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HABILITATION THESIS

– ABSTRACT –

New Methods in Fractional Order Controller Design and their Practical Applications

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Fractional calculus has been first discussed in 1695 in the letters between Leibniz and L'Hospital. At the moment it was a paradox, but as Leibniz prophetically said "Some day it will lead to usefull consequences". 300 years later, after numerous findings and research on the topic, fractional calculus has finally made its mark on various domains with multiple usefull consequences. It would be unethical to not mention here the tremendous work of fractional calculus pioneers such as Abel, Liouville, Oldham, Spanier, Riemann, Sonin, Letnikov, to name just a few.

Controversy was and still is a part of fractional calculus. Current research performed by Caputo, Oustaloup, Podlubny, Chen, Machado and many others, along with the development of powerfull computing devices have facilitated the use of fractional calculus for modeling various phenomena, as well as the generalization of the classical controllers to their fractional order counterparts. Currently, fractional order systems are widely used to describe hereditary effects, with numerous applications in the infinite transmission lines, bio-medical engineering, diffusion of heat into the semi-infinite solid, radars, sonars, digital image sharpening and estimating parameters of fractional noise process, modeling viscoelastic phenomena. Fractional calculus in control systems has arised because of its numerous advantages mainly centered around the ability to enhance the closed loop performance, as well as the robustness. Numerous problems still remain unsolved, especially concerning the stability analysis of fractional order time delay systems, the approximation of generalized fractional order systems, the fractional order delay, etc. The fractional calculus community is on the brink of further expanding the usefull consequences as envisaged by Leibniz.

My research work, following the PhD title in 2011, has been centered around fractional calculus. My most **important contributions** in the field of control engineering arise from the research regarding fractional order controller (FOC) design and implementation. My work has been disseminated in highly ranked journals and prestigious conferences, with more than 150 papers published and a large number of these on fractional order related topics. During the past 10 years, I have developed several novel tuning methods for FOC, including some extensions of fractional calculus to advanced control strategies, new approaches for dealing with time delays in control systems, extension of these methods to multivariable systems (including non minimum phase and time delay processes). Along with my colleagues, we have first tackled the idea of event-based fractional order control by proposing some possible implementation strategies, testing and validation. Additionaly, since research on autotuning methods for FOC is rather scarce. we have developed some simplified methods for autotuning fractional order controllers. To deal with the problems related to the approximation of general fractional order systems, we have also developed a novel low order discrete-time approximation approach for such systems.

In terms of application domains, my research work spans over robust control of chemical plants, isotope speration columns under extreme operating conditions, vibration mitigation in civil structures and airplane wings, unstable processes (magnetic levitation). In the past 4 years, I have gradually immersed in research regarding modeling and control in biomedicine, such as FOC for drug delivery in human blood (with non-Newtonian characteristics), FOC for individualized drug delivery in the combined anaesthesia and hemodynamic systems. This has paved the way for studying fractional order modeling and control of nano-robots in drug delivery and lead to the development of an experimental unit for studying the fractional order characteristics of non-Newtonian fluids. Apart from this, we contributed to the control of the hemodynamic system, by proposing a new multivariable fractional order control approach and to the analysis, modeling and control of anesthesia components. All of these scientific achievements are related to novel research in fractional order modeling and control, also at the core of the current book. Additional research directions, and applications are reviewed in separate chapters.

The thesis is structured into two main parts, preceded by an Introductory chapter. In this chapter, the motivation of the thesis was presented along with an overview of the research, management and teaching activity.

The main focus after the doctoral studies has been directed towards the design of novel fractional order control strategies and implementation possibilities. Thus, the habilitation thesis presents an overview of some of the most important professional achievements in this field.

The first chapter presents the novel fractional order controller design approaches. The second chapter introduces the novel autotuning method for fractional order PI and PD controllers. Most of the tuning techniques for fractional order PID (FO-PID) controllers are based on a process model. However, in the absence of this model, the tuning techniques are not applicable. Auto-tuning methods should be developed, instead. Although research on tuning FO-PID controllers is quite impressive, few auto-tuning methods are discussed. In this chapter, we describe two auto-tuning methods for fractional order PI (FO-PI) and PD (FO-PD) controllers. The third chapter presents the very first developement of an event-based fractional order controller. Event-based control is based on variable sampling of the control action. This idea emerged to allow for central processing unit (CPU) resource optimization. Once the process has reached its steady state value, there is no need to for the CPU to compute the control signal every sampling period, unless a disturbance occurs or the setpoint changes. Thus, a more efficient resource allocation can be achieved by implementing an event-based control strategy. Here, the CPU computes the new control signal when an event has been triggered. This event-based control strategy is suitable especially when dealing with processes that have limited resources such as CPU, bandwidth allocation, reduced energy demand or when multiple processes share the same CPU and even when controlling systems having multiple sampling rates or systems with distributed computing. Event-based control is the efficient alternative to classical control systems when control actions or acquiring information are expensive such as in large manufacturing complexes and computer networks. Research on this topic is rather scarce. During recent years, a few papers have revealed the successful implementation of event-based control systems in industrial applications. The implementation of fractional order controllers in an event-based control system is rather difficult. This is due to the demanding task of providing for a generalized discrete-time equation of the FO controller output as a function of a variable sampling period. No research, apart from ours, explores the possibilities of implementing fractional order controllers in an event-based paradigm. As such, our team has been the first to research and publish on event-based fractional order control strategies. The event-based fractional order control is however promising since it combines the advantages of event-based implementation with those of fractional order controllers. The fourth chapter details the novel low-order discrete-time implementation method for any fractional order systems. Fractional order systems are quite versatile, with application in various disciplines, both in modeling and control. The main issue with these fractional order systems is concerned with their implementation. Numerical approximations are used, but for great accuracy these have to be of high order. The simplicity of the original fractional order system with a few parameters is lost. In order to avoid such problems, we have developed a low-order and efficient method for a direct discrete-time approximation of any fractional order systems. In this chapter we focus on a brief description of the method, defined as the Non-Rational Transfer Function approximation method, along with an illustrative example.

The main chapters 1-4 in this thesis highlight my most important research topics and findings. Apart from those mentioned, I have engaged in other topics. The purpose of this fifth chapter is to briefly describe some other research topics/applications that I have dealt with during the past ten years. The results of these interests are available in an extended version in the cited papers. Since my PhD thesis dealt with control strategies for an isotope separation column, my early research focused on developing and implementing fractional order controllers for such a chemical plant or for similar chemical units, mainly described by delay-dominant multivariable processes. The design of novel fractional order control strategies remained a permanent focus in my research career. Several novel tuning methods, apart from those detailed in the thesis, are worthy of being mentioned here, such as a new vector-based approach, a new design method based on existence conditions or the combination between fractional calculus and imaged based control. In terms of applications, fractional order control was tested and validated in numerous other domains, such as for active control of civil structures, mechatronic systems, waste water treatment plants, refrigeration units, quad rotor systems, office lighting test bench. Apart from fractional order control, offshooting research was performed in time delay compensation, predictive control methods, Internal Model Control, Smith Predictor design for multivariable time delay systems. My research also focused on novel auto-tuning methods for integer order PID controllers, such as the KC autotuner or on improving the disturbance rejection of IMC controllers.

An overview of my research in terms of biomedical applications is presented as follows. The focus is two-fold. Part of the research deals with designing controllers for the anaesthesia and hemodynamic systems. These systems are represented by highly interacting and time delay processes, which makes the controller design task challenging. A related research component deals with the modeling and controller design for a small-scale robot in non-Newtonian environment. An experimental platform has been built to resemble part of the human circulatory system. The core problem was to model and design a suitable controller for position tracking of a small-scale submersible used in targeted drug delivery.

My research work aims at developing control algorithms and new tuning methods, with a special focus on fractional order control. In my future research I will continue on this track as I plan to further improve several areas of fractional calculus in control engineering, especially regarding issues that are still in their early stage, with few research and literature available.

My focus would be to continue with the development of fractional order autotuners and a deeper analysis of fractional order event-based algorithms. Fractional order autotuners are an area that has seen less attention from the research community, although autotuning controllers would facilitate the use of fractional order control algorithms in industrial applications. A simple and straightforward design would make this controller appealing for a wide range of processes where limited data is available to produce an accurate mathematical model of the process. A simple autotuning method combined with a low-order approximation, as well as better closed loop performance and increased robustness would make such fractional order controllers more popular. Further, an event-based implementation of these controllers would make them more efficient. Joining together these two concepts might lead to even better closed loop results. To be able to implement efficiently the event-based algorithm, further analysis needs to be performed. Several improvements for the standard event-based strategies applied to integer order controllers exist that allow for even better minimization of the computational effort, both reference tracking and disturbance rejection, avoiding limit cycles and so on. To this end, these ideas can be incorporated into an event-based fractional order controller to achieve improved performance. An anaylsis regarding other implementation methods is also viable for further research. On the longer term, I wish to develop some toolboxes for automatic design of fractional order controllers, using the autotuning concepts already developed and those planned for the future.

As a near future goal, I plan to further extend my research regarding fractional order control of the general anaesthesia-hemodynamic systems. My ongoing research in this area is concerned with the development of a fractional order model with variable parameters to fit experimental data collected from ICU patients. The purpose of this research is to produce a generlized model for pain, to complete the global anaesthesia-hemodynamic system. In order to efficiently control this system, I plan to develop fractional order controllers that are robust to time delay variations by utilizing a special cost function that minimizes the error and at the same time optimizes the drug dosage.

The *objectives* of my future research, as well as teaching activity are briefly stated as follows:

- Continuous adaptation of the teaching material to include recent ideas in control engineering, as well as new teaching methods. I am planning to use interactive tools to teach students the effect of various controllers and their parameters in terms of reference tracking, disturbance rejection, connection between frequency and time domain tuning methods and closed loop performance
- Develop some new laboratories/ project classes that focus on practical applications. Ideally, these new classes would be suitable for online teaching
- Financial support for young researchers to pursue master and PhD degrees and engage in research
- Attract funding for my research (both on national and international scale). For this, I plan to participate in international projects as a researcher and later submit grant proposals as a principal investigator. In the near future, I plan to improve, update and resubmit my research proposals for the next PCE/ PED national calls, Marie Curie Fellowship and join colleagues from Belgium, Portugal, Poland, Hungary, Turkey in COST actions and EU programms.
- Organize special issues and sessions