Safe Exploration and Exploitation in Nonlinear Processes: A Probabilistic Control Framework

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Abstract: This presentation introduces a principled and comprehensive framework for safe exploration and exploitation in partially unknown nonlinear dynamic processes. It addresses a critical challenge in learning-based control: gathering informative data for system identification while maintaining strict adherence to physical constraints and closed-loop stability. The proposed methodology, as sketched in Figure 1 integrates Gaussian Process (GP) inference with probabilistic control invariant sets to enable safe data collection without violating operational limits. A dual-control strategy is employed, combining an excitation controller for data gathering with a safety filter that prevents destabilizing commands. The exploration-exploitation trade-off is formalized through an automated selection of optimal evaluation points while allowing operators to specify exploration directions through an adjustable range of exploration, a significant step toward human-centered learning control systems. Key contributions include extending classical invariant set theory to probabilistic settings, developing acquisition functions for safe sampling, and providing a practical framework compatible with industrial deployment. The methodology is validated through synthetic 2D nonlinear systems and a multi-tank industrial process, confirming its applicability to realistic multi-input, multi-output nonlinear systems and demonstrating that probabilistic safety guarantees maintain high confidence in constraint satisfaction throughout the learning phase. Despite its strengths, the framework faces challenges, including sensitivity to hyperparameter tuning, computational overhead during online retraining, and limited treatment of unmodeled disturbances. Future work will address these limitations through adaptive hyperparameter strategies, computationally efficient GP algorithms, and extended disturbance models. Overall, this work bridges the gap between theoretical control guarantees and practical data-driven learning, providing a robust foundation for safe, principled exploration in safety-critical industrial applications where trust, stability, and real-world deployability are essential.

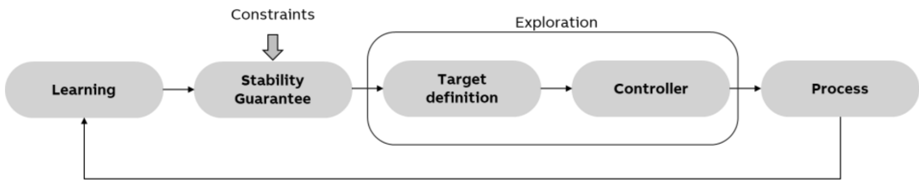

Figure 1 Block diagram of the proposed safe exploration approach

Keywords: Learning-based control, System stability, Data-driven control.

REFERENCES

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