

Towards Intelligent Process Systems: Modeling and Advanced Control Across Biomedical and Environmental Processes

-- Thesis Summary --

This habilitation thesis presents a comprehensive overview of scientific, academic, and professional contributions in the field of control engineering, with a strong interdisciplinary orientation. The central focus is on the modeling and advanced control of complex dynamic systems in biomedical, pharmaceutical, and environmental domains—areas with high societal impact and increasingly stringent performance, safety, and sustainability requirements. The research integrates rigorous theoretical developments in predictive and adaptive control, state estimation, hybrid systems, and sensitivity analysis with real-world applications that demand robust, reliable, and energy-efficient solutions.

A major line of work has addressed the challenge of personalized closed-loop control for intravenous anaesthesia. In collaboration with academic and clinical partners, advanced control strategies were developed to accommodate the nonlinear pharmacokinetics and pharmacodynamics of anaesthetic agents. This research includes multiparametric model predictive control, estimation-enhanced predictive control, and hybrid control frameworks based on piecewise-linearization of pharmacological response models. The proposed controllers were evaluated through simulation studies and benchmark comparisons, demonstrating significant potential for individualized and safe drug administration in real-time clinical settings. These efforts contribute to the broader vision of intelligent, autonomous drug delivery systems.

In pharmaceutical manufacturing, the research has focused on model-based control of continuous processes, particularly in the context of quality-by-design and digital transformation initiatives. An evaporation process was developed and experimentally implemented in collaboration with Eli Lilly and Texas A&M University, supporting the design of predictive control algorithms tailored for nonlinear, constrained systems. In parallel, collaboration with Purdue University enabled the development and testing of advanced control strategies on a pilot-scale rotary tablet press, providing valuable experimental insights into process variability, measurement uncertainty, and actuator limitations. The work also addressed global sensitivity analysis, embedded implementation of multiparametric controllers, and supervisory control architectures. These activities were further reinforced through national and international research projects centered on pharmaceutical digitalization, process integration, and intelligent quality control.

Further contributions were made to the modeling and control of bioprocesses in tissue engineering. In partnership with the University of Surrey and East China University of Science and Technology, computational fluid dynamics (CFD) models of perfusion bioreactors were used to analyze flow distribution, oxygen delivery, and shear stress in 3D scaffold environments. Based on these models, control strategies were developed to regulate key process variables such as oxygen concentration and pressure drop, which are critical for uniform tissue growth. The integration of control theory with biological process modeling advances the design of controllable, scalable

tissue engineering platforms and demonstrates the versatility of control engineering principles in emerging biomedical applications.

In the environmental domain, the research focused on the energy-efficient control of biological treatment stages in wastewater treatment plants (WWTPs), with particular attention to aeration systems. Given that aeration accounts for the majority of energy consumption in WWTPs, predictive and adaptive control strategies were developed to regulate dissolved oxygen concentrations under highly variable influent conditions. These contributions were supported by Romanian national research projects and involved the development of dynamic models, sensitivity analysis, and hierarchical control strategies tested in simulation and pilot-scale environments. The proposed methods showed improved energy efficiency and robustness compared to traditional operation.

These scientific achievements are underpinned by a sustained academic trajectory that includes teaching and mentoring across multiple international institutions. With experience in over six countries and on three continents, courses have been delivered in diverse academic systems and cultural contexts, ranging from top-tier institutions in the UK and the US to major universities in Asia and Eastern Europe. This exposure has fostered a deep understanding of cross-cultural educational dynamics, pedagogical flexibility, and student-centered teaching philosophies. Supervision of student projects, active involvement in curriculum development, and participation in joint academic initiatives further support a holistic academic profile.

Looking ahead, the research vision is to further develop advanced modeling and control frameworks tailored to interconnected, data-rich process systems. Emphasis will be placed on energy optimization, autonomy, and resilience in both industrial and biomedical systems, as well as on the integration of digital technologies to support decision-making and sustainability. Through interdisciplinary collaboration and applied innovation, the aim is to contribute to the next generation of intelligent, sustainable process systems at the interface of engineering, health, and environmental sciences.