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

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

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CSRA/CISOIS 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;
Some Robots Built At USU

CSCOIS 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

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.

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

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• We won #1 in AUVSI 2009 UAS Competition!!
  – $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
• We won #1 again in AUVSI’11 UAS Competition!!
  – $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](http://aggieair.usu.edu)
Mote-Based Distributed Robots

Prototype plume-tracking testbed - 2004

$2000 2^{nd} Place Prize in 2005 Crossbow Smart-Dust Challenge
WaterWatch?

- Water resources, Gates, flumes
- Weather, climate
- Water rights
- Irrigation control
- Irrigators
- Geo-Domain
  - human
  - crops
  - animals etc.

- UAVs
- Ground sensor pods
- calibration

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=fractional (over 1.1M docs, #5)
- http://www.hub.sciverse.com/action/search/results?st=%22fractional+processes%22
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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
Cognitive Process Control: Where? When?

Keys:
- M: metrology
- VM: virtual metrology
- MSet: metrology setpoint
- FB: feedback
- FF: feedforward
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Jitter Margin

\[
\Delta m(t) = m(t - \delta(t)) \text{ s.t. } 0 \leq \delta(t) \leq \delta_{\text{max}},
\]

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


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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 \( y = x + \alpha x^3 \).

\[ \alpha = 0 \]  \hspace{1cm}  \[ \alpha = 0.1 \]
Nonlinearity Detection: Motivation

The basic idea of static nonlinearity compensation:

[Diagram showing a control system with reference input, controller, plant, and output with nonlinearities indicated]
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

\[
NLI \equiv \left| b\hat{c}^2_{\text{max}} - \left( b\hat{c}^2 + 2\sigma b\hat{c}^2 \right) \right|.
\]

\(NLI\) 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


• 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.


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ILC – Iterative Learning Control


Also first in ILC+HDD servo

- 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”
ILC linked to “Real-time SPC”

- R2R is a type of ILC, see
More information


Our ILC books

Lecture Notes in Control and Information Sciences 248
Yangquan Chen and Changyun Wen
Iterative Learning Control
Convergence, Robustness and Applications

Iterative Learning Control
Robustness and Monotonic Convergence for Interval Systems

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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

“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: \( 1/s \)

What is \( s^\alpha \) when \( \alpha \) is a non-integer?
Fractional Order Integrator

\[ G(s) = \frac{1}{\sqrt{s}} \]

Legal in MATLAB and everywhere?

\[ a=-0.5;w=\text{logspace}(-2,2,1000);fi=(j.*w).^a; \]
\[ \text{figure} \]; \text{subplot}(2,1,1); \text{semilogx}(w,20*\text{log10}(\text{abs}(fi))); \]
\[ \text{xlabel('frequency (rad./sec.)')} ; \text{ylabel('dB')} ; \text{grid on} \]
\[ \text{subplot}(2,1,2); \text{semilogx}(w,180*\text{angle}(fi)/\text{pi}); \]
\[ \text{xlabel('frequency (rad./sec.)')} ; \text{ylabel('degree')} ; \text{grid on} \]
Possible? Possible! Legal!!

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

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

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


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Fractor: Analogue device

Fractional Calculus Day at USU, April 19, 2005

\[ G(s) = -\frac{K}{R(s\tau)^\lambda} \]
Oustaloup’s Recursive Approximation for fractional order differentiators/integrator

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

\[
\begin{align*}
&\text{w}_L=0.1; \text{w}_H=1000; \gamma=-0.5; \text{figure; } N=3; \text{sysl}=\text{tf}(1,[1,0]); \\
&\text{sys}_N_\text{tf}=\text{ora}_\text{foc}(r,N,\text{w}_L,\text{w}_H); \text{bode(sys}_N_\text{tf,'k:'},\text{sysl,'r-'}); \text{grid on;}
&\text{title(} ['\text{Oustaloup-Recursive-Approximation for } \{\text{it } s\}^{\wedge}\{\wedge\}',\text{num2str(r)}])
\end{align*}
\]


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

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

What is $s^\alpha$ when $\alpha$ is a non-integer?

A generalization of differential and integral operators:

$$aD_t^\alpha = \begin{cases} 
  d^\alpha/dt^\alpha & \Re(\alpha) > 0, \\
  1 & \Re(\alpha) = 0, \\
  \int_a^t (d\tau)^{-\alpha} & \Re(\alpha) < 0.
\end{cases}$$

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: $\sin(t)$
Fractional derivatives of ramp function.
Nothing surprising so far.

Quite intuitive in fact.

For example,
... from integer to non-integer ...

\[ x^n = \underbrace{x \cdot x \cdot \ldots \cdot x}_n \]

\[ x^n = e^{n \ln x} \]

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

\[ \Gamma(x) = \int_0^\infty e^{-t} t^{x-1} \, dt, \quad x > 0, \]

\[ \Gamma(n + 1) = 1 \cdot 2 \cdot 3 \cdot \ldots \cdot n = n! \]
... from integer to non-integer ...

$D = 1$

$D = 2$

$D = 3$

$D = 1.26$

$D = 1.89$

$D = 2.73$

Slide credit: Igor Podlubny
Interpolation of operations

\[ f, \frac{df}{dt}, \frac{d^2 f}{dt^2}, \frac{d^3 f}{dt^3}, \ldots \]

\[ f, \int f(t)dt, \int dt \int f(t)dt, \int dt \int dt \int f(t)dt, \ldots \]

\[ \ldots, \frac{d^{-2} f}{dt^{-2}}, \frac{d^{-1} f}{dt^{-1}}, f, \frac{df}{dt}, \frac{d^2 f}{dt^2}, \ldots \]
“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

What if the order will be $n = \frac{1}{2}$?

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


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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

<table>
<thead>
<tr>
<th>1695</th>
<th>1960s</th>
<th><strong>You are here</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>static models</td>
<td>dynamical models</td>
<td>fractional order modeling</td>
</tr>
<tr>
<td>geometry, algebra</td>
<td>differential and integral calculus</td>
<td>fractional calculus</td>
</tr>
</tbody>
</table>

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: \( y(0, t) = m(t) \)

\( y(x, 0) = 0 \)

\( \lim_{x \to \infty} y(x, t) < \infty \)

Initial condition

Physical limit

Transfer function:

\[
\frac{d^2 Y(x, s)}{dx^2} = k^2 s Y(x, s)
\]

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

\( \lim_{x \to \infty} Y(x, s) < \infty \)
Irrational Transfer Function.
Taylor series expansion: polynomial of half order integrators!!
Ideal physical plant model:

First Order Plus Time Delay (FOPTD) Model:

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

Time Delay with Single Fractional Pole Model:

\[ G_{IO}(s) = \frac{K_1}{T_1s + 1} e^{-L_1 s} \]

\[ G_{FO}(s) = \frac{K_2}{T_2s^{0.5} + 1} e^{-L_2 s} \]

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”

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

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

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

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

% 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])

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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**
FOPDT optimal fitting result J=0.13541

TDWFP optimal fitting result J=0.020817

K1          T1          L1          K2          T2          L2
0.9120       2.2393      0           1.0197      1.2312      0.0001

J = 0.13541  J = 0.020817
Fitting code for

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

% 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;

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 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) tdwpfpl(x, ht, Ts), [1, 2, 0], options); toc
% May need to wait 1000+ seconds!
K1 = x(1); L1 = x(2); T1 = 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] = tdwpfpl(x, y0, Ts);
K1 = x(1); L1 = x(2); T1 = 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
  \[ G_p(s) = e^{-\sqrt{s}} \]

- Reaction curve fitting: Better than the best
  \[ G_{FO}(s) = \frac{K_2}{T_2s^{0.5} + 1}e^{-L_2s} \]

- Could be a nice starting point for better controller design?

\[ G_{IO}(s) = \frac{K_1}{T_1s + 1}e^{-L_1s} \]
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: \( C(s) = k_1 \frac{k_2 s^\alpha + 1}{s} \), \( k_2 = T \) giving a constant phase margin:

\[
\Phi_m = \arg \left[ C(j\omega)G(j\omega) \right] + \pi = \arg \left[ \frac{k_1 k}{(j\omega)^{(1+\alpha)}} \right] + \pi
\]

\[
= \arg \left[ (j\omega)^{-(1+\alpha)} \right] + \pi = \pi - (1 + \alpha) \frac{\pi}{2}
\]

Step response:

\[
y(t) = \mathcal{L}^{-1} \left\{ \frac{kk_1/J}{s^{1+\alpha} + kk_1/J} \right\} = \left( \frac{kk_1}{J} \right) t^{1+\alpha} E_{1+\alpha,2+\alpha} \left( -\frac{kk_1}{J} t^{1+\alpha} \right)
\]

(62)
Mittag-Leffler function: definition

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

\[ E_{1,1}(z) = e^z, \]

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

\[ E_{1/2,1}(z) = e^{z^2} \text{erfc}(-z); \]

\[ \text{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_{z}^{\infty} e^{-t^2} dt. \]
Note the iso-damping (similar overshoot!)
Fractional order PID control

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

\[ u(t) = K_p(e(t) + T_i D_t^{-\lambda} e(t) + \frac{1}{T_d} D_t^{\mu} e(t)). \quad (D_t^{(*)} \equiv_0 D_t^{(*)}). \]

---


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

3/13/2012
CPC @ Lam Research
• 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 (??)
How to design/tune FOC for motion control?

\[ C(s) = K_p(1 + K_ds^\mu) \]

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

(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

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

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.

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\textsuperscript{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

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 $\alpha$:
(a) $\alpha = 2.0$; (b) $\alpha = 1.9$; (c) $\alpha = 1.5$; (d) $\alpha = 1.1$. 
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 $\alpha$, only the moments of orders less than $\alpha$ 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

\[
\begin{align*}
  r_Y(k) &= EY(k)Y(0) \sim c_Y |k|^{-\gamma}, k \to \infty, 0 < \gamma < 1 \\
  s_Y(\xi) &= c_s |\xi|^{-\alpha}, 0 < \alpha < 1,
\end{align*}
\]
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 km².
- 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
Optimal filtering in fractional order Fourier domain
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,

\[ H(s) = \frac{1}{s^\alpha} \]

\[ y(t) = \frac{t^{\alpha-1}}{\Gamma(\alpha)} \]

\[ R_{yy}(\tau) = \sigma^2 \frac{|\tau|^{2\alpha-1}}{2\Gamma(2\alpha) \cos \alpha \pi} \]

\( y(t) \) is a Brownian motion when \( \alpha = 1 \), i.e., \( \frac{1}{f^2} \) 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 (biox) …
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

Proposed Model building flow chart

Poly Raw Data
a. Time series based
b. 70 variables

1st phase outlier detection
(time series based)

Data Extraction:
Mean, Max, Min, Std of variables

Data scaling
1. 0 mean, unit variance
2. Scale to [-1,1] for
   Neural network and SVM
   modeling

2nd Phase outlier detection

Outlier modeling

Outliers

Continue until better R^2

Input selection

1. Least square regression PCA
2. PLS
3. Feed-forward Neural Net

Modeling without classification

1. Knowledge based
2. PCA and PLS

Modeling with classification

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
PROBLEM? running variance estimate is not convergent

(a) Network delay samples

(b) infinite or divergent variance
CONCEPTS RELATED TO OUTLIER MODELING AND PREDICTION

Outliers in time series

- Long-range dependence
- Hurst parameter
- ARFIMA
- Fractional Gaussian noise (FGn)
- “Heavy tails”
- “Spikiness”
- Fractional Brownian motion (FBm)
- Self-similar
- $\alpha$-stable distributions

“Spikiness”

CONCEPTS RELATED TO OUTLIER MODELING AND PREDICTION

- Long-range dependence
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- ARFIMA
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- “Heavy tails”
- “Spikiness”
- Fractional Brownian motion (FBm)
- Self-similar
- $\alpha$-stable distributions
MODELS IN LITERATURE

Outlier MODELS?

Fractional Brownian motion (FBm)


α-stable distributions


Fractional Autorregresive Moving Average (ARFIMA) process


MODELS IN LITERATURE

FRACTIONAL BROWNIAN MOTIONS
(a) $H = 0.01$
(b) $H = 0.1$
(c) $H = 0.9$

FRACTIONAL GAUSSIAN NOISES
(a) From $H = 0.01$
(b) From $H = 0.1$
(c) From $H = 0.9$
MODELS IN LITERATURE

(a) $\alpha = 1.1$

(b) $\alpha = 1.5$

(c) $\alpha = 1.9$
MODELS IN LITERATURE


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

\[ D^\beta \tau(t) = B(t) \]

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

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  – New Ideas in Virtual Metrology/Outlier Modeling
  – MIMO Robust Control and Performance Monitoring
Possible “Robust Control” Topics Useful to Lam Research

- $H_{\infty}$ 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)
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

81 robots sprayers, one contaminant source

9 robots sprayers, two contaminant sources

4 robots sprayers, two contaminant sources (moving)
Wafer-fab as a Cyber-Physical System
Thank you for your attention!
Acknowledgements

- Lam for invitation and Tao Zhang for serving as my role model!
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- NSF SBIR Phase-1 Grant, 2006 (Gary Bohannan, PI)
- 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.*
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


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

![Graph showing fractional order vs. cycle number with a simplified viscoelastic model line](image-url)
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 $D^\alpha$-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.
  
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