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**Plan of Lectures**

**Objectives of lectures**

The aim of these lectures is to give an initial feeling of what fractional calculus and fractional-order control can realize, and in particular to provide basic knowledge elements that allow understanding the possibilities offered by fractional calculus in the field of automatic control. The delivered information can be useful to start a successive in-depth analysis of the fractional calculus tools available for mathematical modelling and control. In particular, the attendance should be able to understand and use some methods for systematic design, tuning and implementation of fractional-order controllers, which will be shown not only by theoretical elements but also by results of simulation and experiments of the developed controllers.

**General contents**

The contents of the lectures will be focused on the application of fractional calculus to control systems engineering, with special emphasis on modelling and control problems. Both techniques for developing/identifying models will be described and innovative control strategies will be shown. In all cases, the mathematical tools are based on differentiation or integration of non-integer order. Examples of application will be the control of electro-mechanical systems, industrial drives, and parts of automotive engines and mechatronics systems.

In more details, the lectures will describe techniques for developing non-integer-order models and methods for designing, tuning and implementing fractional-order controllers that are controllers in which the classical integration or differentiation of the error is replaced by an integration or differentiation of non-integer (fractional) order. A synthesis of the covered topics is the following:

* Introduction to fractional calculus and to non-integer-order systems, often named fractional-order systems
* Modelling and identification of non-integer-order systems
* Controllers of non-integer order, PIλDμ-controllers, fractional-order controllers: historical perspective and review, design, tuning, implementation
* Applications and case-studies
* Topics for further investigation, projects, thesis

The contents of the lectures can be organized in the five parts that are specified below. However, according to the available hours, some parts can be synthesized, grouped and delivered together at the same time, continuously, for a long teaching time slot. Otherwise, some parts can be extended and split in two or more teaching slots and generate more lectures.

***Part # 1***

This lecture introduces the attendance to fractional calculus in a simple way. This field is today exploding and attracting interest of many researchers and practitioners, but it originally started from scientists and mathematicians of the past. Most people refer to a famous exchange of letters between Leibniz and de L’Hôpital that regarded the meaning and usefulness of derivatives with non-integer orders, e.g. the order 0.5. After that, many contributions emerged and let the field grow. After an historical review and background, basic mathematical and numerical tools will be shortly explained in this lecture. Moreover, the paradigm of fractional calculus will be illustrated by examples, by solutions of mathematical and engineering problems taken from the past, and also by discussing the “philosophical” and scientific motivation that can be very useful to solve current science and engineering problems. Some special attention will be given to properties of fractional systems like long-term memory. Finally, interesting examples of application of fractional calculus in several fields and disciplines will be given as well as reference to literature for further study.

***Part # 2***

This other lecture is to show some applications of fractional calculus to mathematical modelling and identification. It is well-known that the best model is always different from the real phenomenon, process, plant, object or, in general, dynamical element which is under analysis and must be represented. But here it is shown as models based on fractional differentiation or integration can be, in many cases, closer to reality or more useful for engineering purpose. The intention is not to give an exhaustive list and overview of successful studies. However, the lecture will start from some famous examples in various fields (mathematics, viscoelastic materials, electrical circuits, etc.) and will arrive to particularly interesting, recent results in modelling and identification of fractional-order systems. The message of this lecture is to consider fractional calculus tools as useful means for new investigation of systems and processes.

***Part # 3***

This lecture is focused on specific, recent results on modelling and identification of fractional-order systems, mainly in the field of mechatronics and automotive systems, that are of particular interest for industry. Namely, mathematical modelling, identification, estimation, optimization are important steps to develop advanced and efficient model-based approaches for control. An application to modelling for control of communication will be also considered. The lecture will consider three cases: 1) Modelling the high-pressure fluid-dynamic flows in an electro-injector by a fractional-order transfer function; 2) Modelling the high-pressure fluid-dynamic flows in an electro-injector by a fractional-order partial differential equation; 3) Modelling the multimedia streaming of 3D stereoscopic videos. The models shown in this lecture can be the basis for further developments and investigation in the considered researches and can also inspire application of fractional calculus in other contexts.

***Part # 4***

This lecture introduces the attendance to the specific sector of fractional-order control. Firstly, explanations are given to motivate the use of fractional calculus in control systems engineering. Why we should, for example, replace classical integer-order integral and derivative actions of standard PID controllers by non-integer-order integration and differentiation? An overview of seminal ideas and works by famous scientists will be given (Bode, Manabe, Tustin, Yoshida, etc.) and then more recent achievements in control will be illustrated. Secondly, the benefits and opportunities available by fractional-order controllers will be shown with particular emphasis on industrial applications, without neglecting the requirements and limitations for an application at reduced cost in a complex environment. The final message of this lecture is that fractional-order controllers must be considered as an opportunity in-between classical PID controllers and different but more complex controllers, a way to take advantage of non-integer (fractional) orders to improve robustness, at limited cost as required by many engineering applications, but obviously they are not a *panacea* to solve each problem in the desired way.

***Part # 5***

In this lecture, fractional-order controllers will be shown “in action” on real case-studies and applications that were recently considered. Design and tuning methods will be described in detail as well as the necessary implementation techniques. It will also be shown that some underlying principles or ideas for designing fractional-order controllers come from well-known control objectives. Sometimes the design methods and specifications take inspiration from and improve classical control techniques that are very popular among practitioners. In this lecture, To better illustrate the derived benefits, the fractional-order controllers will be applied to benchmark plant mathematical models that are usually considered for many industrial control problems. The lecture will also show comparisons to standard PI/PID controllers that are designed by classical and popular methods in industrial applications. To this aim, performance and robustness indexes will be considered. In particular, three control problems will be considered to show the real application of fractional-order controllers: 1) Control of DC servomotors; 2) Control of industrial drives; 3) Control of common rail pressure in a Compressed Natural Gas engine.