

AI-Enhanced Robust Control of Nonlinear Systems Using Fractional-Order Methods and Data-Driven Uncertainty Quantification

AI-rozšířené robustní řízení nelineárních systémů s využitím neceločíselného řádu a datově založené kvantifikace nejistot

(Pozn: povinně uvést název i v české jazyce)

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Abstract:

This dissertation will focus on the development of novel intelligent robust control methods for nonlinear dynamical systems combining artificial intelligence, fractional-order approaches, and modern robust control techniques. The motivation stems from the fact that mathematical models of real-world technical systems often involve significant uncertainties that are difficult to describe accurately, while conventional model-based control methods may become sensitive to parameter variations, unmodelled dynamics, and external disturbances under such conditions. At the same time, fractional-order approaches can provide an effective means of describing and predicting dynamical phenomena with memory effects, as well as an additional degree of freedom in control design, thereby offering new possibilities for the development of the overall control methodology.

The main objective of the dissertation will be to develop a methodology in which artificial intelligence techniques are primarily used for data-driven identification of unknown or difficult-to-model parts of the system dynamics, estimation of their variations, and quantification of prediction uncertainty. The methodology will also investigate the appropriate use of fractional-order models and methods within different stages of modelling, identification, prediction, and control. The obtained information will subsequently be incorporated into the design of a robust control system. A fundamental principle of the proposed approach will be to separate the learning and adaptation mechanisms from those responsible for ensuring the robustness and stability of the closed-loop control system. The AI model will therefore not act as an uncontrolled substitute for the feedback controller, but rather as a means of obtaining additional information about the system dynamics and its associated uncertainties.

The research will address the design and analysis of robust control methods based, for example, on fractional-order PI/PID control, robust state-space control, H_∞ methods, LMI-based formulations, or robust model predictive control, where fractional-order concepts may be employed directly in the controller as well as in the system model or prediction mechanism. Particular attention will be paid to adaptive adjustment of controller parameters using operating data and the current estimate of system uncertainty. Modern statistical approaches to predictive uncertainty quantification, such as conformal prediction, may also be investigated and integrated with robust stability and trajectory-tracking conditions.

The theoretical part of the dissertation will focus primarily on the formulation of conditions for stability, robust performance, and limited sensitivity to AI model errors and dynamic uncertainties. The relationship between the accuracy of the data-driven model, the nature and magnitude of the estimated uncertainty, and the resulting properties of the closed-loop control system will also be investigated. Particular attention will be paid to the influence of the selected fractional order and the use of fractional-order operators on the properties of the model, prediction, and resulting control performance. An important part of the research will be the development of methods that incorporate model uncertainty directly into the robust control design while preserving the practical implementability of the resulting control algorithms.

The proposed methods will first be evaluated on selected nonlinear models and subsequently validated experimentally on an appropriate real-world mechatronic system. The evaluation will consider control performance, robustness to parameter variations, unmodelled dynamics, external disturbances, and measurement noise, as well as computational complexity and real-time implementation requirements. The expected outcome of the dissertation is a general methodology for combining data-driven learning with robust control of nonlinear systems through the use of fractional-order approaches in modelling, prediction, and/or control, exploiting the adaptability of artificial intelligence methods while preserving analytically justifiable properties of the closed-loop control system.

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