Title: Who's Afraid of Fractional Order Laplace?

Tutorial abstract:

Fractional calculus is a powerful emerging mathematical tool in engineering, which consists of a generalization of the classical integer-order derivatives and integrals to non–integer orders. From time domain to Laplace domain, such a generalization implies computing a Laplace operator to a non-integer order, which makes it interesting for application in control engineering. Although it originated from abstract science as mathematics, further applied in chemistry, physics and biology, the concept of "non-integer Laplace operator" has gained a lot of interest from the research community in the last two decades.

With the aid of powerful computers, the complex mathematical computations are no longer a bottleneck and these emerging powerful tools are now ready to be employed in solving current problems in control engineering.

The tutorial is composed of two distinctive parts that review the most important aspects, findings and current trends in both modeling and control applications. The first part offers an introduction to fractional calculus and its numerous applications in the modeling of complex processes. The second part presents the fractional order control applications, both for the single-input-single-output, as well as for the multivariable processes. The final aim of this tutorial is to bring forward advantages and challenges of these emerging tools and raise awareness in the control engineering community.

Part 1: Fractional calculus in modeling applications

We are now in the pioneering position where clinicians with their stethoscopes poised over the healthy heart, radiologists tracking the blood flow, and physiologists probing the nervous system, are all exploring the frontiers of chaos and fractals. Two concepts are necessary to be introduced: a) chaos theory says that a very minor disturbance in initial conditions leads to an entirely different outcome; and b) fractals are self-similar structures on many or all scales (i.e. the principle of regularity and order) [1,2,3]. These topics are central concepts in the new discipline of nonlinear dynamics developed in physics and mathematics – see Figure 1.

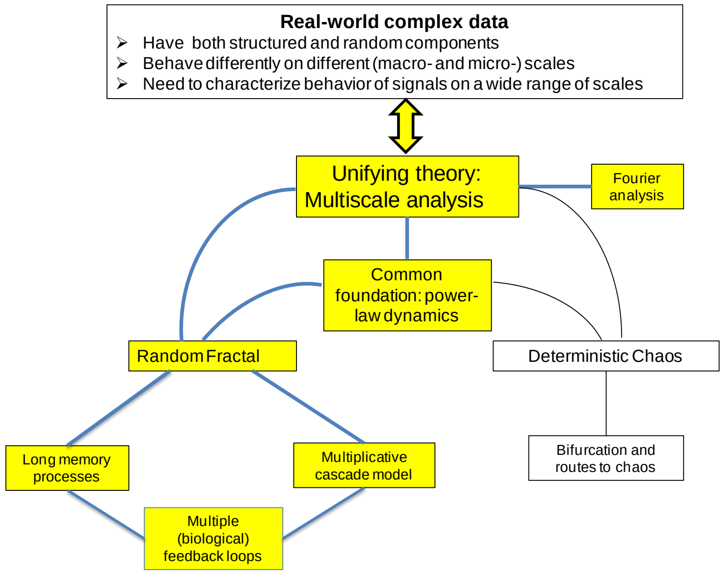

Figure 1: overview of the context and areas in which the research group will be active (tutorial will discuss applications from marked yellow boxes)

However, the most compelling applications of these abstract concepts are not in the physical sciences [4], but in medicine, where fractals and chaos may change radically long-held views about order and variability in health and disease [5]. A transition to a more ordered or less complicated state may be an indicative of disease (or equivalent a change in the nominal activity). Investigators have, only in the past 5 years or so, discovered that the heart and other physiological systems may behave most erratically when they are young and healthy (i.e. random fractal properties, power law dynamics, can be well characterized by cascaded impedance models). Counter-intuitively, increasingly regular dynamic patterns accompany aging and disease (i.e by using Fourier analysis tools one can detect these locked dynamics) [6,7,8].

The last decades have shown an increased interest in the research community to employ parametric model structures of fractional-order for analyzing nonlinear biological systems [8]. The concept of fractional-order (FO) -- or non-integer order -- systems refers to those dynamical systems whose model structure contains arbitrary order derivatives and/or integrals [9,10,11]. The dynamical systems whose model can be approximated in a natural way using FO terms, exhibit specific features: viscoelasticity, diffusion and fractal structure [12,13,14].

However, the theoretical concepts of fractals, chaos and multiscale analysis have not yet been enabled breakthrough mainly due to a lack of awareness within the research community.

Part 2: Fractional calculus in control applications

There is currently a continuously increasing interest in generalizing classical control theories and developing novel control strategies that use fractional calculus. The most commonly used method for controlling a great range of processes is the PID controller. Classical integer order PID controllers represent in fact a special case of fractional order PIDs (FO–PID). The design problem of fractional order controllers has been the interest of many authors, with some valuable works, in which the fractional order (FO) controllers have been applied to a variety of processes to enhance the robustness and performance of the control systems [15,16,17,18]. The choice of fractional order $PI^{\mu}D^{\lambda}$ controllers is based on their potential to improve the control performance, due to the supplementary tuning variables involved, μ and λ. Since the fractional controller has more parameters than the conventional controller, more specifications can be fulfilled, improving the overall performance of the system and making it more robust to plant uncertainties, such as gain and time constant changes.

Several processes exhibit varying time delays that need to be compensated robustly in order to maintain the closed loop specifications both under nominal conditions and under time delay uncertainties. Among others, the tutorial offers an elegant solution for designing fractional order PI controllers combined with Smith Predictors, for varying time delay processes. In the first part of the tutorial, the fractional order PID controller is designed based on frequency domain specifications and optimization techniques. In the subsequent part of the tutorial, the proposed method for designing fractional order PID controllers is based on time domain performance specifications—more accessible to the process engineer, rather than the more abstract notions related to the frequency domain. A second advantage of the proposed method relies on additional robustness to plant uncertainties, achieved by maximizing open-loop gain margin. The convergence problems associated with optimization techniques, previously used in fractional order controller designs, are eliminated by an iterative procedure in computing the gain margin.

Some of the most common discretization methods for fractional order PID controllers are presented [19]. A complete tutorial for identification, fractional order PI controller design for DC motor speed control, discretization and implementation procedure on an FPGA (Field Programmable Gate Array) is presented, followed by experimental results and conclusions.

Since the concept of fractional order control is very young, significant advances have been made in single-input-single-output (SISO) processes. However, in real life, many biomedical and industrial control problems are multivariable. The tutorial presents an approach to design a multivariable fractional order PI controller for systems with multiple time delays. The proposed method is simple and offers significant robustness against gain uncertainties.

The tutorial finalizes with a state-of-the-art of the existing fractional order generalizations to advanced control strategies, such as fractional optimal control [20,21], fractional fuzzy adaptive control [22], fractional iterative learning control [23], and fractional predictive control [24]. A major part of this tutorial focuses on fractional predictive control. A case study consisting in the definition of the performance specifications, controller design and results is presented. The remainder of the presentation also includes a different approach to fractional order model predictive control, in which the prediction of the process output is done using a fractional order model, rather than an integer order model.

Target audience:

The aim of this tutorial is to add to the development of fractional order calculus in the field of control engineering, in terms of identification methods, modeling and controller design. The target audience includes all young and experienced researchers who want to stay akin the latest trends in control engineering applications. The tutorial targets researchers involved in research fields that could benefit from novel approaches based on fractional order calculus, such as electrical engineering, electromagnetism, electrochemistry, thermal engineering, mechanics, mechatronics, automatic control, biology, biophysics, physics, medicine, chemical engineering, etc.

Duration: half-day tutorial (8.30-12.30 OR 14.30-18.30)

List of speakers:

Cristina I. Muresan

She received the degree in Engineering from the Technical University of Cluj-Napoca, Romania, in 2007, her master's degree in Advanced Process Control in 2009 and the Ph.D. title in 2011. She is currently lecturer at the Technical University of Cluj-Napoca, Automation Department,
Romania.
Since 2007, she has published over 30 papers and book chapters, amongst which 2 have been awarded by the Romanian government. She has been and currently is involved in 4 research grants, all dealing with multivariable and fractional order control.
Her research interests include modern control strategies, such as predictive algorithms, robust nonlinear control, fractional order control, time delay compensation methods and multivariable systems.

Clara M. Ionescu

She received the M.Sc. degree in industrial informatics and automation from "Dunarea de Jos" University, Galati, Romania, in 2003. She obtained the Ph.D. degree at Ghent University, Gent, Belgium in 2009, on identification of human respiratory system by means of fractional order models. Currently, she is a post-doc fellow in the same university, involved in several international projects, with both industrial and biomedical applications, for both identification and control purposes. Her main research interests include biomedical applications, with identification and advanced control objectives. She is the holder of the prestigious post- doctoral grant from Flanders Research Center (FWO).
She is member of the editorial board in several journals on the topic of nonlinear dynamics, fractional calculus and the guest editor of several journals on the topic of fractional calculus as an emerging tool in engineering applications.
She has published more than 200 book chapters and papers in prestigious journals and international conferences, and has 1 patent on the detection of nonlinear effects in the respiratory impedance by means of fractional order Laplace impedance models. She is also writing a book for Springer, to appear in 2013, on the interplay between fractal structure, dynamics and
She is currently leader of 2 projects supported by the Belgian Government, both dealing with fractional order modeling and nonlinear analysis of respiratory system.

For both speakers, detailed CV and list of publications can be obtained on request.

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