

KERNELIZED LEARNING METHODS IN AUTOMATIC CONTROL

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par

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Lausanne, EPFL, 2022



Besides this'll be easy with the two of us.

We've got science on our side.

— Bonnibel Bubblegum

Acknowledgment

Pausing for a moment to recognize others' contributions to your personal development makes you realize how life unfolds in intertwined, intricate ways.

Writing this thesis and defending my PhD would not have been possible if it were not for professor Colin Jones. I am sincerely grateful for your having invited me to join LA back in 2018, for your having given me the opportunity to develop my work in such a bright research environment. Your always-positive and light-weight approach to work was much appreciated, along with your talent to constantly bring forth new ideas. Thank you for all, truly.

Here's to all other professors and the defense committee...

LA is a great place to do your PhD at. The group is diverse and amicable, people are intellectually bright, and the overall atmosphere is on point. I am indebted to Mr. Harsh Ambarishkumar Shukla for being an awesome friend, for all the long talks about every possible subject one could imagine, most often accompanied by one drink or two. Throughout this journey, Yingzhao Lian has been my PhD twin, always making provocative research remarks and sharing his wine and food expertise with remarkable excitement. Paul Scharnhorst's contributions were mainly in two forms: being a key collaborator with whom the main theoretical results covered herein were derived, and constituting the Bienne-Nêuchâtel alliance that organized quite a number of dinners ending in Qwirkle matches. My time spent at the office would have not been as interesting without Mustafa Turan, for listening to my never-ending semi-philosophical blabbers and for being always ready to talk about the latest and greatest recipe. Cite Pulkit, Alessio, Sohail, Philippe, Clara, J1, J2,

The foremost group is certainly my fiancée and my family. I have an immense respect for my parents who have risen their children ensuring the absorption of important core values, including mutual respect, fairness and empathy. To this day, I look up to you. *Muito obrigado por tudo*, Bruno, Erica, Fabio and Renato. Since we met,

I am grateful for having met truly special people during my Bachelor studies who encouraged me to go beyond what seemed to be our limits at the time. In particular I wish to thank prof. Ruben Barros Godoy who played a fundamental role in my early academic years.

Bienne, September 5, 2022

Emilio Tanowe Maddalena

Preface

A preface is not mandatory. It would typically be written by some other person (eg your thesis director).

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Lausanne, 12 Mars 2011

T. D.

Abstract

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Zusammenfassung

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Résumé

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1 Introduction

A non-numbered chapter...

1.1 Outline and Contribution

1.2 Publications

The subsequent chapters of this dissertation were based on the following publications:

- E. T. Maddalena, Y. Lian, and C. N. Jones. "Data-driven methods for building control—A review and promising future directions." *Control Engineering Practice* 95 (2020): 104211.
- E.T. Maddalena, P. Scharnhorst, and C. N. Jones. "Deterministic error bounds for kernel-based learning techniques under bounded noise." *Automatica* 134 (2021): 109896.
- P. Scharnhorst, E.T. Maddalena, Y. Jiang, and C. N. Jones. "Robust Uncertainty Bounds in Reproducing Kernel Hilbert Spaces: A Convex Optimization Approach." *arXiv*.
- E. T. Maddalena, P. Scharnhorst, Y. Jiang, and C. N. Jones. "KPC: Learning-based model predictive control with deterministic guarantees." *Learning for Dynamics and Control*. PMLR, 2021.
- E. T. Maddalena, S. A. Müller, R. M. dos Santos, C. Salzmann, C. N. Jones. "Experimental Data-Driven Model Predictive Control of a Hospital HVAC System During Regular Use." *Energy and Buildings*: 112316 (2022).

Works developed during the course of this PhD that are related to the thesis, but not

discussed herein include:

- E. T. Maddalena, M. W. F. Specq, V. L. Wisniewski, and C. N. Jones. "Embedded PWM predictive control of DC-DC power converters via piecewise-affine neural networks." *IEEE Open Journal of the Industrial Electronics Society* (2021): 199-206.
- E.T. Maddalena, and C. N. Jones. "NSM converges to a k-NN regressor under loose Lipschitz estimates." *IEEE Control Systems Letters* 134 (2020): 880-885.
- E. T. Maddalena, C. G. S. Moraes, G. Waltrich, and C. N. Jones. "A neural network architecture to learn explicit MPC controllers from data." *IFAC-PapersOnLine* (2020): 11362-11367.
- A. Chakrabarty, E. T. Maddalena, H. Qiao, and C. Laughman. "Scalable Bayesian optimization for model calibration: Case study on coupled building and HVAC dynamics." *Energy and Buildings* 253, 111460
- E. T. Maddalena, and C. N. Jones. "Learning non-parametric models with guarantees: A smooth Lipschitz regression approach." *IFAC-PapersOnLine* (2020): 965-970.
- U. Rosolia, Y. Lian, E. T. Maddalena, G. Ferrari-Trecate, and C. N. Jones "On the Optimality and Convergence Properties of the Iterative Learning Model Predictive Controller." *IEEE Transactions on Automatic Control*.
- L. di Natale, Y. Lian, E. T. Maddalena, J. Shi, and C. N. Jones "Lessons Learned from Data-Driven Building Control Experiments: Contrasting Gaussian Process-based MPC, Bilevel DeePC, and Deep Reinforcement Learning." *arXiv*.

2 Safely learning with kernels

In this chapter, we discuss the problem of learning and elucidate what viewpoint will be taken to tackle it. Next, novel results are presented concerning uncertainty estimation in a kernelized setting. Finally, some examples are given to illustrate the general use of the theory.

2.1 The problem of learning

At its core, learning refers to the process of *gathering information* and using it to *improve one's knowledge* about the subject or phenomenon under study. The standing assumption here is then clearly that a link is in place, tying information and phenomenon together, even if such link is partially corrupted.

Information comes in many science fields in the form of data, samples, sometimes referred to as examples. In modern machine learning, people study a number of rather abstract subjects ranging from the traits that distinguish images of muffins and chihuahuas, to the link between passengers' features and their survival likelihood in case of a ship sinking event. The mathematical formalism often used to study the link between examples and these phenomena is statistics. This choice is convenient because it can describe the possible non-determinism of outcomes through the concepts of distributions and samples; and because it provides us with plenty of tools to carry out learning, i.e., improve our knowledge about the phenomenon through the samples at hand. In this chapter, we will however adopt a different standpoint to study and tackle the problem of learning, which is, as we will later argue, more aligned with the ways control engineers are taught to see physical systems. This standpoint is the one offered by approximation theory.

Statistical learning and approximation theory are not in opposition. Indeed, we can define the function of interest as the conditional Temlyakov (2008), perhaps talk about

Belkin's work linking the two and advocating for using the approximation lenses.

Definition 1 (Kernel) *Given an arbitrary non-empty set Ω , a kernel k is any symmetric function of the form*

$$k : \Omega \times \Omega \rightarrow \mathbb{R} \quad (2.1)$$

Talk about kernels (can be seen as a library of non-linearities) and show examples of kernels. Say however, we'll restrict our attention to a specific class of them.

Definition 2 (Kernel matrix) *Given finite set of inputs $X = \{x_1, \dots, x_N\} \subset \Omega$, the $N \times N$ matrix K_{XX} with entries $[K_{XX}]_{ij} = k(x_i, x_j)$ is called the kernel matrix of k associated with the points X .*

Definition 3 (Mercer kernel) *A kernel function k is called a Mercer kernel if for any finite subset of points $X \subset \Omega$, its kernel matrix is positive definite $K_{XX} > 0$.*

2.2 The problem of uncertainty quantification

Theorem 1 *This is some truth*

Bla bla

A An appendix

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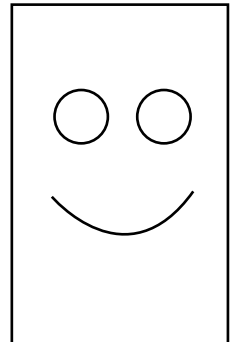
Temlyakov, V. (2008). Approximation in learning theory. *Constructive Approximation*, 27(1):33–74.

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Special experience : Europe work experience

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Personal profile:

As a Bachelor of Business Administration and after obtaining first relevant international work experience within the hospitality industry, I am now ready to take on new responsibilities to further my professional career. My key strengths include strong analytical and logical skills, an eye for detail, communication and interpersonal skills.
I enjoy working in a team and help others progress. At the same time I work well independently.
As a highly motivated and driven individual I strive on taking up challenges.

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Sports

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Mar 04 - Ongoing	<p>Assistant Manager (Rooms Division/Food & Beverage)</p> <p>Hotel Atlantic Kempinski Hamburg www.kempinski.com 5 star business hotel, part of Leading Hotels of the World 412 guest rooms, large function facilities, 3 food & beverage outlets</p> <p>Optimization of bar procedures, reinforcing SOPs</p> <p>Developing & implementing promotions</p> <p>Responsible for day-to-day operations</p> <p>Optimization and streamlining of housekeeping and laundry procedures</p> <p>Implementation of new SOPs</p> <p>Analyzing monthly reports for rooms division performance and sub departments</p>
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References:

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