

Utah State University CSOIS

### Fractional Order Calculus and Fractional Order Dynamics Systems and Controls

*a.k.a.*

### Non-integer Order Calculus and Non-integer Order Dynamic Systems and Controls

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### Outline

- Introduction
  - CSOIS and Research strengths (10 min)
  - Speaker 1: Igor Podlubny (30 min)
  - Speaker-2: Concha Monje (20 min)

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### 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 seven years by the State of Utah's Center of Excellence Program (CEEP)
- 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 since 1998
- Three spin-off companies since 1994.

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### 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!**

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22,000 students study at USU's Logan campus, nestled in the Rocky Mountains of the inter-mountain west

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

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### CSOIS research impacts (1998-2004)

- **Educational**
  - 2 PhD graduates with 2 others expected this year
  - 28 MS and ME students graduated
  - Numerous ECE and MAE Senior Design Projects
- **Scholarly**
  - Five faculty collaborating between three different departments
  - Four books
  - Over 100 refereed journal and conference publications
  - 18 visiting research scholars from 7 countries (3 month to 1 year visits)
- **Economic**
  - 14 full-time staff employed (average of 7 FTE per year)
  - 8 PhD students employed
  - 64 MS and ME students employed
  - 31 Undergraduate students employed
  - 12 Other staff employed
  - A payroll of over \$5 million in salaries paid to students, faculty, and staff
  - Purchases of over \$1.5M in the U.S. economy

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### CSOIS Projects

- Since 1992: Approximately
  - 15 automation and control projects
  - 15 robotics/autonomous vehicle projects
  - Funding from both private industry and government
- Current focus on vehicle automation and robotics
- Major US Army Tank-Automotive Command (TACOM) program, 1998-present

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### Representative CSOIS Projects

- Intelligent Irrigation Systems (Campbell Scientific, Inc.)
- Exercise Machines (Icon Inc.)
- Automated Wheelchairs (Marriner S. Eccles Foundation)
- Real River Educational Product (Visionary Products Inc.)
- NN Coin Recognition Device (Monetary Systems)
- Secondary Water Meter (Design Analysis Associates)
- Internet Teleservice Control
- Potato Harvest Yield Monitor
- Flat Panel Multi-Agent Interface Software (Driver Tech Inc.)
- Computer-Controlled Autonomous Wheeled Platforms for Hazardous Environment Applications (INEEL/DOR)
- Computer-Controlled Advanced Farm Systems (INEEL/DOR/Commercial)
- "Hopping" Robots
- Foundry Control Systems
- Small- to Mid-Size Robotic Systems (US Army)

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### Current CSOIS Projects

- Intelligent Mobility Project (Moore/Fann/Wood, funded by TACOM)
- Distributed Sensor Nets (Moore/Chen, funded by DARPA)
- Gimbal Control via ILC and Vision (Moore/Chen/Fulmer)

### Recently-Completed CSOIS Projects

- Packing Optimization Project (Flann, funded INEEL)
- Automated Orchard Spraying Project (Moore/Fann, private funding)
- Vehicle Safety Project (Moore/Flann, funded by TACOM)
- Welding Control Project (Moore, funded internally)
- Shape-shifting robot (funded by VPI through a DARPA SBIR)
- WATV robot (CSOIS internally funded)
- Radar sensor project (private funding)
- Large tractor automation project (private funding)
- USASAT (CSOIS internal funding of one student)
- Foundry Control Project (Moore, funded by DOE)
- Hopping Robot Project (Berkemeier, funded by JPL/NASA)
- Swimming Robot Project (Berkemeier, funded by NSF)

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### CSRA/CSOIS Courses

- **Undergraduate Courses**
  - MAE480 (Instrumentation, Measurements), ECE3640 (Laplace, Fourier)
  - MAE510/ECE410 Control I (classical, state space)
  - MAE520 Manufacturing Automation
  - ECE/MAE530 Mechatronics (elec, lab intensive)
  - ECE/MAE530 Mobile Robots (elec, lab intensive)
- **Basic Graduate Courses**
  - MAE/ECE630 Spacecraft attitude control
  - ECE/MAE620 Linear multivariable control
  - ECE/MAE630 Nonlinear and adaptive control
  - ECE/MAE650 Robotics
- **Advanced Graduate Courses**
  - ECE/MAE750 Intelligent Control Systems
  - ECE/MAE750 Robot and Optimal Control
  - ECE/MAE750 Distributed Control Systems

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### Some Robots Built At USU

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### USU ODV Technology

- USU has worked on a mobility capability called the "smart wheel"
- Each "smart wheel" has two or three independent degrees of freedom:
  - Drive
  - Steering (infinite rotation)
  - Height
- Multiple smart wheels on a chassis creates a "nearly-holonomic" or omni-directional (ODV) vehicle

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### YangQuan Chen's background

Acting Director of CSOIS since June 2004.

Ph.D 1998. Nanyang Tech. Univ., Singapore  
1999-2000: Seagate, S' pore Science Park  
2000-present: Utah State University

**Keywords:** Dynamic systems and control (linear, nonlinear, adaptive, robust, optimal, intelligent, distributed, biological, mechatronic, biomimetic)

**Publication:** 12 granted and 2 pending US patents on HDD servomechanics, over 150 papers, over 50 industrial tech. reports, 2 research monographs (1995, 1999) and two textbooks (2002, 2004).

Now (enjoying) struggling for tenure at Utah State University (s2002). Teaching/research/service.

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### CSOIS Research Strengths

- ODV (omni-directional vehicle) Robotics
- MAS-net (mobile actuator and sensor networks)
- Iterative Learning Techniques
- Smart Mechatronics, Biomechatronics
- **Fractional Dynamic Systems and Control**

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### T1 Omni Directional Vehicle (ODV)

Maneuverability of the ODV design concept

Mobility enhancements achieved by ODV design

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### ODV On Duty in Baghdad

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

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Ten ODIS Manufactured

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

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

ODIS On Duty in Baghdad

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ThreatWATCH Concept

Sensor-carrying UAVs and UGVs assess and track the development of a hazardous plume resulting from a CBR terrorism act.

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1. Plume generating event triggers system deployment
2. Ground station crew releases UAVs to predicted plume location
3. UAVs carry sensors into the plume

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Mobile Actuator-Sensor Network (MAS-net)

NOTE - This line of research has just been funded by NSF DDDAS/SEP (Dynamic Data Driven Application Systems)

Motivation

- Efficiently deploy a group of mobile sensors to characterize the dynamically evolving diffusion boundary
- Using the same mobility platform, mobile actuators can actively control the formation of the diffusion boundary to a desired zone/shape

Application scenarios -

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MAS-net: Three Application Scenarios

- Application Scenario 1 (land): The safe ground boundary determination of the radiation field from multiple nuclear radiation sources. In this case, each networked sensor is mounted on a ground mobile robot. The mission is to determine the safe radiation boundary of the radiation field from possibly multiple nuclear radiation sources. Each robot is actuated according to spatial and temporal sensed information (radiation gradient, spatial position etc.) from more than one actuated or mobile sensors.
- Application Scenario 2 (water): The nonstatic reservoir water surface boundary determination by using sensor boats on the water diffusion source. Similar to Application Scenario 1 if the toxic diffusion source is a one-time poisoning and the diffusion is in steady state. However, the boundary may be dynamically evolving if the toxic source keeps polluting the reservoir. The actuated or mobile sensors are autonomous boats mounted with toxic chemical concentration sensors. The boats are commanded according to the spatial-temporal sensed information from more than one sensor. Furthermore, assume that some of the boats (not all of the boats) are equipped with the relevant neutralizing chemicals to make the water detoxified. By a proper design of distributed sensing and actuation control strategies, it is possible to control the zone or shape of the toxic region to reach the given desirable zone/shape. Now we have a complex distributed feedback control system that is more challenging than the networked actuators and sensors themselves.
- Application Scenario 3 (air): The safe automatic 3D boundary determination and zone control of biological or chemical contamination in the air. This scenario is similar to the above water case, but it is more complicated since 3D space must be explored. Here, the actuated or mobile sensors are unmanned aerial vehicles (UAVs) equipped with concentration detectors and anti-contamination chemical agent(s) distributors.

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4. UAV sensor data is transmitted to ground station
5. Command and control system uses sensor data to predict plume movement
6. UAVs are directed to take new measurements at new predicted plume location

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MASNET Experimental Platform (Conceptual Block Diagram)

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MAS-net platform built

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Smart Mechatronics

- Plan to play artificial muscle and some other "smart" materials. I wish to demo that **smart control of smart materials can only be achieved by using smart materials based control components.**
- Of course, seeking funding is always the most important part.
- We are expert in disturbance compensation, nonlinearity compensation etc. in smart mechatronic systems

YangQuan Chen, Dingyao Xie, and Huiyang Dou. "Fractional Calculus and Biomimetic Control" IEEE Int. Conf on Robotics and Biomimetics (ROBIO), August 22-25, 2004, Shenyang, China  
 Huiyang Dou, YangQuan Chen, and Huiyang Dou. "State-Periodic Adaptive Compensation of Coulumb and Friction in Permanent Magnet Linear Motors" IEEE Trans on Systems, Man, and Cybernetics - Part B, vol. 41, no. 1, pp. 90-98, 2011.  
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CSOIS Vision Capability

- Visual servoing, Laser servoing, Pointing system
- Dr. Lili Ma. "Vision-based Measurement for Dynamic Systems Control", PhD Dissertation, Dec. 2004. ECE Dept. of USU
- http://cc.usu.edu/~lilima

[1] Range Identification for Perspective Dynamic Systems with a Single Homogeneous Observation, YangQuan Chen, and Kevin E. Moore, International Journal of Applied Mathematics and Computer vol. 15, No. 1, 2005, Accepted.  
 [2] Rational Radial Dissection Models of Camera Lenses with Analytical Solution for Distortion Correction, Lili Ma, YangQuan Chen, and Kevin E. Moore, International Journal of Information Acquisition, vol. No. 2, pp. 135-147, June 2004.

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10 MASmotes

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ILC - iterative learning control

- US6,437,936 Repeatable runout compensation using a learning algorithm with scheduled parameters
- US6,574,067 Optimally designed parsimonious repetitive learning compensator for hard disc drives having high track density
- ILC: <http://www.csois.usu.edu/ilc/>

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CSOIS Biomechanics

- Dr Huiyang Dou offered a summer course on Biomechanics.
- Rehabilitation system, biomedical instrumentation and control.
- Bio-electrochemical sensor etc.

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Dr. Wei Ren - CSOIS New Faculty (Since Fall 2005)

- Multi-robot coordination control
- Cooperative control of UAVs
- Consensus building among networked sensors
- Guidance, Navigation and Control
- Collaborative Kalman filtering
- Mobile robots/agents

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## CSOIS Research Strengths

- ODV (omni-directional vehicle) Robotics
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## Fractional Order Dynamic Systems and Control

- "Fractional Future?" A Panel Discussion
- NSF Sponsored Joint France-US Workshop on Fractional Derivatives and Their Applications (FDTA), July 22-23, 2004, Bordeaux, France
- <http://mechatronics.ece.usu.edu/foc/>
- Fractional order dynamic systems and control (FODSC) has a good future.
  - Motivated by Swamie Westerlund's book "Dead Matter has Memory" <http://www.causal.st/book.html>
- FODSC will be as popular as "fuzzy logic" soon. (Think in-between)
  - 2003 Chicago: I shared this thinking in the first meeting of ASME "Fractional Dynamics" subcommittee

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So,

- Igor is going to give a tutorial on **fractional order calculus and its physical and geometrical interpretation**
- Concha is going to present her Ph.D. work on **fractional order controller designs (fractional order lead-lag, fractional order PI/D etc., applications)**

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## Professor Igor Podlubny

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- Prof. RNDr. Igor Podlubny, CSc. Head, Department of Information and Control of Processes, Faculty BERG, <http://www.berg.tuke.sk/~podlubny/>, 04200 Slovakia, Republic
- Podlubny, I.: *Fractional Differential Equations. An Introduction to Fractional Derivatives, Fractional Differential Equations, Some Methods of Their Solution and Some of Their Applications*. Academic Press, San Diego-Boston-New York-London-Tokyo, Toronto, 1999, 368 pages, ISBN 0125588402.
- FOC page: <http://www.tuke.sk/podlubny/fc.html>

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## Fractional Signal Processing

We stand at the turning point. With the invention of integer order calculus, dynamics can be described. With "fractional order calculus", many natural dynamic phenomena can be suitably characterized.

- Fractional differentiators/filters
- Fractional integration: ARFIMA (autoregressive fractional integral moving average), or FARIMA
- Long Range Dependence, Power Law,  $1/f^\alpha$
- RS Hurst exponent estimation
- FD (fractional dimension) estimation
- FFT (fractional Fourier transform) – TFR, Wavelet etc. are special cases. (I think)

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## Fractional order control

- 90% are PI/PID type in industry

$$u(t) = K_p e(t) + T D_c^{-\lambda} e(t) + \frac{1}{T_I} \int_0^t e(t) dt, \quad (D_c^{-\lambda} \approx_0 D_c^{-\lambda})$$

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

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## Other FOC related info

- First federal grant: NRC Twinning Grant (YangQuan Chen, Kevin L. Moore and Igor Podlubny)
- First IEEE CDC tutorial on FOC (2002, Las Vegas, Blas Vinagre and YangQuan Chen)
- Odd year – ASME DETC FDTA Symposium
- Even year – IFAC Workshop on FDA.
- NSF (PIRE) Partnership in International Research and Education.
- ASME Subcommittee on "Fractional Dynamics" (s2003)
- More at <http://mechatronics.ece.usu.edu/foc/>

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