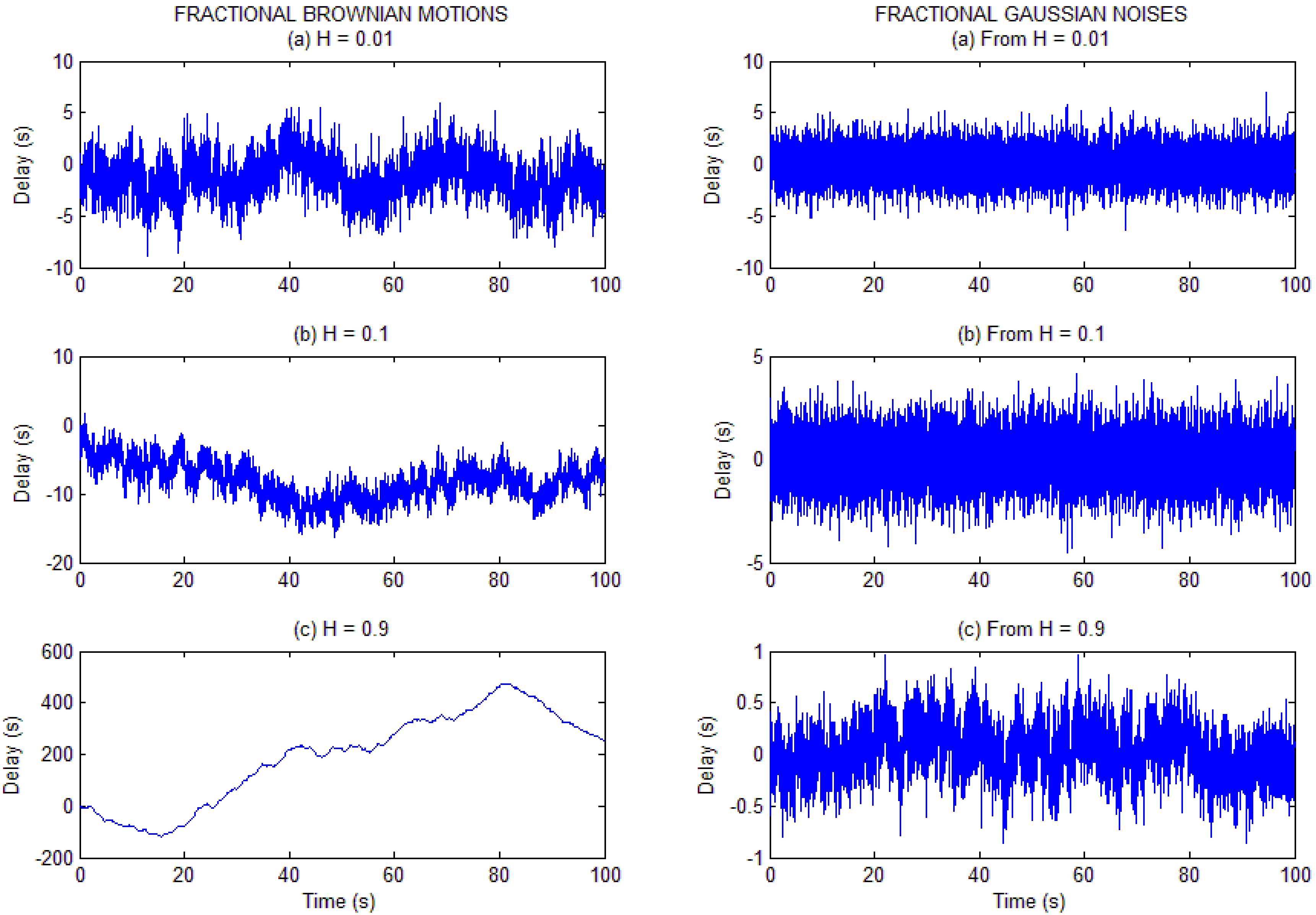
Fractional Autorregresive Moving Average (ARFIMA) proccess

[7] S. Stoev, and M.S. Taqqu, "Simulation Methods for Linear Fractional Stable Motion and FARIMA Using the Fast Fourier Transform". *Fractals*. Vol. 12, No. 1, pp. 95-121, 2004.

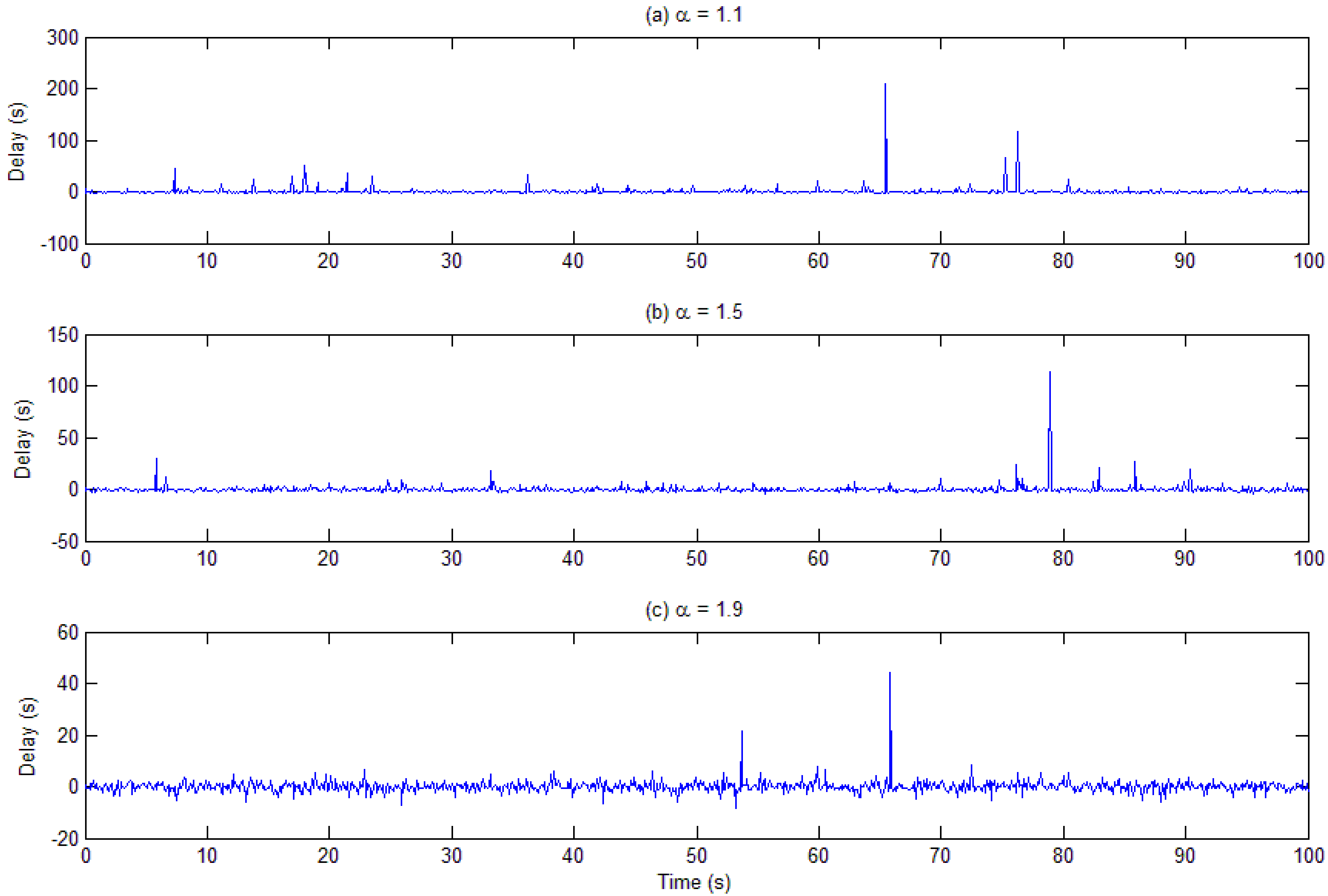
[27] A. Scherrer, N. Larrieu, P. Owerzarski, P. Borgnat, and P. Abry, "Non-Gaussian and Long Memory Statistical Characterisations for Internet Traffic with Anomalies". *IEEE Transactions on Dependable and Secure Computing*, Vol. 4, No. 1, pp. 56-70, 2007.

UEX UNIVERSIDAD DE EXTREMADURA

MODELS IN LITERATURE

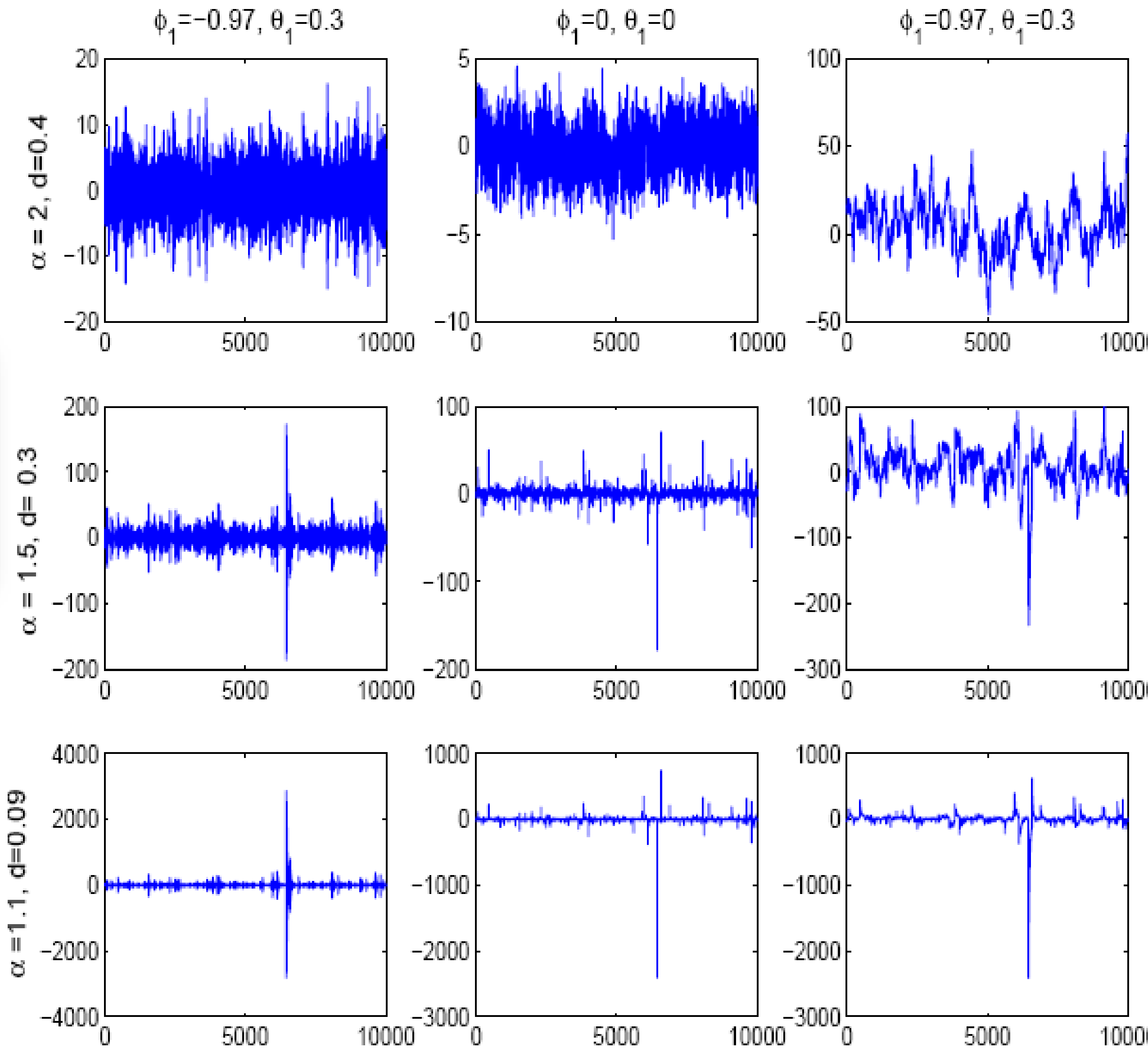


MODELS IN LITERATURE



MODELS IN LITERATURE

[7] S. Stoev, and M.S. Taqqu, "Simulation Methods for Linear Fractional Stable Motion and FARIMA Using the Fast Fourier Transform". *Fractals*, 2004.



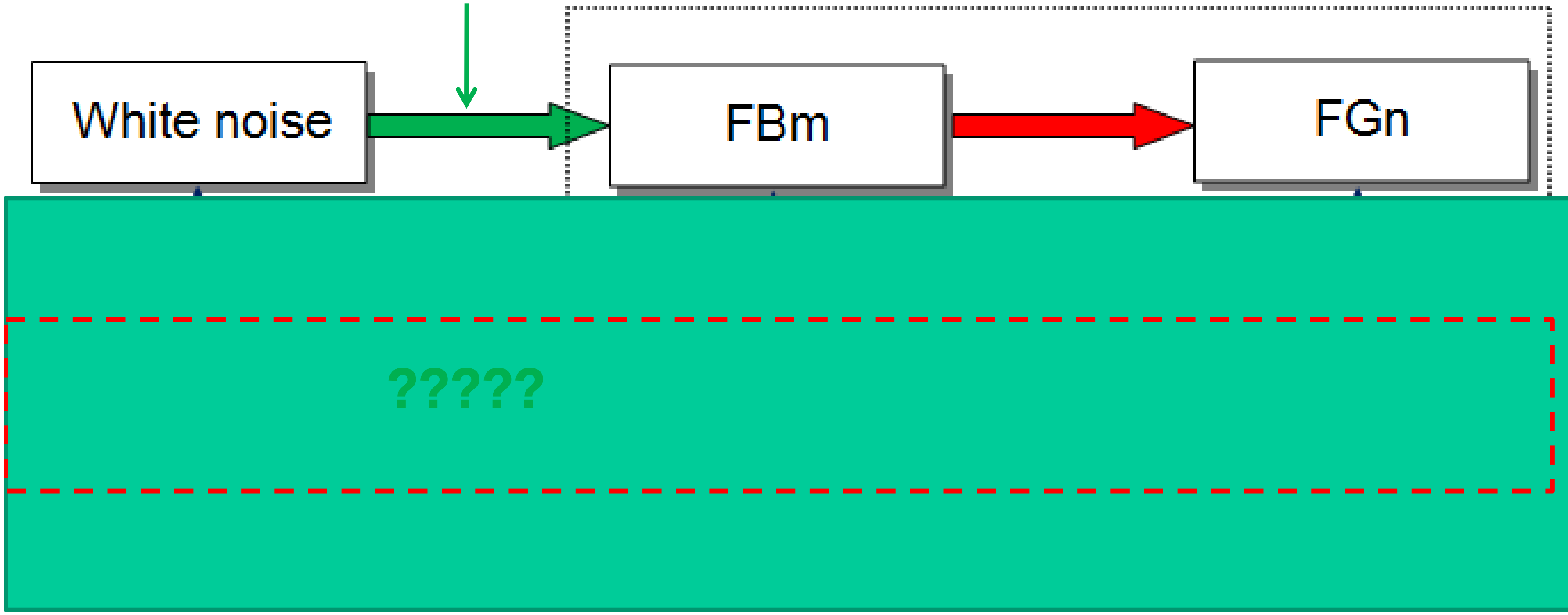
FARIMA$(1, d, 1)$

FO NETWORK DELAY DYNAMICS

$$D^{\beta}\tau(t) = B(t)$$

β the fractional-order,
$\tau(t)$ the network-induced delay,
$B(t)$ white noise.

[18] V. Pipiras, and M.S Taqqu, "Fractional calculus and its connections to fractional Brownian motion". *Theory and Applications of Long-range Dependence*, 2003.



- Self-similarity => Hurst parameter
- "Spikiness".

Operation: $D^{-\beta}$
Operation: *increments*
Self-similar processes

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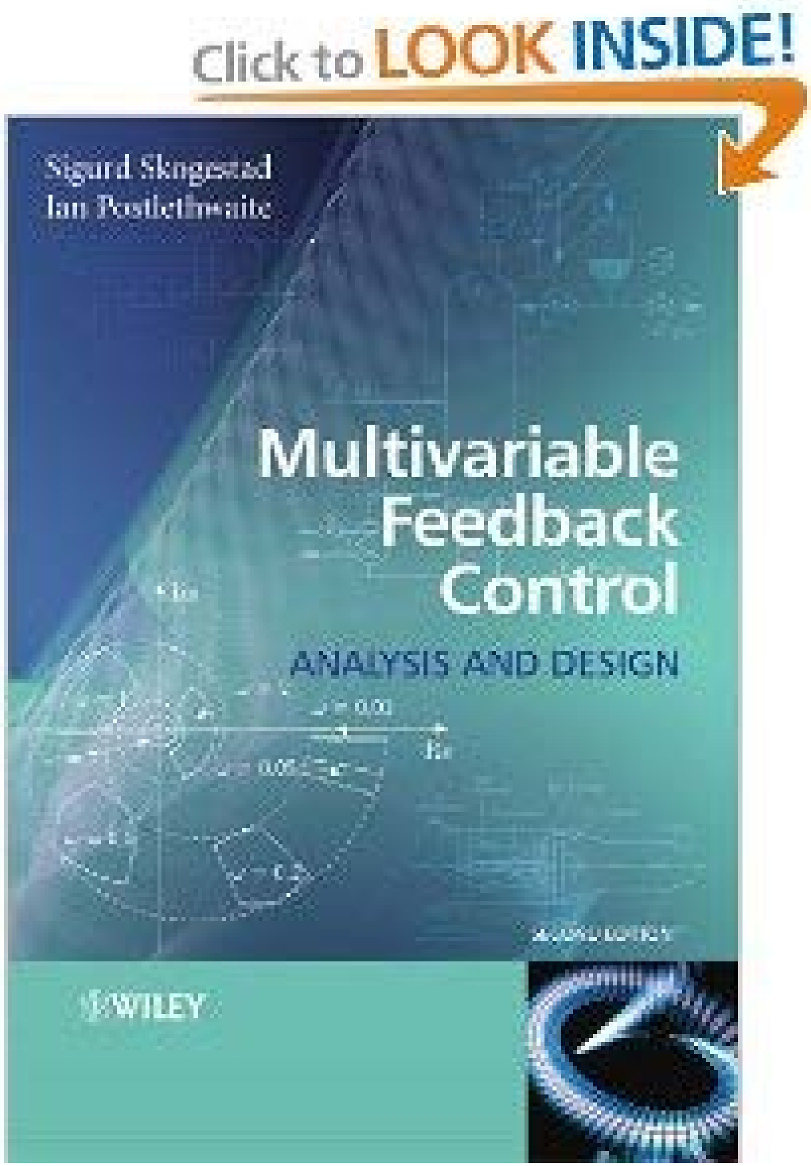
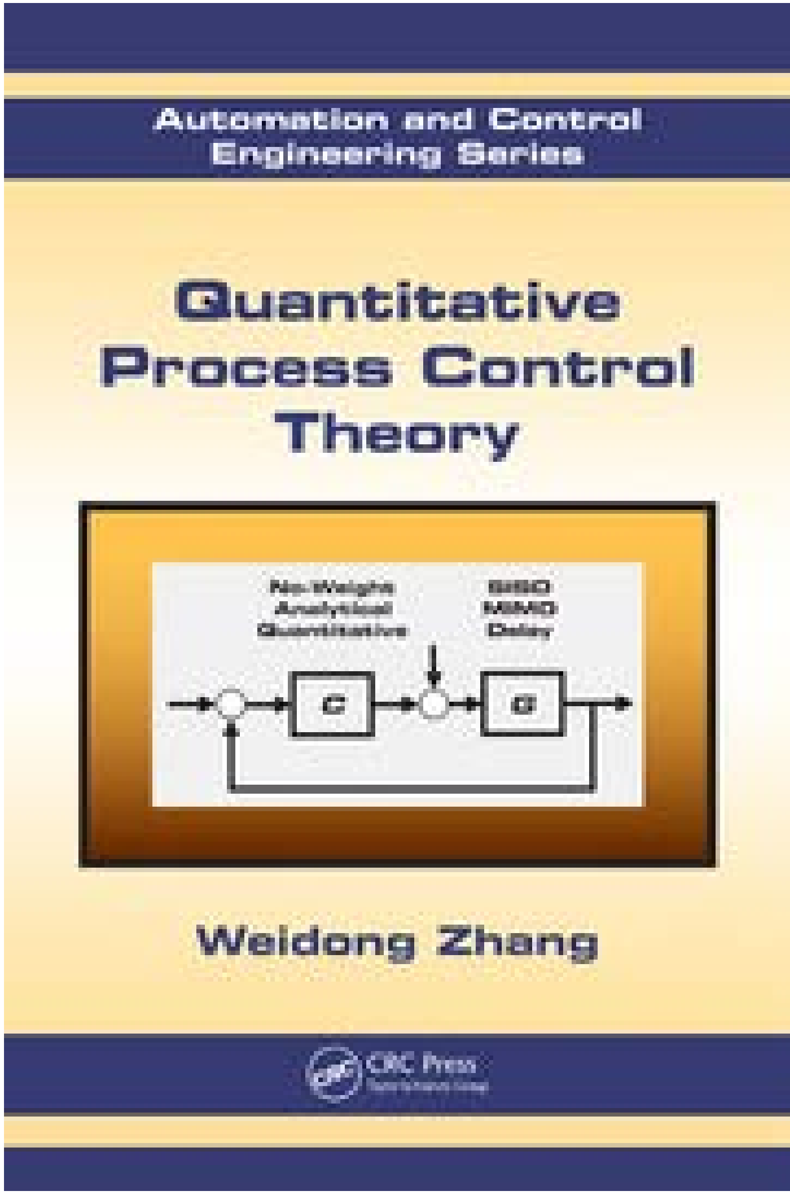
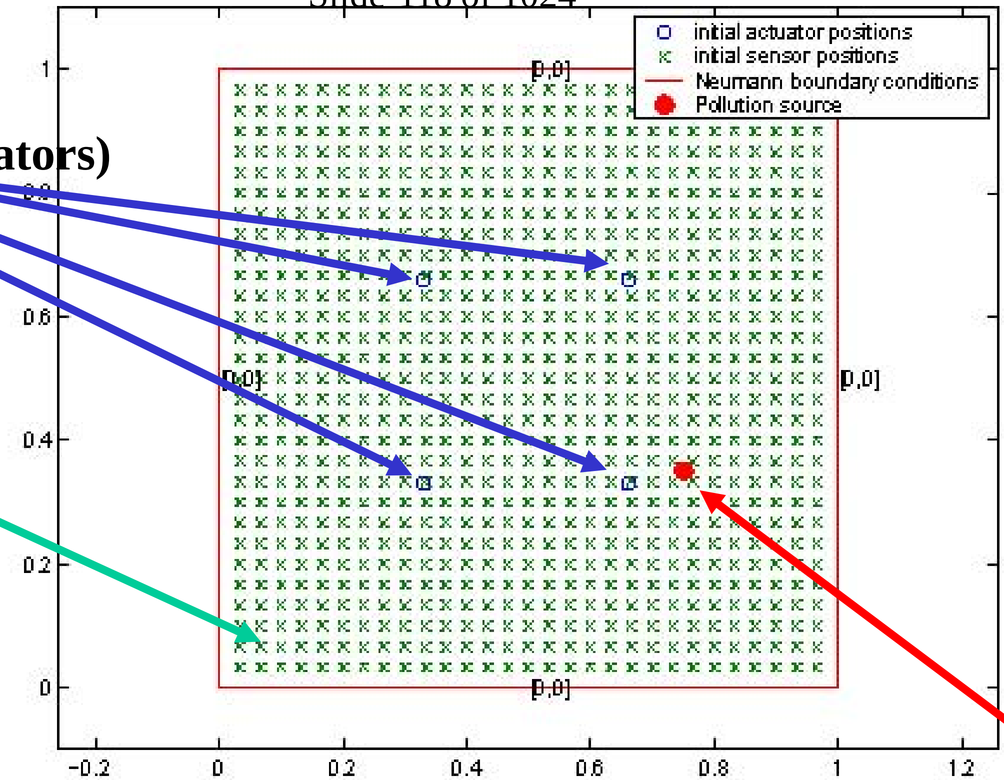

Click to LOOK INSIDE!
Sigurd Skogestad
Ian Postlethwaite
Multivariable Feedback Control
ANALYSIS AND DESIGN
WILEY


Automation and Control Engineering Series
Quantitative Process Control Theory
No-Weight
Analytical
Quantitative
SISO
MIMO
Delay
C
G
Weidong Zhang
CRC Press

Possible "Robust Control" Topics Useful to Lam Research

- H_inf loopshaping
- MIMO decoupler design
- Delay compensation in MIMO systems

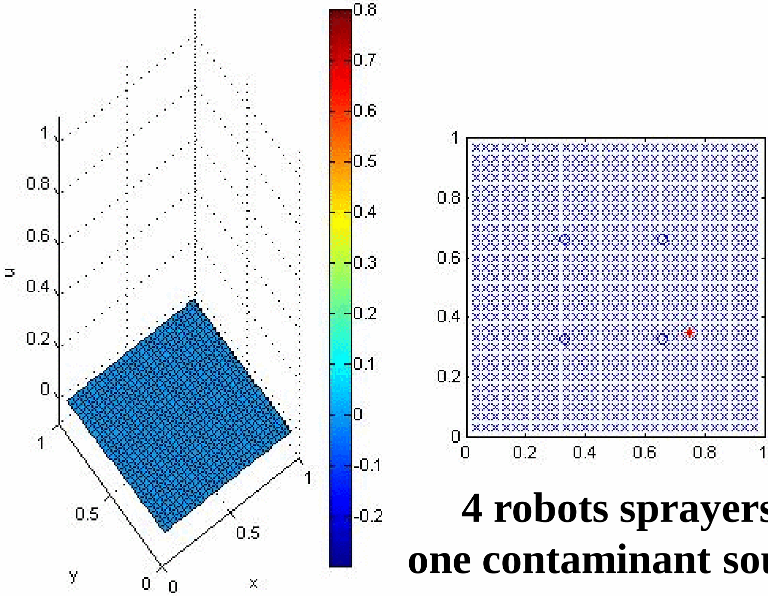
- Spatial robustness
  - Optimal spatial uniformity control
  - Spatial domain loop shaping
  - Optimal spatial actuation scheduling
    - (movie next)



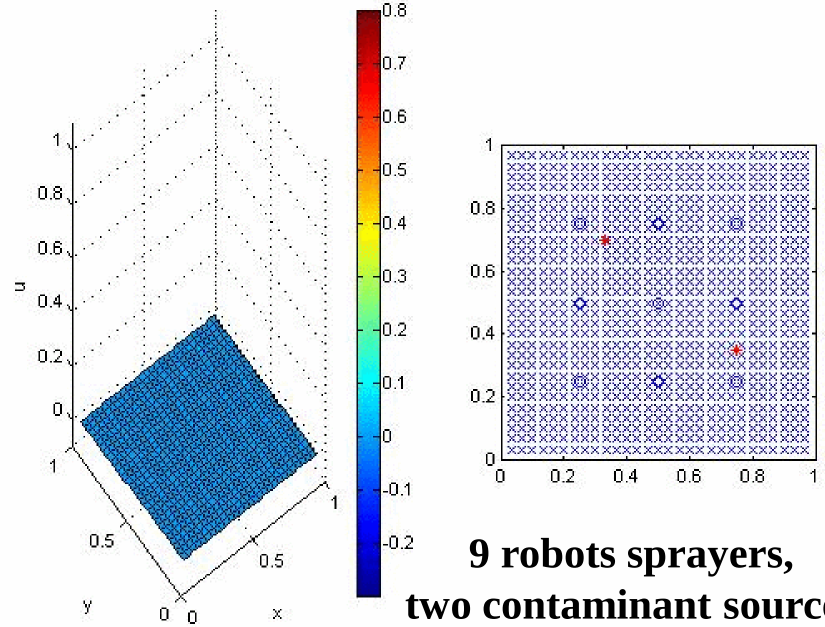
Initial layout of actuators and sensors.

Strategy:

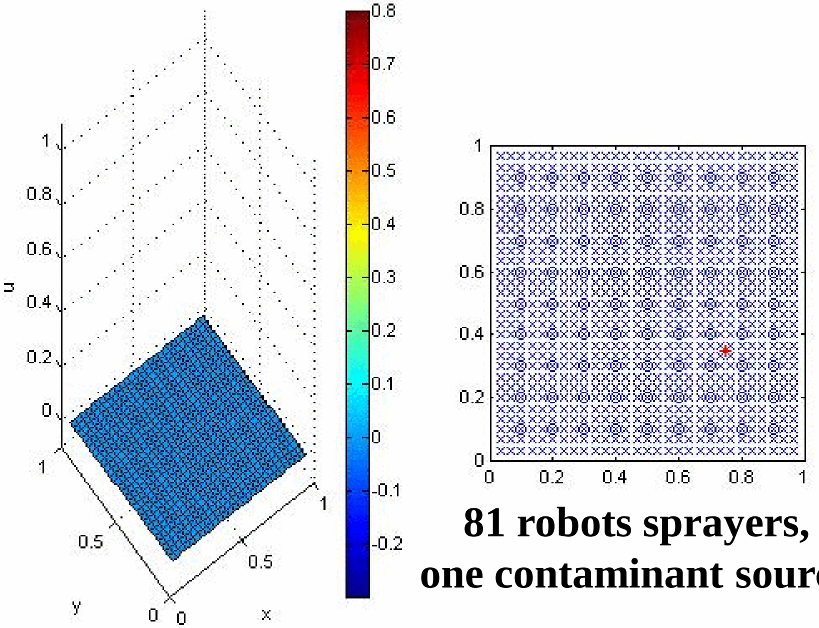
1) **Form Voronoi tessellation**
2) **Move each robot to the mass centroid of its region**
3) **Spray neutralizing chemical in amount proportional to concentration in region**



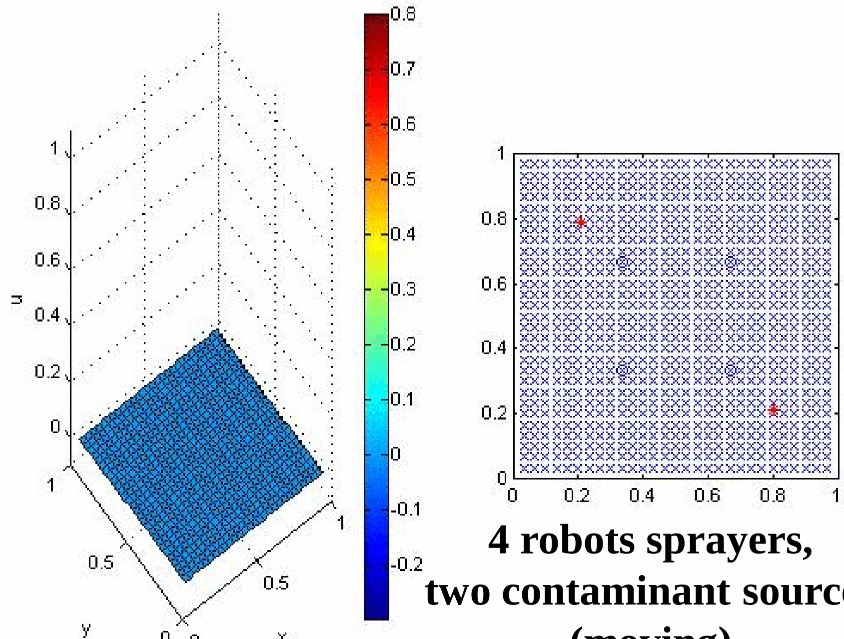
4 robots sprayers,
one contaminant source



9 robots sprayers,
two contaminant sources

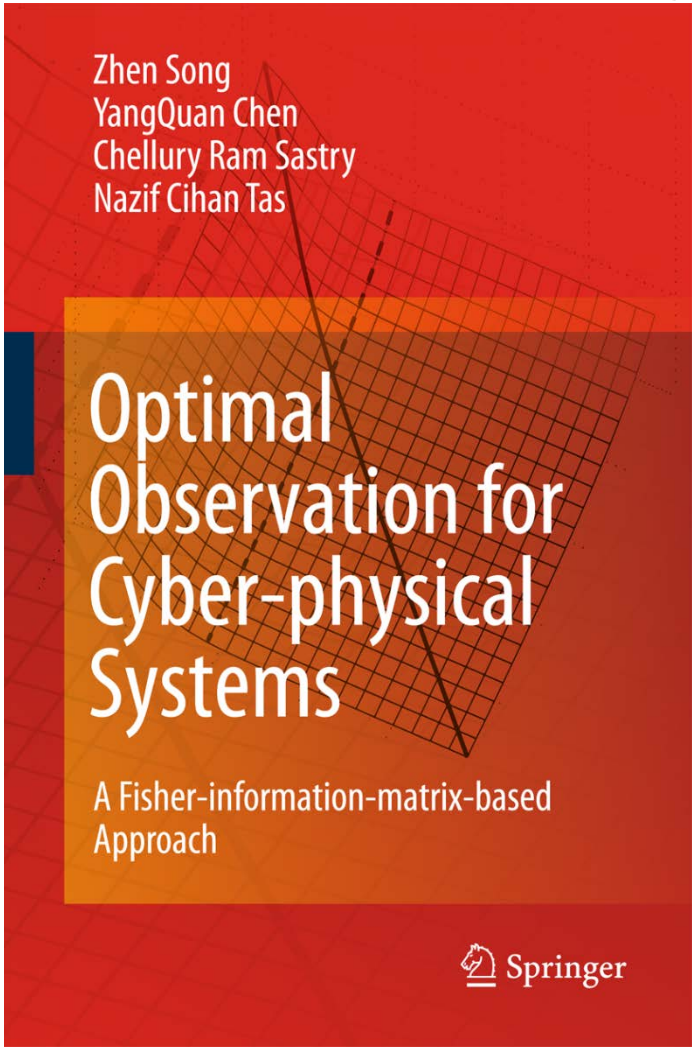


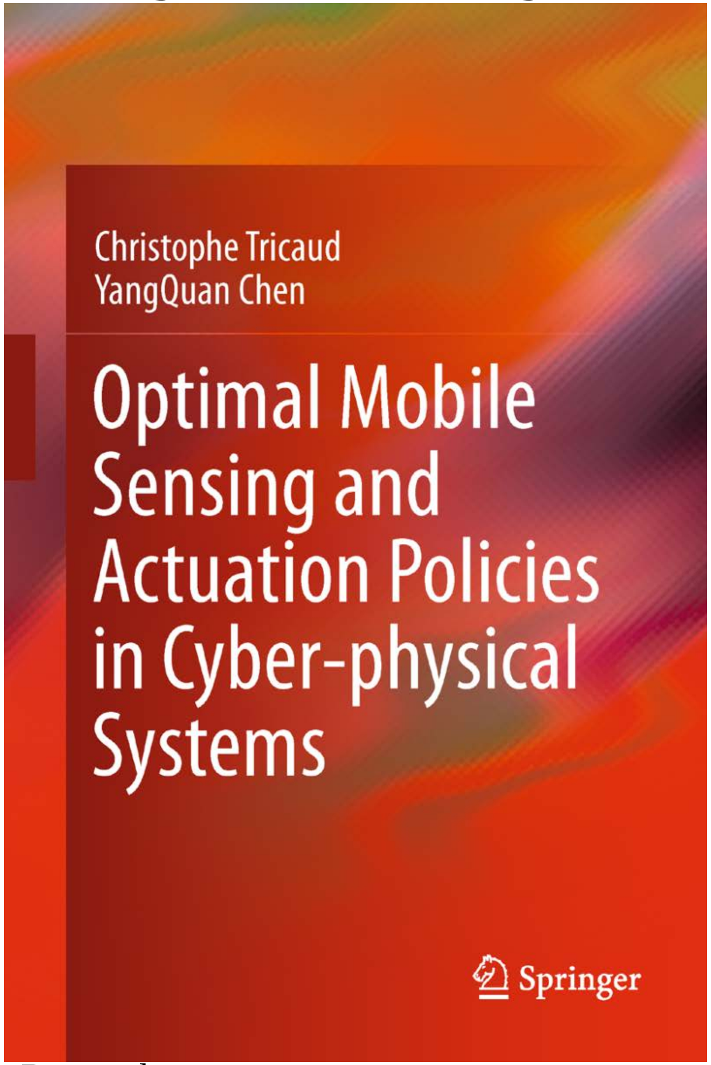
81 robots sprayers,
one contaminant source



4 robots sprayers,
two contaminant sources
(moving)

Wafer-fab as a **C**yber-**P**hysical **S**ystem





Thank you for your attention!

Acknowledgements

- Lam for invitation and Tao Zhang for serving as my role model!
- NRC Twinning Grant, 2003-2005. (Igor Podlubny, K. Moore co-PIs)
- NSF Workshop Grant, 2004 (Om Agrawal, PI)
- USU New Faculty Research Grant, 2002-2003
- USU TCO Technology Bridge Grant, 2005
- USU SDL Skunk Works Grant, 2005-2006 (Anhong Zhou, co-PI)
- NSF SBIR Phase-1 Grant, 2006 (Gary Bohannan, PI)
- Igor Podlubny, Ivo Petras, Lubomir Dorcak, Blas Vinagre, Shunji Manabe, J.T.M. Machado, J. Sabatier, Om Agrawal, Kevin L. Moore, Dingyu Xue, Anhong Zhou, Richard L. Magin, Wen Chen, Changpin Li, Yan Li, Gary Bohannan.
- Concepción A. Monje, José Ignacio Suárez, Chunna Zhao, Jinsong Liang, Hyosung Ahn, Tripti Bhaskaran, Theodore Ndzana, Christophe Tricaud, Rongtao Sun, Nikita Zaveri, …

Backup slides

- Youtube channels of CSOIS:
  - **http://www.youtube.com/user/MASnetPlatform**
  - **http://www.youtube.com/user/USUOSAM**

  - **http://www.youtube.com/user/FractionalCalculus**

More on FOSP/FOC

Smart Mechatronics

Biomimetic Materials and Biomimetic Actuators

- EAP (electroactive polymers), a.k.a. artificial muscle
- ferroelectric and relaxor materials
- piezoceramic and piezopolymetric materials
- liquid crystal elastomers
- electro and magnetostrictive materials
- shape memory alloys/polymers
- intelligent gels etc.

However, little has been reported on the controls of actuators made with these biomimetic materials.

Compensation of nonlinearity with memory

- e.g., hysteresis, backlash.
- My Assertion: Fractional calculus may better help us.

A Hidden Evidence

IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 9, NO. 1, JANUARY 2001 17

Phase Control Approach to Hysteresis Reduction

Juan Manuel Cruz-Hernández, *Member, IEEE,* and Vincent Hayward, *Member, IEEE,*

***Abstract*—This paper describes a method for the design of compensators able to reduce hysteresis in transducers, as well as two measures to quantify and compare controller performance. Rate independent hysteresis, as represented by the Preisach model of hysteresis, is seen as an input–output phase lag. The compensation is based on controllers derived from the "phaser," a unitary gain operator that shifts a periodic signal by a single phase angle. A "variable phaser" is shown to be able to handle minor hysteresis loops. Practical implementations of these controllers are given and discussed. Experimental results exemplify the use of these techniques.**

***Index Terms*—Compensation, hysteresis, intelligent materials, phase control, piezoelectric transducers, smart materials, transducers.**

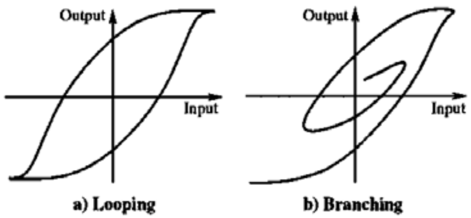


Fig. 1. Hysteresis loop and branching.

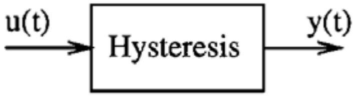


Fig. 2. A black box representation of hysteresis.

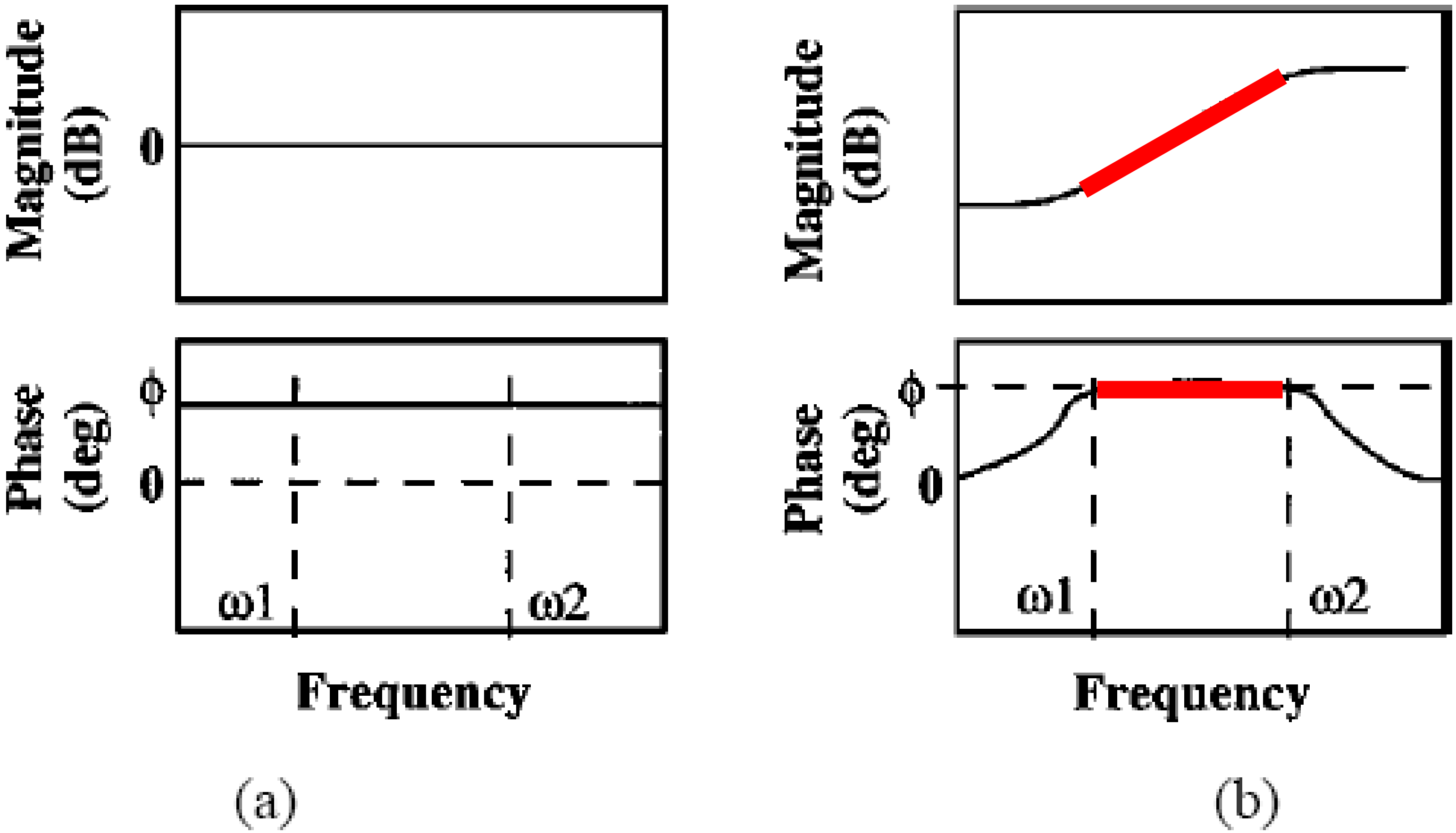


Fig. 10. Frequency response. (a) Ideal phaser. (b) Approximation.

"smart material" based Fractor™

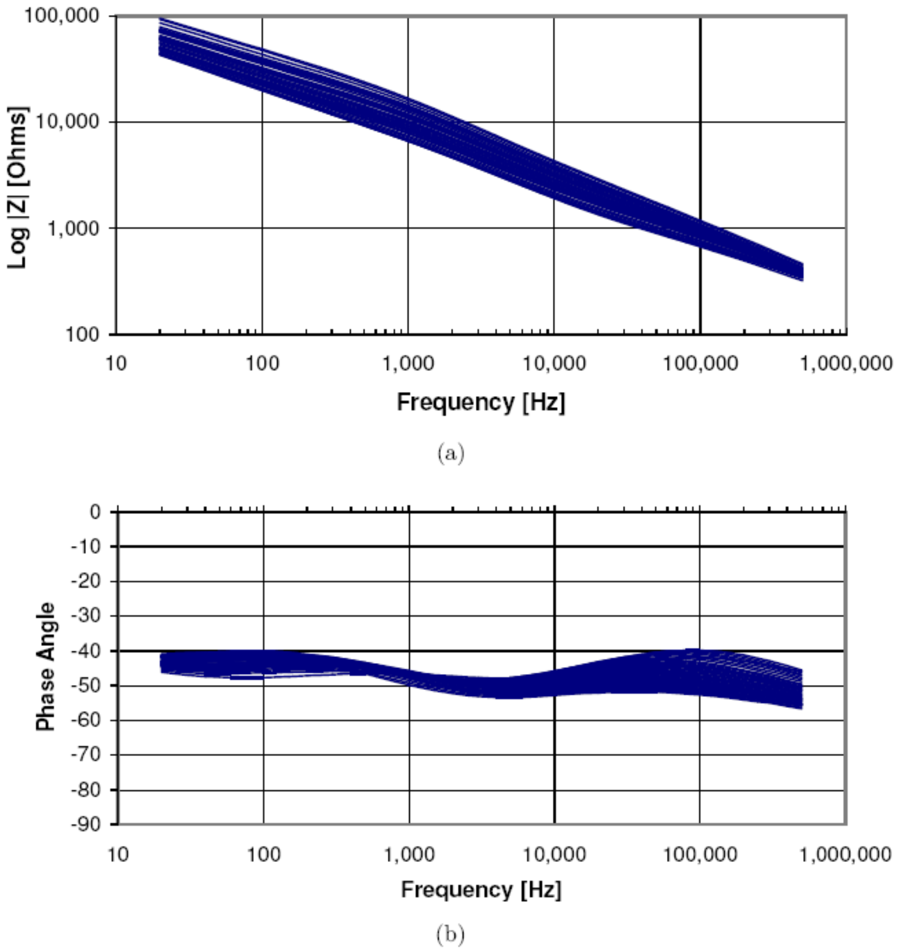


Fig. 1. Spectral response of the Fractor™ used in this demonstration project; (a) the impedance magnitude and (b) impedance phase. The multiple lines show the variation over 26 impedance measurement scans.

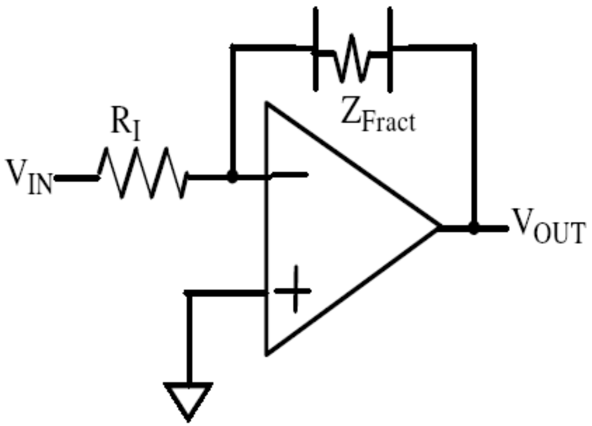


Fig. 2. Schematic for a fractional order integrator. Z_F represents the Fractor™ element. The schematic symbol for the Fractor™ was designed to give the impression of a generalized Warburg impedance; a mixture of resistive and capacitive characteristics.

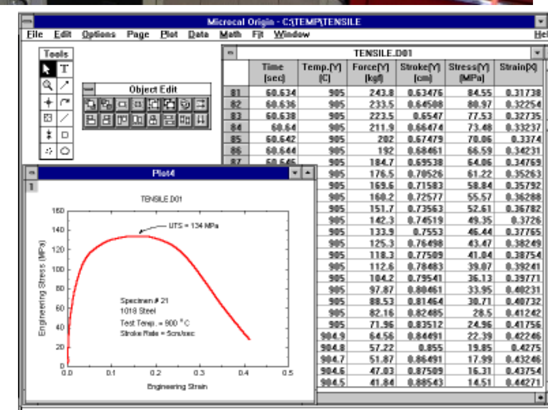
Gary W. Bohannan "**Analog Fractional Order Controller in a Temperature Control Application**". Proc. of the 2nd IFAC FDA06, July 19-21, 2006, Porto, Portugal.

Big Picture, or,
The take-home message

- The big picture for the future is the intelligent control of biomimetic system using biomimetic materials with fractional order calculus embedded. In other words, it is definitely worth to have a look of the notion of ``*intelligent control of intelligent materials using intelligent materials*."

USU Material Research Laboratory

- **Materials Processing, Heat Treating, Materials Joining, and Powder Metallurgy Studies using the Gleeble 1500D System**

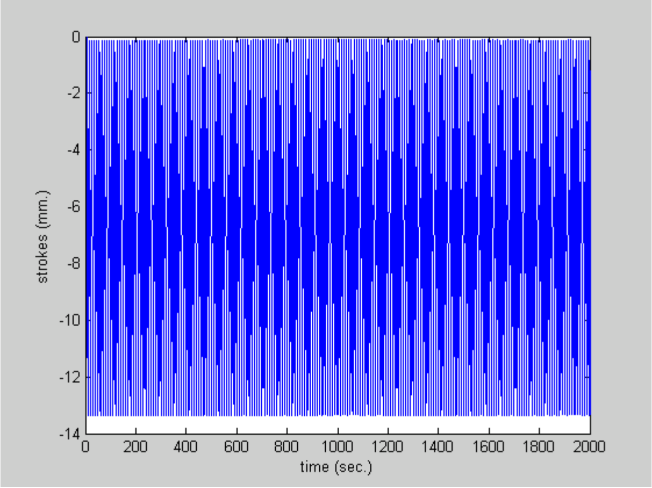


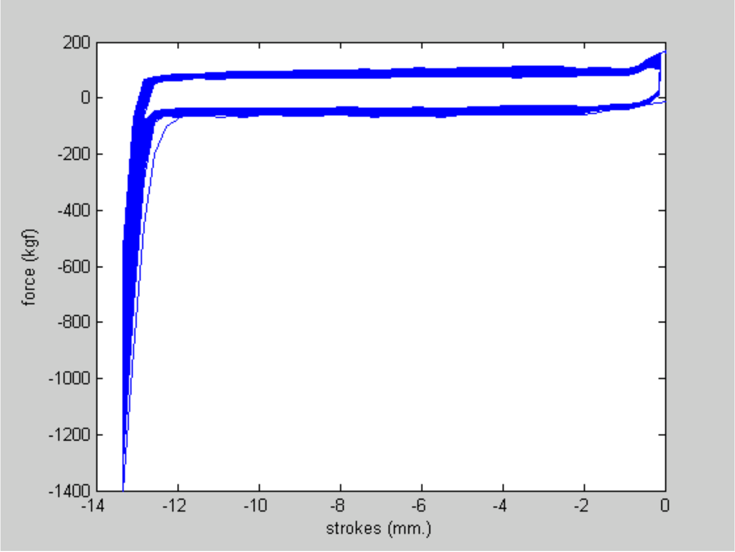
Source: http://www.mae.usu.edu/faculty/leijun/gleeble.html

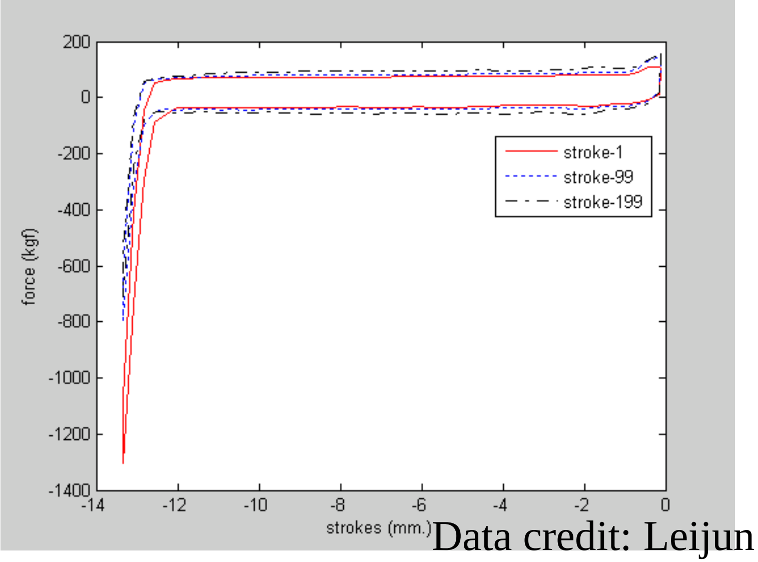
NSF NER: Solid-state synthesis of nano-scale hydrogen storage materials by bulk mechanical alloying
http://www.mae.usu.edu/faculty/leijun/

Fractional order calculus?

- Dynamic force measurements vs. strokes

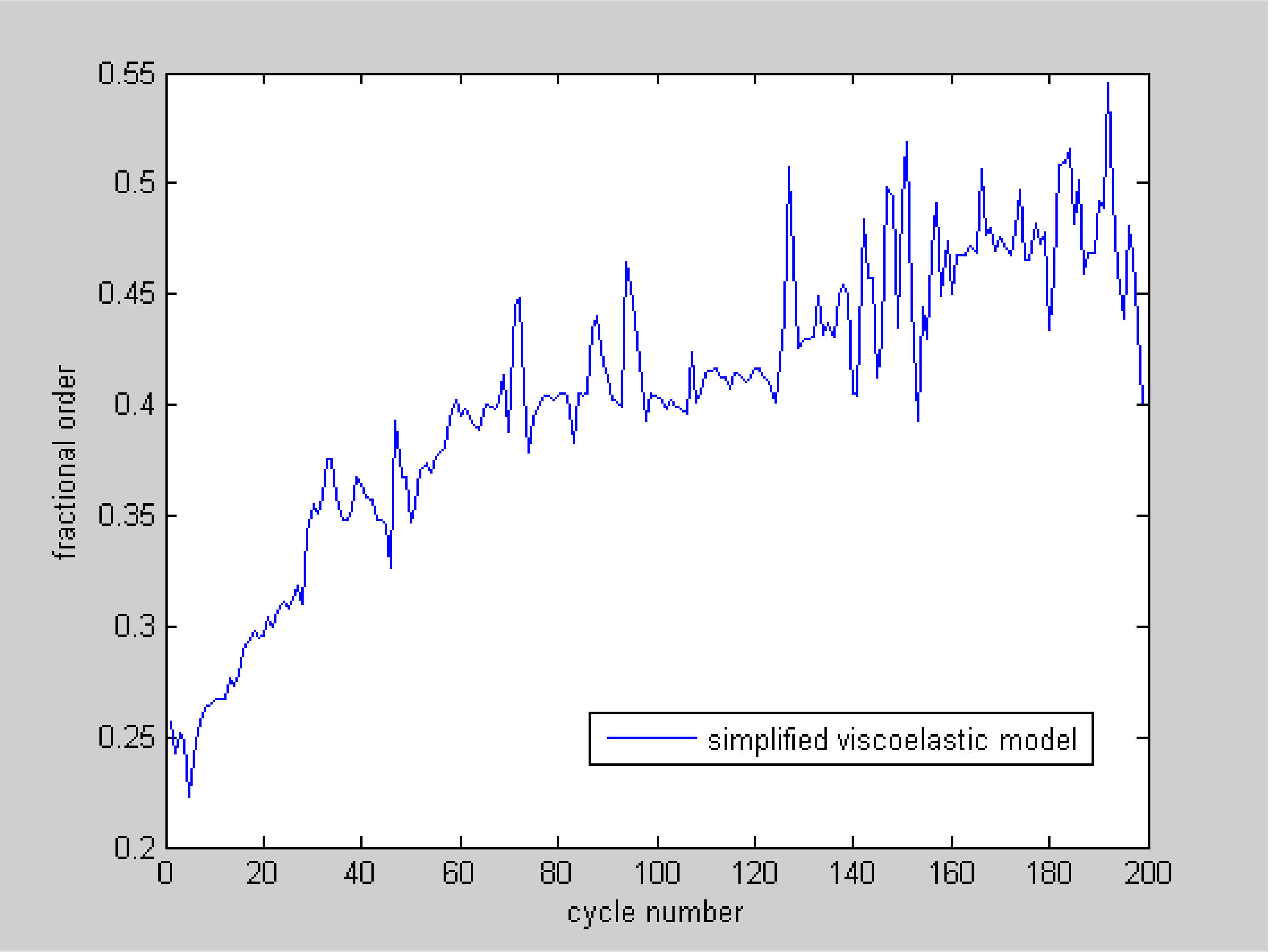






Data credit: Leijun Li

Fractional order vs. strokes



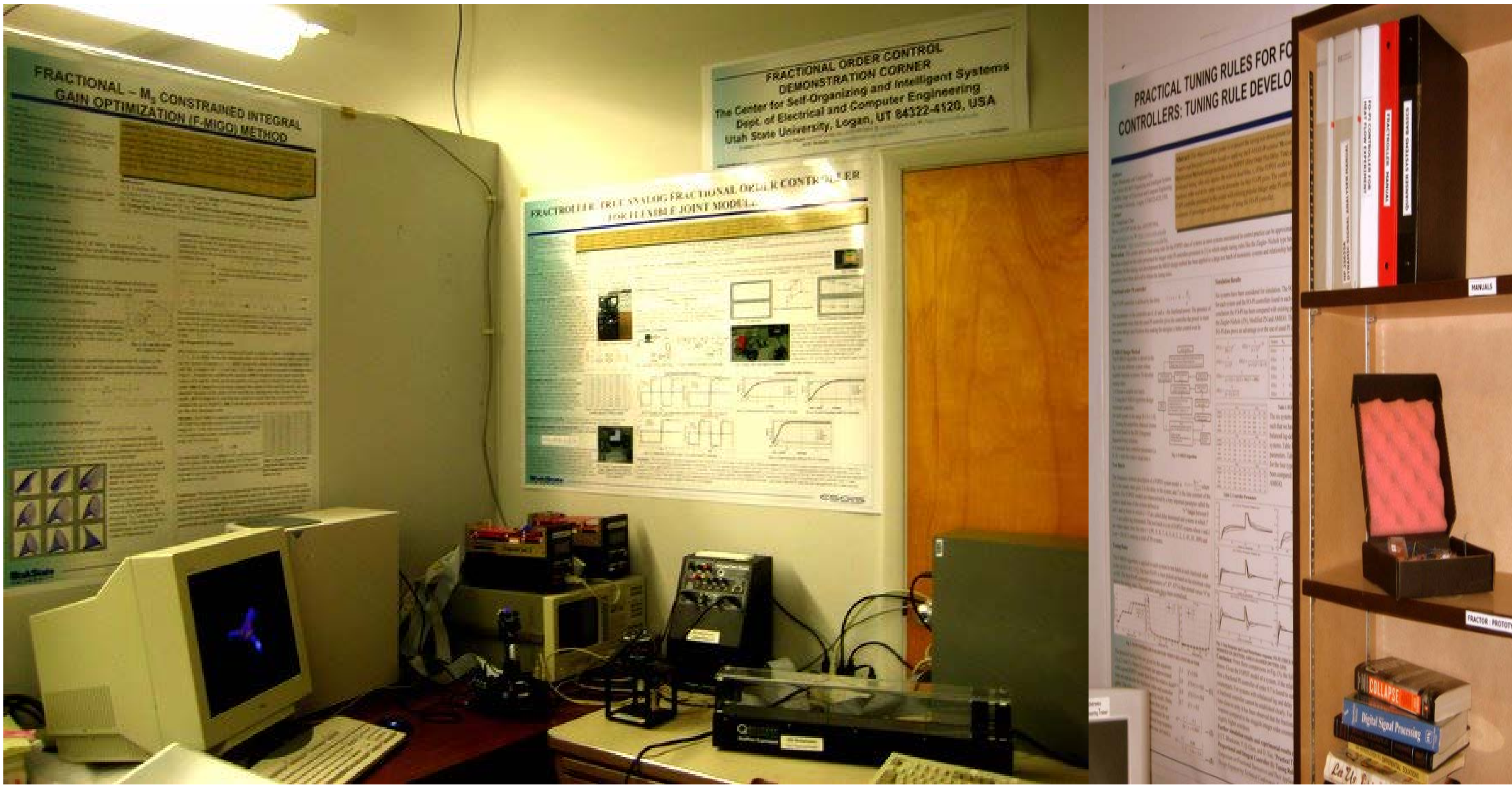
Big picture of nanoparticle manufacturing

- Now: given cycles, given stroke profile, see how particulate process evolves.
- Future: Production process development – given final particle grain size distribution, how to achieve this by using minimum number of cycles with possible cycle-to-cycle, or run-to-run (per several cycles) adaptive learning control with variable stroke profiles.

Fractional order ILC (iterative learning control)?

- D-alpha type ILC with a (really good) reason?!
  - YangQuan Chen and Kevin L. Moore. ``*On D^α-type Iterative Learning Control*''. Presented at the IEEE Conference on Decision and Control (CDC'01), Dec. 3-7, 2001, Orlando, FL, USA. pp.4451-4456. http://www.csois.usu.edu/publications/pdf/pub054.pdf

CFOSE - DEMONSTRATION CORNER



Applications – C-FOSE Proposal (Center for Fractional Order Systems Engineering)

1. Human-augmentation
2. Human Nerve System
3. Robotic equipment
4. Electric drive systems
5. Power Converters
6. Disk drive servo
7. Audio signal processing
8. Aircraft
9. Automobiles
10. Fuel cells
11. Lidar, radar, sonar, ultrasonic imaging
12. Battery chargers
13. Nuclear reactors
14. Temperature Control
15. Biosensor signal processing