The ERNSI workshop 2023 – Book of abstracts

24–27 September

Stockholm, Sweden

kth.se/ernsi2023

Contents

About

ERNSI

Welcome to the 2023 workshop of the European Research Network on System Identification (ERNSI). The ERNSI 2023 workshop takes place from Sunday 24 until Wednesday 27 September 2023 at Ersta Hotell och Konferens .It is organized by the Division of Decision and Control Systems, School of Electrical Engineering and Computer Science.

Scientific committee

Marion Gilson-Bagrel, Université de Lorraine

Martin Enqvist, Linköping University

Håkan Hjalmarsson, KTH

Cristian Rojas, KTH

Bo Wahlberg, KTH

Organizing committee

Håkan Hjalmarsson, KTH

Cristian Rojas, KTH

Martin Enqvist, Linköping University

Bo Wahlberg, KTH

Local organizing team

Annica Johannesson

Annika Wendell

Moa Hörnquist

Useful information

- The venue for the workshop is Ersta Hotell och Konferens, Erstagatan 1K, Stockholm
- Talks will be held in Bringsalen in the main building
- Poster sessions will be held in Norrbysalen in the main building. Posters will be available throughout the workshop
- Lunches and dinners (except Tuesday, see below) will be offered at Ersta terrass (the building towards the sea, Erstagatan 1N)
- The conference dinner on Tuesday September 26 will be held in Bringsalen and Norrbysalen
- WiFi: Choose *Ersta Guest* and approve the conditions

Excursion – Social Program

Tuesday September 26: Ghost Walk in the Old Town. At **15:00** there will be a guided tour in the Old Town starting at Järntorget 84, Gamla stan (Old Town), next to the statue of Evert Taube (one of Sweden's most respected musicians of all times). The tour is 90 minutes. Bring strong nerves!

Tuesday September 26: Banquet dinner. At **19:00** there will be a three course dinner at Bringsalen and Norrbysalen

Timetable

IS: Invited Speaker. CT: Contributed Talk.

Sunday 24 September

17:00-20:00		Registration at Ersta Hotell & Konferens	
20:00-22:00		Dinner at Ersta Terrass	

Monday 25 September

08:50-09:00		Welcome remarks	
09:00-10:00	IS	**Florian Dörfler** ETH Zürich	Data-Driven Control Based on Behavioral Systems Theory
10:00-10:30		Poster Highlights 1	
10:30-10:45		Coffee Break	
10:45-11:45		Poster Session 1 and Coffee Break	
11:45-12:15	CT	**Alessandro Chiuso** University of Padova	Data Driven Control - the thin line between model based and model free
12:15-12:30		Discussion	
12:30-14:00		Lunch at Ersta Terrass	
14:00-15:00	IS	**Alexandre Proutiere** KTH	Finite-time Analysis of Linear System Identification: Sample Complexity Lower Bounds and Optimal Algorithms
15:00-15:30		Poster Highlights 2	
15:30-16:45		Poster Session 2 and Coffee Break	
16:45-17:45	IS	**Vikram Krishnamurthy** Cornell University	Social sensing and inverse reinforcement learning
19:00		Dinner at Ersta Terrass	

Tuesday 26 September

08:50-09:00		Welcome remarks	
09:00-10:00	Survey	**Daniel Gedon** Uppsala University	Deep networks for system identification: a survey
10:00-10:30	CT	**Paul Van den Hof** Eindhoven University of Technology	Identification of local models in interconnected systems – confounding variables, data-informativity and MATLAB toolbox
10:30-11:45		Poster Session and Coffee Break	
11:45-12:15	CT	**Mingzhou Yin** ETH Zürich	Error Bounds for Kernel-Based Linear System Identification with Unknown Hyperparameters
12:15-12:30		Discussion	
12:30-14:00		Lunch at Ersta Terrass	
15:00-16:30		Ghost Walk. Start at Järntorget 84 in Gamla Stan (next to the statue of Evert Taube)	
19:00		Dinner at Bringsalen and Norrbysalen	

Wednesday 27 September

08:50-09:00		Welcome remarks	
09:00-09:30	CT	**Timothy Rogers** University of Sheffield	A Bayesian View on Stochastic Subspace Identification with Extension to Statistical Robustness
09:30-10:00	CT	**Gerben I. Beintema** Eindhoven University of Technology	Meta-state-space learning: A Novel Approach for the Identification of Stochastic Dynamic Systems
10:00-10:30	CT	**Mohammad Khosravi** Delft University of Technology	Representer Theorem for Learning Koopman Operators
10:30-11:15		Coffee Break	
11:15-11:45	CT	**Matteo Scandella** Imperial College London	Kernel Methods for identification of nonlinear systems
11:45-12:15	CT	**Tomas McKelvey** Chalmers University of Technology	Radar platform tracking for airborne bistatic systems
12:15-12:30		Discussion	
12:30-14:00		Lunch at Ersta Terrass	

Poster session 1

1. **Omar Arahbi**, Fractional modeling and impedance model parameters identification of Lithium-ion batteries
2. **Robert Bereza**, Towards scalable identification of non-linear differential-algebraic equations with process disturbances
3. **Sarthak De**, Global identifiability of parameterized nonlinear dynamical models
4. **Michael Döhler**, High dimensional data reduction in modal analysis with stochastic subspace identification
5. **Stefanie Fonken**, Local identification in dynamic networks using a multi-step method
6. **Anubhab Ghosh**, DeepBayes - an estimator for parameter estimation in stochastic nonlinear dynamical models
7. **Rodrigo González,** Identification of linear state-space models subject to truncated Gaussian disturbances
8. **Szymon Gres**, Parameter-state estimation for mechanical systems with small model errors
9. **Noël Hallemansa**, Electrochemical impedance spectroscopy beyond linearity and stationarity
10. **Taleb Hamdan**, Control of calendering process, an initial step in tire manufacture
11. **Jiabao He**, Non-asymptotic identification of Markov parameters using weighted least-squares
12. **Xin He**, A pipeline for analyzing large-scale time-course bulk mRNA data
13. **Yue Ju**, Asymptotic theory for Stein's unbiased risk estimation and generalized cross-validation hyper-parameter estimators
14. **Hugo Koide**, Robust adaptive filtering methods for online mass estimation of electric vehicles
15. **Krzysztof Kowalczyk**, Learning with guarantees for multi-agent systems
16. **Braghadeesh Lakshminarayanan**, Parameter estimation: Simulation driven and privacy preserving approaches
17. **Francois Lamoline,** Gene expression modelling from single-cell data using optimal mass transport
18. **Jimei Li**, Lithium-ion battery identification through online concurrent state and parameter estimation
19. **Yuhan Liu**, Efficient Bayesian learning of Gaussian process state-space models with probabilistic stability guarantees
20. **Inês Lourenco**, Learning from interactions: Beliefs, policies, and rewards
21. **Stefano Magni**, Toward inference of gene regulatory networks from single-cell RNA-sequencing data by the chemical master equation and the chemical Langevin equation
22. **Gabriel Maik**, Cyclostationarity in a loop?

Poster session 2

23. **Magnus Malmström**, Multimodal representation of the uncertainty of the prediction from neural networks

24. **Per Mattsson**, On the regularization in DeePC

25. **Mirko Mazzoleni**, Characterization of the identification variance of kernel-based models with randomized approaches and its use in robust control and fault diagnosis

26. **Jared Miller**, Frequency-domain system identification via sparse rational optimization

27. **Sarvin Moradi**, Output error port-Hamiltonian neural networks

28. **Ilja van Oort**, SYSDYNET: MATLAB app and toolbox for system identification in dynamic networks

29. **Javad Parsa**, Coherence-based input design for nonlinear systems

30. **Antônio Ribeiro**, Regularization properties of adversarially-trained linear regression

31. **Hans van Rooij**, Exploring the critical values of multivariate polynomial optimization problems in system identification applications

32. **Fahim Shakib**, Parameterisation of a family of neuralODEs optimally fitting steady-state data

33. **Bowen Song**, Do we need models for control? A system theoretic study of data-driven policy iteration

34. **Luuk Spin**, Instrumental variables for direct data-driven control

35. **Koen Tiels**, Control variates for multivariate truncated probability density functions with application in system identification

36. **Freja Vandeputte**, Parametric estimation of fractional order impedance models to study battery aging

37. **Lukas Vanpoucke**, Globally optimal misfit identification of multidimensional difference equations

38. **Amedeo Varano**, ROVA, a practical and parsimonious Volterra model

39. **Christof Vermeersch**, Using the (Block) Macaulay Matrix in the Chebyshev Polynomial Basis

40. **Prabhu Vijayan**, Demonstrating equivalence between PNLSS and Volterra models for some SISO block-oriented models

41. **Johanna Wilroth**, Mapping EEG measurements to the brain activation location

42. **Rebecka Winqvist**, Optimal transport for correctional learning

43. **Krzysztof Zając**, Measurement embedding for transformer-based system identification

44. **Stefanie Zimmermann**, On estimating frequency response functions of a 6-axis robot

List of Abstracts – Talks

Monday September 25

Data-Driven Control Based on Behavioral Systems Theory

Florian Dörfler

ETH Zürich

We consider the problem of optimal and constrained control for unknown systems. A novel data-enabled predictive control method is presented that computes optimal and safe control policies. Using a finite number of data samples from the unknown system, our method uses a behavioral systems theory approach to learn a non-parametric system model used to predict future trajectories. To cope with nonlinearities and stochasticities, we propose salient regularizations to our problem formulation. Using techniques from optimal transport and distributionally robust optimization, we prove that these regularization indeed robustify our method. We show that, in the case of deterministic linear time-invariant systems, our method is equivalent to the widely adopted model predictive control, but it can also outperform subsequent system identification and model-based control. We illustrate our results with nonlinear and noisy simulations and experiments from robotics, power electronics, and power systems.

Data Driven Control - the thin line between model based and model free

Alessandro Chiuso

University of Padova

In this presentation I will discuss an optimal, receding horizon, predictive control problem in a data driven context. The optimal solution will be derived, in a Bayesian framework, under very mild high-level assumptions on the unknown data generating mechanism. It will be shown that well known procedures recently introduced in the literature such as DeePC/γ-DDPC and their variants, where regularization is introduced ad-hoc to counter the effect of noise, are suboptimal special cases of our procedure. The Bayesian framework provides a convenient mean to link so called model-free and model-based procedures.

Finite-time Analysis of Linear System Identification: Sample Complexity Lower Bounds and Optimal Algorithms

Alexandre Proutiere

KTH Royal Institute of Technology

This talk is based on joint work with Yassir Jedra (KTH). We survey recent advances in the finite-time analysis of linear system identification. This analysis is performed in the so-called fixed-budget and fixed confidence settings. In the fixed budget setting, the learner aims at estimating the state transition and the state-action transition matrices from a random system trajectory of fixed length, whereas in the fixed confidence setting, the learner further controls the length of the observed trajectory – she can stop when she believes that enough information has been gathered. In both settings, we analyze the sample complexity in the PAC framework defined as the length of the observed trajectory required to identify the system parameters with prescribed accuracy and confidence levels (epsilon, delta). The first part of the talk is devoted to the introduction of versatile information-theoretical techniques leading to instance-specific sample complexity lower bounds. By instance-specific, we mean that the lower bounds explicitly depend on the system to be identified, and hence, unlike the classical minimax bounds, really captures the identification hardness specific to the system. In the second part of the talk, we present a few results from random matrix theory that are instrumental in the finite-time performance analysis of classical estimation algorithms such as the Least Squares Estimator (LSE). Based on this analysis, we discuss scenarios where the optimality of the LSE can be established (in those scenarios, its performance matches our instance-specific sample complexity lower bounds).

Social sensing and reinforcement learning

Vikram Krishnamurthy

Cornell University

This seminar is in two related parts. The first part discusses models for sequential decision making involving social learning. We also discuss sequential detection involving multi-agent decision makers and rational inattention models. The second part of the talk discusses inverse reinforcement learning (IRL) - namely how to estimate the utility function of a decision maker given its decisions. We discuss revealed preferences and Afriat's theorem from microeconomics for IRL, and also Bayesian IRL methods to detect the presence of a sequential detector from its decisions. As an illustrative example we discuss multimedia user engagement.

Tuesday September 26

Deep networks for system identification: a survey

Gianluigi Pillonetto, Aleksandr Aravkin, Daniel Gedon, Lennart Ljung, Antônio H. Ribeiro, Thomas B. Schön

University of Padova, Washington University, Uppsala University, Linköping University, Uppsala University, Uppsala University

Deep learning is a topic of considerable current interest. The availability of massive data collections and powerful software resources has led to an impressive amount of results in many application areas that reveal essential but hidden properties of the observations. System identification learns mathematical descriptions of dynamic systems from input-output data and can thus benefit from the advances of deep neural networks to enrich the possible range of models to choose from. For this reason, we provide a survey of deep learning from a system identification perspective. We cover a wide spectrum of topics to enable researchers to understand the methods, providing rigorous practical and theoretical insights into the benefits and challenges of using them. The main aim of the identified model is to predict new data from previous observations. This can be achieved with different deep learning based modelling techniques and we discuss architectures commonly adopted in the literature, like feedforward, convolutional, and recurrent networks. Their parameters have to be estimated from past data trying to optimize the prediction performance. For this purpose, we discuss a specific set of first-order optimization tools that is emerged as efficient. The survey then draws connections to the well-studied area of kernel-based methods. They control the data fit by regularization terms that penalize models not in line with prior assumptions. We illustrate how to cast them in deep architectures to obtain deep kernel-based methods. The success of deep learning also resulted in surprising empirical observations, like the counter-intuitive behaviour of models with many parameters. We discuss the role of overparameterized models, including their connection to kernels, as well as implicit regularization mechanisms which affect generalization, specifically the interesting phenomena of benign overfitting.

Identification of local models in interconnected systems – confounding variables, data-informativity and MATLAB toolbox

Paul Van den Hof, Karthik Ramaswamy, Stefanie Fonken, Shengling Shi

Eindhoven University of Technology

Identification of a local model in an interconnected system through prediction error methods requires the appropriate selection of a predictor model, consisting of predictor inputs and predicted outputs. In this setting several conditions need to be satisfied in order to guarantee accurate –consistent- model estimates, including the handling of confounding variables and the conditions for data-informativity. Generically these conditions can be satisfied through path-based conditions on the graph of the network model. An update of recent results will be presented, showing that data-informativity cannot simply be obtained by adding a sufficient number of excitation signals, but requires the appropriate selection of inputs and outputs in the predictor model. The results will be illustrated through the recently released MATLAB Toolbox for identification in dynamic networks.

Error Bounds for Kernel-Based Linear System Identification with Unknown Hyperparameters

***Mingzhou Yin*, Roy S. Smith**

ETH Zürich

Applying regularization in reproducing kernel Hilbert spaces has been successful in linear system identification using stable kernel designs. From a Gaussian process perspective, it automatically provides probabilistic error bounds for the identified models from the posterior covariance, which are useful in robust and stochastic control. However, the error bounds require knowledge of the true hyperparameters in the kernel design. They can be inaccurate with estimated hyperparameters for lightly damped systems or in the presence of high noise. In this work, we provide reliable quantification of the estimation error when the hyperparameters are unknown. The bounds are obtained by first constructing a high-probability set for the true hyperparameters from the marginal likelihood function. Then the worst-case posterior covariance is found within the set. The proposed bound is proven to contain the true model with a high probability and its validity is demonstrated in numerical simulation.

Wednesday September 27

A Bayesian View on Stochastic Subspace Identification with Extension to Statistical Robustness

Brandon O'Connell, Elizabeth Cross and Timothy Rogers

University of Sheffield

The family of Stochastic Subspace Identification (SSI) methods is one of the most popular and effective methods for system identification. Within structural dynamics, it is considered to be the state-of-the-art approach for operational modal analysis (output-only/blind system identification). This is due to it's robustness to noise, ease of model order selection and empirically strong results. Development of SSI can be shown via a set of orthogonal or oblique projections onto a linear subspace (hence the naming) or it can be viewed as performing Canonical Correlation Analysis (CCA) between the "past" and "future" Hankel matrices formed by a time-delay embedding of the measured responses. Following the view of CCA, it can be noted that the decomposition (along with other matrix factorisations, e.g, Principal Component Analysis, PCA) has an interpretation as a probabilistic latent variable model. Armed with this representation, it can be shown that classical SSI is a maximum likelihood solution to this probabilistic model and the door to a Bayesian treatment is open. The journey through this door is the contribution of this talk. As well as recovery of posterior uncertainty over the system properties via Bayesian inference, it will be shown how the probabilistic interpretation is amenable to powerful extensions. One shown here will statistical robustness to outlying data in the measured time-series through the application of a Student's-T prior in the latent space of the model. It will be presented how this novel robust Bayesian is able to avoid misidentification which is seen in the classical SSI algorithm when presented with intentionally corrupted data designed to mimic realistic issues encountered in field recordings, e.g. sensor dropout.

Meta-state-space learning: A Novel Approach for the Identification of Stochastic Dynamic Systems

Gerben I. Beintema, Maarten Schoukens, Roland Tóth

Eindhoven University of Technology

The available methods for identifying stochastic dynamical systems from input-output data impose restricting structural assumptions on either the noise structure or the state probability distributions. This presentation introduces a novel identification method for nonlinear stochastic systems without making major structural assumptions. The method is formulated by first deriving a novel and exact representation of stochastic systems called meta-state-space representation. In this representation, the meta-state can be interpreted as a parameterization of the state probability function space. The meta-state-space representation is uniquely suited for identification since the meta-state transition function is deterministic allowing the adaptation of conventional identification methods with relatively little modifications.

We also propose a neural meta-state-space model and identification method that is computationally tractable and that uses neural networks as universal function approximators. Using simulation and benchmark studies, we demonstrate that this identification method can obtain models with a log-likelihood close to the theoretical limit, even for highly nonlinear, highly stochastic systems.

Representer Theorem for Learning Koopman Operators

Mohammad Khosravi

Delft University of Technology

In this work, we consider the problem of learning the Koopman operator for discrete-time autonomous systems. The learning problem is formulated as a generic constrained regularized empirical loss minimization in the infinite-dimensional space of linear operators. We show that a representer theorem holds for the introduced learning problem under certain but general conditions, which allows convex reformulation of the problem in a specific finite-dimensional space without any approximation and loss of precision. We discuss the inclusion of various forms of regularization and constraints in the learning problem, such as the operator norm, the Frobenius norm, the operator rank, the nuclear norm, and the stability. Subsequently, we derive the corresponding equivalent finite-dimensional problem. Furthermore, we demonstrate the connection between the proposed formulation and the extended dynamic mode decomposition. We present several numerical examples to illustrate the theoretical results and verify the performance of regularized learning of the Koopman operators.

Kernel methods for identification of nonlinear systems

***Matteo Scandella*, Michelangelo Bin, Thomas Parisini**

Imperial College London, University of Bologna, Imperial College London

Identifying dynamical systems possessing specific stability properties is of crucial importance in applications. Existing results mainly focus on linear systems or some limited classes of nonlinear systems, and a systematic procedure to identify nonlinear systems characterized by specific stability properties is still an open problem. In this presentation, we propose a kernel-based nonlinear identification methodology to directly and systematically identify stable nonlinear discrete-time systems. To achieve this aim, we build on the regularized regression in the reproducing kernel Hilbert spaces, which is modified by including stability constraints in the kernel properties and in the hyperparameters' selection algorithm. The proposed method can be used to enforce, on the identified model, bounded-input-bounded-state stability, asymptotic gain, and input-to-state stability properties, as well as their incremental versions. Once the methodology is detailed, and sufficient conditions for stability are singled out, the presentation reviews some widely used kernels and their applicability within the proposed methodology.

Radar platform tracking for airborne bistatic systems

Tomas McKelvey

Chalmers University of Technology

For a receiver in a bistatic radar system, the relative position and velocity of the transmitter need to be known to the processor. In this presentation, we describe a clutter model and a method that over time tracks the transmitter position and velocity using the ground clutter response. For a given bistatic range the ground clutter response sensed by the receiver originates from ground scatterers located around an ellipsis. Each point on the ellipsis will correspond to a specific angle and Doppler frequency that depends on the relative geometry between the transmitter and receiver, and the velocities of both platforms. Assuming clutter response from one coherent processing interval (CPI), the position and velocity of the transmitter can be estimated by combining data for all relevant range bins and solving the associated maximum likelihood problem. The estimate is improved by incorporating a motion model and performing sequential filtering, i.e., tracking. In numerical simulations, the estimate from the tracking is compared with the maximum likelihood estimate. The numerical simulations clearly show that the estimate of the position and velocity from the tracker has lower variance and RMSE than the maximum likelihood estimate.

List of Abstracts – Posters

Poster Session 1

1. Fractional modeling and impedance model parameters identification of Lithium-ion batteries

***Omar Arahbi**, Benoit Huard, Jean-Denis Gabano, Thierry Poinot*

University of Poitiers

Electrochemical Impedance Spectroscopy (EIS) measurements is a widely used technique in frequency domain to determine an equivalent electrical circuit. A Randles circuit is used to fit the measured impedance spectra in order to take into account two fundamental electrochemical processes involved such as charge transfer and species mass diffusion. These processes lead to a pseudo physical impedance model which implies non-integer integrators which can be simulated in the frequency domain only. Nevertheless, the main drawback of EIS is the long-time requirement, typically more than 25 min, to obtain experimental data, especially for diffusion phenomenon occurring at the lower frequencies. For this reason, chronopotentiometry experiments represent a real alternative to solve this problem. It consists in applying an input excitation current lasting less than 3 seconds using a Pseudo Random Binary Sequence. Current and voltage signals are collected to perform identification. Therefore, fractional operators are designed so as to be able to simulate the impedance model also in the time domain which allows to perform identification using an output error algorithm. Parameters identified in time domain are closed to those obtained with EIS which confirms the interest of the approach. A map of parameter estimates variations relative to battery State of Charge (SOC) has been carried out. The results of this parameter mapping show the strong dependence of parameters on SOC.

2. Towards scalable identification of non-linear differential-algebraic equations with process disturbances

***Robert Bereza**, Oscar Eriksson, Mohamed R.-H. Abdalmoaty, David Broman, Håkan Hjalmarsson*

KTH, ETH Zürich

Differential-algebraic equations (DAEs) are commonly used to model physical systems, and are also the mathematical basis for many equation-based object-oriented modeling languages. Such models can contain unknown parameters that need to be estimated using measured data. However, physical systems are often affected by unknown process disturbances, and it is well-known that neglecting such disturbances during identification can result in biased estimates. Despite this, many existing estimation methods for DAEs neglect process disturbances because of the difficulties with handling them for non-linear models. In our prior work we have proposed stochastic approximation methods for this type of problem that are computationally tractable for cases with a few unknown parameters. In this work, we demonstrate how to extend the methods for identification of parameters also in the unknown disturbance model, and how to improve the methods' scalability for cases with many unknown parameters.

3. Global identifiability of parameterized nonlinear dynamical models

***Sarthak De*, Bart De Moor**

KU Leuven

Many real-world phenomena can be modeled using parameterized nonlinear dynamical systems. A fundamental inquiry in this domain is Identifiability, which seeks to determine if the parameters of such models can be uniquely identified from observable data. In this poster we present a novel symbolic-numeric approach for assessing the global Identifiability of parameterized nonlinear models. We will introduce two approaches based on the Input-Output (IO) equations of the nonlinear state-space models, derived using differential elimination. The first, where the identifiability of the aforementioned models is re-written as a system of polynomial equations in the model parameters and second, where we recruit the misfit-identification framework to re-write the identifiability problem as a multiparameter eigenvalue problem in the model parameters. We show that studying the solutions of both the problems allow us to comment on the identifiability of these models. As our methods closely resemble a system identification loop, we demonstrate that they can serve as a logical progression for examining the practical identifiability of these nonlinear models.

4. High dimensional data reduction in modal analysis with stochastic subspace identification

Zhilei Luo, Boualem Merainani, Michael Döhler, Vincent Baltazart, Qinghua Zhang

INRIA

Subspace system identification methods are widely used in output-only vibration analysis of civil structures, known as operational modal analysis. With the advent of new sensor technologies, such as video camera-based full field displacement or velocity measurements, the number of measured outputs is quickly increasing. In this contribution, we propose principal component analysis-based data size reduction methods for efficient application of subspace methods, while preserving the high spatial resolution of the identified mode shapes for detailed modal analysis.

5. Local identification in dynamic networks using a multi-step method

Stefanie J. M. Fonken, Karthik R. Ramaswamy, Paul M. J. Van den Hof

Eindhoven University of Technology

For identification of a single module in a linear dynamic network with correlated disturbances different methods are available in a prediction error setting. While indirect methods fully rely on the presence of a sufficient number of external excitation signals for achieving data-informativity, the local direct method with a MIMO predictor model can exploit also non-measured disturbance signals for data-informativity. However this local direct method can be conservative in terms of the number of external excitation signals that is required. Inspired by a recently introduced multi-step method for full network identification, we present a multi-step method for single module identification. In a first indirect step a model is estimated that is used to reconstruct the innovation on a set of output signals, which in a second step is used to directly estimate the module dynamics with a MISO predictor model. The resulting path-based conditions for data-informativity show that the multi-step method requires a smaller number of excitation signals for data-informativity than the local direct method.

6. DeepBayes - an estimator for parameter estimation in stochastic nonlinear dynamical models

***Anubhab Ghosh**, Mohamed Abdalmoaty, Saikat Chatterjee, Håkan Hjalmarsson*

KTH, ETH Zürich

Stochastic nonlinear dynamical systems are ubiquitous in modern, real-world applications. Yet, estimating the unknown parameters of stochastic, nonlinear dynamical models remains a challenging problem. The majority of existing methods employ maximum likelihood or Bayesian estimation. However, these methods suffer from some limitations, most notably the substantial computational time for inference coupled with limited flexibility in application. In this work, we propose DeepBayes estimators that leverage the power of deep recurrent neural networks. The method consists of first training a recurrent neural network to minimize the mean-squared estimation error over a set of synthetically generated data using models drawn from the model set of interest. The a priori trained estimator can then be used directly for inference by evaluating the network with the estimation data. The deep recurrent neural network architectures can be trained offline and ensure significant time savings during inference. We experiment with two popular recurrent neural networks - long short term memory network (LSTM) and gated recurrent unit (GRU). We demonstrate the applicability of our proposed method on different example models and perform detailed comparisons with state-of-the-art approaches. We also provide a study on a real-world nonlinear benchmark problem. The experimental evaluations show that the proposed approach is asymptotically as good as the Bayes estimator.

7. Identification of linear state-space models subject to truncated Gaussian disturbances

***Rodrigo A. González**, Angel L. Cedeño, Koen Tiels, Tom Oomen*

Eindhoven University of Technology, UTFSM

Within Bayesian state estimation, an important effort has been put to incorporate constraints into state estimation for process optimization, state monitoring, fault detection and control. Nonetheless, in the domain of state-space system identification, the prevalent practice entails constructing models under Gaussian noise assumptions, which suffer from inaccuracies when the noise follows bounded distributions. This poster introduces a novel data-driven method rooted in maximum likelihood principles, aimed at identifying linear state-space models subject to truncated Gaussian noise. This approach enables the concurrent estimation of model parameters, noise statistics, and noise truncation bounds, by solving a series of quadratic programs and nonlinear sets of equations.

8. Parameter-state estimation for mechanical systems with small model errors

***Szymon Gres**, Konstantinos Tatsis, Vasilis Dertimanis, Michael Döhler, Eleni Chatzi*

Aarhus University

The performance of algorithms for parameter-state estimation can be hindered by the need to recompute the parametric system matrices at each parameter iteration step. This work aims to alleviate this computational burden by expressing model errors that stem from parametric uncertainties, as additive parametric terms in the state and observation equations. For this purpose, errors in the eigenstructure of a parametrized mechanical system are propagated to the physical parameters and eventually modelled as additive terms by means of perturbation analysis. A state observer is derived under the assumption that the change between the current and a true model parameter is deterministic and known. An estimate of the possible parameter discrepancy is obtained by minimizing the value of a generalized likelihood ratio test applied on a Kalman filter innovation sequence.

9. Electrochemical impedance spectroscopy beyond linearity and stationarity

***Noël Hallemansa*, David Howey, Alberto Battistel, Fabio LaMantia, Annick Hubin, Widanalage Dhammika Widanage, John Lataire**

Vrije Universiteit Brussel, University of Warwick, Oxford University, Furtwangen University, Bremen University

Electrochemical impedance spectroscopy (EIS) is a widely used experimental technique for characterising materials and electrode reactions by observing their frequency-dependent impedance. Classical EIS measurements require the electrochemical process to behave as a linear time-invariant system. However, electrochemical processes do not naturally satisfy this assumption: the relation between voltage and current is inherently nonlinear and evolves over time. An example is the charging and cycling of Li-ion batteries. As such, classical EIS only offers models linearised at specific operating points. During the last decade, solutions were developed for estimating nonlinear and time-varying impedances, contributing to more general models. Here, we review the concept of impedance beyond linearity and stationarity, and detail methods to estimate this from measured current and voltage data, with emphasis on frequency domain approaches using multisine excitation. Moreover, we measure and provide examples demonstrating impedance estimation for a Li-ion battery, beyond linearity and stationarity, both while resting and while charging.

10. Control of calendering process, an initial step in tire manufacture

***T. Bou Hamdan*, S. Al Basha, G. Mercère, T. Dairay, P. Coirault**

University of Poitiers, The Michelin Company

Through the tire manufacturing process, rubber undergoes compression and refining through a sequence of rotating cylinders known as the calendering process. This mechanical technique is harnessed to generate fine rubber layers intended for subsequent stages in tire production.

Throughout calendering, the visco-elastic properties of the rubber makes it subject to escalated viscous heating. This induced heating increases with the augmentation of production rate, marked by an increase in the rotational speed of the calendering cylinders. It is important, however, to maintain the rubber temperature at a predefined setpoint to ensure optimal rubber quality and seamless calendering. The objective is to control the temperature of the rubber by adjusting the calendering wheels rotational velocities. Given the physical limitations governing the rotational velocities and the rubber temperatures, a predictive control methodology is considered. This poster showcases the implementation of two distinctive data-driven techniques for predictive control implementation: subspace predictive control and model predictive control, with the latter utilising a model based on the Dynamic Mode Decomposition approach.

11. Non-asymptotic identification of Markov parameters using weighted least-squares

***Jiabao He*, Håkan Hjalmarsson**

KTH

Markov parameters play an important role in system identification. Most subspace identification methods start with estimating Markov parameters of a system, and then give a balanced realization in the state-space form. For the former, the ordinary least-squares (OLS) estimator is commonly used. In particular, there has been an increasing interest in finite sample complexity and non-asymptotic analysis for OLS. In most cases, however, OLS is not the best linear unbiased estimator (BLUE) as it ignores unequal variance of residuals, which means that the resulting error bound is not tight. In this contribution, we provide finite-time analysis for learning Markov parameters based on the weighted least-squares (WLS) estimator using multiple trajectories, which covers both stable and unstable systems. For single-input-single-output (SISO) systems, we show that with the optimal weighting matrix, WLS gives a tighter error bound than OLS. Moreover, as the optimal weighting matrix depends on the system's true parameters, we introduce how to consistently estimate the weighting matrix. Numerical experiments demonstrate tighter error bounds of the proposed method than existing ones.

12. A pipeline for analyzing large-scale time-course bulk mRNA data

***Xin He*, Jorge Goncalves**

University of Luxembourg

Analyzing large-scale bulk biological time series datasets, such as transcriptomics or proteomics, is a challenging problem due to the limited number of time points and the large number of measurements. In particular, uncovering causal relationships between measurements and external perturbations requires identifying the (typically) small percentage of measurements that respond to those perturbations.

This work proposes a pipeline for bulk omics time series data that includes: 1) differential time-series expression, 2) clustering, and 3) causal network identification. These data-driven steps can be complemented with other prior knowledge such as ReMap2022 (PMC8728178) or ChIP-Hub (PMC9197862). The pipeline aims to extract key genes and causal network relationships under perturbation to improve our understanding of biological systems and guide future experiments. By forming an iterative loop of experimental analysis, the pipeline facilitates data-driven experimental design. We evaluate the performance of the pipeline using synthesized and real data, demonstrating improved accuracy in network inference compared to baseline methods.

13. Asymptotic theory for Stein's unbiased risk estimation and generalized cross-validation hyper-parameter estimators

***Yue Ju*, Bo Wahlberg, Håkan Hjalmarsson**

KTH

Regularized system identification has drawn wide attention in the past decade. One related topic is the asymptotic theory, which is concerned with the convergence properties of the model estimators as the sample size goes to infinity. This presentation will focus on the regularized finite impulse response model estimation with hyper-parameter estimated by the Stein's unbiased risk estimation (SURE) and generalized cross-validation (GCV) methods. It aims to expose factors that influence the convergence properties of these two hyper-parameter estimators and their corresponding model estimators, e.g., the regression matrix and the kernel matrix. For some special case, the convergence properties of the empirical Bayes, SURE and GCV hyper-parameter estimators and corresponding model estimators will be compared both analytically and numerically.

14. Robust adaptive filtering methods for online mass estimation of electric vehicles

***Hugo Koide*, Guillaume Mercère, Jeremy Vayssettes**

University of Poitiers, The Michelin Company

In the light of the development of automated driving systems and the improvement of Advanced Driver Assistance Systems (ADAS) for vehicle control, it has become necessary to have an accurate estimation of vehicle mass in real time. Online estimation is necessary to account for mass fluctuations due to varying external loads, changing passengers, and fuel consumption amongst other factors. This study compares the accuracy and robustness of various adaptive filtering techniques, notably variants of the Recursive Least Squares filter (RLS) and the Kalman Filter (KF) in providing a recursive estimation of vehicle mass from on-board diagnostics data. The estimations are carried out on experimental data, and the online tracking capabilities are tested by imposing mass variations during the vehicle experiments. The chosen method can estimate mass to within ±3% accuracy for electric vehicles, which accounts for a sharper resolution than what is predominantly found in literature. The proposed methodology does not require knowledge of GPS data or estimation of road grade, relying on basic signals obtained for the vehicle Control Area Network system. This gives the proposed solution an edge in terms of industrialisation and computational efficiency compared to more complex solutions found in literature.

15. Learning with guarantees for multi-agent systems

Krzysztof Kowalczyk*, *Paweł Wachel

Wroclaw University

We investigate the problem of distributed learning of a nonlinear multi-dimensional phenomenon partially observed by the network of agents. In the considered setting, agents collect their local measurements disturbed by a noise (possibly varying between the agents). Due to communication restrictions, agents are only able to exchange information with their direct neighbourhood, which may strongly complicate effective central processing. For this setup, we propose a new in-network processing algorithm and aim to provide high-probability confidence bounds for a finite set of measurements under mild a priori knowledge.

16. Parameter estimation: Simulation driven and privacy preserving approaches

Braghadeesh Lakshminarayanan*, *Cristian R. Rojas

KTH

Estimating the parameters of models is an important problem in statistics and system identification. Since these estimates depend on data which may sometimes contain sensitive information, privacy preserving approaches have gained attention in research.

In this work, we propose (i) a Two-Stage Gradient Boosted Machine (TSGBM) estimator that gives reliable estimates of unknown parameters with limited prior knowledge, and (ii) a Unified Bayes Private Point (UBaPP) estimator that gives accurate estimates of unknown parameters subject to differential privacy constraints.

We finally show numerical simulations to demonstrate our proposed approaches.

17. Gene expression modelling from single-cell data using optimal mass transport

Francois Lamoline*, *Atte Aalto, Isabel Haasler, Johan Karlsson, Jorge Goncalves

University of Luxembourg, EPFL, KTH

Understanding cellular functions and exploring the regulatory relationships between genes is a central problem in systems biology and medicine. This would help to reveal the underlying mechanisms of specific diseases and to find treatments eventually. Recently, single-cell technology has revolutionised the field by enabling sequencing at the resolution of individual cells, offering new possibilities to infer gene regulatory networks. Unfortunately, due to the destructive nature of the measurement process, individual cells cannot be observed over time. Most methods for inferring GRNs from single-cell data are based on co-expression, regression, or information theoretic concepts. These approaches often struggle to fully capture the richness of information present in single-cell data. In this work, we develop a tool based on the theory of optimal transport for inferring a linear differential equation model from time course single-cell data. The idea consists in tracking the evolution of the distribution of cells over time and finding the dynamical system that minimizes the transport cost between consecutive time points. We demonstrate that our approach performs competitively against the state-of-art methods on the recent synthetic datasets from the BEELINE benchmark. Our method has the potential to improve our understanding of gene regulation and thus facilitate the development of new treatments for diseases.

18. Lithium-ion battery identification through online concurrent state and parameter estimation

***Jimei Li**, Yang Wang, Riccardo M.G. Ferrari, Jan Swevers, Feng Ding*

KU Leuven, Delft University of Technology, Jiangnan University

Online identification of Lithium-ion batteries is crucial for the operation of their battery management systems. For the battery modeling, we implement an equivalent circuit model (ECM) because of its interpretability and moderate computation cost. However, the significant state dependency of ECM parameters makes it difficult to construct a precise model from observed data. To tackle this, we propose to approximate the ECM model parameter variations as polynomials in a variable that represents the state of discharge of the battery. This transforms the ECM into a time-invariant gray box state space model. A recursive least squares algorithm is used for the parameter estimation, and a particle filter with systematic resampling is adopted to estimate the unmeasurable states. The online concurrent estimation scheme alternately estimates the states and parameters. The developed estimation approach is validated on a Cylindrical Battery Cell example. Estimates of the open circuit voltage (OCV) are compared with experimental data measured during an incremental current OCV test. The obtained model yields a root mean square battery voltage estimation error of 0.35 mV for data measured under Federal Urban Driving Schedule test conditions and demonstrates superior performance over state-of-the-art approaches.

19. Efficient Bayesian learning of Gaussian process state-space models with probabilistic stability guarantees

***Yuhan Liu**, Roland Tóth*

Eindhoven University of Technology

Systems in real applications are usually affected by nonlinear couplings, external disturbances, and unmodeled dynamics that may have significant impact on the achievable control performance. Gaussian process (GP) regression is an effective tool to build the nonparametric, probabilistic model directly from input/output data. In this work, we introduce a new strategy for efficient Bayesian learning with GP state-space models (GPSSM), where the wide class of nonlinear systems are transformed into linear parameter-varying (LPV) representations at the level of probability density functions (PDF). The proposed strategy can provide computationally efficient state propagation, which significantly benefits the online implementation of model predictive control with GP models. Furthermore, theoretical proof of Lyapunov stability of the proposed method-driven closed-loop system is provided in the probabilistic sense.

20. Learning from interactions: Beliefs, policies, and rewards

***Inês Lourenco**, Rebecka Winqvist, Cristian R. Rojas, Bo Wahlberg*

KTH

Decision-making is the mechanism of using available information to develop solutions to given problems by forming preferences, beliefs, or selecting courses of action amongst several alternatives. In our work, we study the mechanisms that generate behavior (the forward problem) and how their characteristics can explain observed behavior (the inverse problem). Both problems take a central role in current research due to the desire to understand the features of system behavior, many times under situations of risk and uncertainty. Our work explores different parts of the decision-making process where agents learn from interacting with each other and the environment that surrounds them. We tackle fundamental problems of behavior modeling, parameter estimation in the form of beliefs, intentions and reward functions, and then finally interactions with other agents; which lay the foundation for a complete and integrative framework for decision-making and learning.

21. Toward inference of gene regulatory networks from single-cell RNA-sequencing data by the chemical master equation and the chemical Langevin equation

***Stefano Magni*, Gabriela Retamales, Atte Aalto, Jorge Goncalves**

University of Luxembourg

Single-cell RNA-Sequencing (Sc RNA-Seq) is revolutionizing how we characterize cells at the transcriptional level. The data generated by these techniques are high dimensional and require tailored computational approaches to extract the large amount of information they contain. Despite the existence of basic computational methods, there is a lack of tailored mathematical modelling approaches able to infer causal gene regulations from such data. Here we focus on developing two approaches to fit dynamical mechanistic models, based on the chemical master equation and the chemical Langevin equation, to Sc RNA-Seq data, with the final goal to infer causal gene regulatory networks (GRNs). The first approach is based on numerically solving the chemical master equation and identifying model parameters by Bayesian inference implemented via a Markov Chain Monte Carlo approach. The second approach is based on numerically solving the Chemical Langevin equation by the Euler-Maruyama scheme and inferring model parameters by gradient descent. Results on inferring small GRNs from synthetic data are presented, showcasing the feasibility of the approach. In terms of applications, we previously characterized the onset of Parkinson's Disease (PD) at the transcriptional level by Sc RNA-Seq. Thus our final aim is to develop and apply our computational approaches to the inference of the GRN underlying onset of PD, to pinpoint potential entry points for the development of novel treatments.

22. Cyclostationarity in a loop?

***Gabriel Maik*, Paweł Wachel, Grzegorz Mzyk**

Wroclaw University

We investigate the concept of using output noise as an advantage in closed-loop non-linear system identification. In open-loop problems, the deterministic periodic input signals can be insufficient to achieve satisfactory identification results. In contrast, in the closed-loop system with a deterministic periodic reference, a system is excited by a stochastic signal, richer than a deterministic one, but also autocorrelated (in IIR sense).

In this work, for the exemplary class of nonlinear systems, we investigate the influence of cyclostationarity on the identification outcomes and show selected numerical results.

Poster Session 2

23. Multimodal representation of the uncertainty of the prediction from neural networks

***Magnus Malmström**, Isaac Skog, Daniel Axehill, Fredrik Gustafsson*

Linköping University

This work presents a method to represent the uncertainty of the prediction from neural networks as a multimodal distribution. For predictions from neural networks to be used in safety-critical applications it is necessary to have a measure of uncertainty in the prediction from them. One method to quantify the uncertainty in the prediction is the so-called linearized Laplacian approximation of a Bayesian neural network. The approximation is based on a local assumption to specify the covariance of the parameters. Afterward, a linearization of the neural network is used to propagate the uncertainty in the parameters to uncertainty in the prediction. However, since this is a local approximation, it cannot represent a multimodal distribution, which might be desirable. To solve this problem an extension is suggested where an ensemble of neural networks is used to give a multimodal representation of the distribution. It is shown in experiments on image classification that the ability to represent a multimodal distribution improves the capability to detect out-of-distribution examples.

24. On the regularization in DeePC

***Per Mattsson**, Thomas B. Schön*

Uppsala University

Data-enabled predictive control (DeePC) is an approach to data-driven direct control that has gained considerable interest recently. In this work we show that the main equations of DeePC can be derived from a linear regression model based on the input/output equations for a linear system that can be estimated using linear least squares. Our main contribution is an analysis showing that DeePC---using different types of regularization---gives predictions that equal those of an estimated model if the regularization weight is large enough. The numerical example indicates that the optimal weights are sufficiently large for all considered types of regularization. This suggests that the use of an indirect method based on the linear regression model implicitly estimated by DeePC can be beneficial since this avoids tuning of weights, does not distort the control criterion, and makes the online optimization considerably faster. Furthermore, a slightly modified estimate is considered, that reduces the number of unknown parameters in the linear regression model by taking causality into account.

25. Characterization of the identification variance of kernel-based models with randomized approaches and its use in robust control and fault diagnosis

Mirko Mazzoleni

University of Bergamo

The characterization of bias and variance of identified models plays a key role in the design of robust controllers or robust residual generators. In this work, we investigate the frequency domain representation of the identification variance of models identified by kernel methods, neglecting their low estimation bias, and its use for robust control and robust fault diagnosis. The proposed approach is based on randomized methods and allows to overcome a priori choices such weight functions in robust control or a priori bounds on model parameters in robust fault diagnosis. Simulation and experimental results are compared with the traditional PEM frequency domain characterization of the identification variance.

26. Frequency-domain system identification via sparse rational optimization

Mohamed Abdalmoaty, Jared Miller, Mingzhou Yin, Roy Smith

ETH Zürich

This work proposes a computationally tractable method for the identification of canonical discrete-time rational transfer function models, using a finite set of input-output measurements. The problem is formulated in frequency-domain as a global optimization problem whose cost function is the sum of weighted squared residuals at each observed frequency datapoint. It is solved by the sum-of-squares hierarchy of semidefinite programs, through a framework for sum-of-rational-functions optimization from Bugarin, Henrion, Lasserre 2016. The generated program contains decomposable term and correlative sparsity, which can be exploited for further computational complexity reductions. Convergence of the sum-of-squares program is guaranteed as the polynomial degree approaches infinity. We discuss extensions of this rational-program method for identification in the closed-loop, continuous-time, and MIMO settings.

27. Output error port-Hamiltonian neural networks

Sarvin Moradi, Gerben I. Beintema, Nick Jaensson, Roland Tóth, Maarten Schoukens

Eindhoven University of Technology

Hamiltonian Neural Networks (HNNs) represent a promising class of physics-informed deep learning methods that leverage Hamiltonian theory as foundational knowledge within data-driven model learning with neural networks. However, their direct application to engineering systems is often hindered by practical challenges, including the presence of external inputs, dissipation, and noisy measurements. This study introduces a novel framework that enhances the capabilities of HNNs to address these real-life factors. We integrate port Hamiltonian theory into the neural network structure, allowing for the inclusion of external inputs and dissipation, while mitigating the impact of measurement noise through an output-error (OE) model structure. The resulting port Hamiltonian neural networks (pHNNs) can be adapted to tackle data-driven modeling complex engineering systems with noisy measurements. Furthermore, we develop an extension of the subspace encoder approach (SUBNET) for identification of pHNNs, which efficiently approximates the complete simulation loss using short simulations on subsections of the data and an encoder function to predict initial states. By integrating SUBNET with pHNNs, we achieve robust and physics-driven data-based learning of complex engineering systems under noisy measurements. We demonstrate the effectiveness of our approach on engineering benchmarks, showing its potential as a powerful tool for modeling dynamic systems in real-world applications.

28. SYSDYNET: MATLAB app and toolbox for system identification in dynamic networks

Paul M.J. Van den Hof and Ilja van Oort

Eindhoven University of Technology

Highly complex large-scale interconnected systems are increasingly prevalent in the engineering domain. When performing identification tasks in dynamic networks for the purpose of data-driven modeling and decision-making, the underlying interconnection structure (topology) of the network plays an important role. Over recent years a substantial set of methods and algorithms have been introduced for the structural analysis and the identifiability and identification of linear dynamic networks. With the SYSDYNET toolbox, we aim to integrate the developed algorithms into a comprehensive set of tools for the data-driven modelling in dynamic networks. In its most recent release, the toolbox provides both command-line functions and a user-friendly graphical user interface for the structural manipulation and analysis of the topology of networked dynamic systems. Based on the provided topology, structural operations and tests can be performed, including:

- Tests for the appropriate selection of node signals to be measured,
- Generic identifiability tests for a (sub)network
- Allocation of external excitation signals for achieving identifiability and data-informativity
- Synthesis and analysis of structured predictor models for single module identification.

The graphical user interface provides a complete workflow starting from analysing the network topology to delivering a predictor model that satisfies the structural conditions for consistent estimation of either a full network or a single module. Currently the toolbox is being expanded towards actual identification algorithms and network simulation tools. Recently developed algorithms, including direct and multistep prediction error methods, for both single module and full network identification will be integrated.

29. Coherence-based input design for nonlinear systems

Javad Parsa, Cristian R. Rojas, Håkan Hjalmarsson

KTH

Many non-linear models inherently exhibit sparse parametrizations, with examples like the Volterra series and non-linear Auto-Regressive with eXogeneous inputs (NARX) models. It is well-established that sparse estimation in such models demands low mutual coherence, which, in practical terms, translates into a requirement for input sequences to possess specific low-correlation properties.

This poster underscores a critical issue in existing methodologies: standard optimal input design methods do not adequately consider this requirement. This oversight can result in the generation of input sequences that are ill-suited for these types of model structures. In response to this challenge, we propose the incorporation of a coherence constraint into conventional input design problems. The coherence constraint is defined as the ratio between the diagonal and non-diagonal elements of the Fisher information matrix (FIM). Remarkably, this constraint can be seamlessly introduced into any input design problem for nonlinear systems while maintaining the convexity of the problem.

In addition to presenting this innovative approach, we conduct a theoretical analysis to elucidate how the coherence constraint influences the optimal objective function's range in the original problem. Furthermore, we comprehensively evaluate the performance of our proposed method through a numerical study. This assessment includes a comparative analysis with state-of-the-art algorithms and employs a Volterra series model as a case study for a more precise evaluation.

30. Regularization properties of adversarially-trained linear regression

***Antônio H. Ribeiro**, Dave Zachariah, Francis Bach, Thomas, B. Schon*

Uppsala University, École Normale Supérieure

State-of-the-art machine learning models can be vulnerable to very small input perturbations that are adversarially constructed. Adversarial training is an effective approach to defend against it. Formulated as a min-max problem, it searches for the best solution when the training data were corrupted by the worst-case attacks. Linear models are among the simplest models where vulnerabilities can be observed and are the focus of our study. In this case, adversarial training leads to a convex optimization problem and can be formulated as the minimization of a finite sum. We provide a comparative analysis between the solution of adversarial training in linear regression and other regularization methods. Our main findings are that: (A) adversarial training yields the minimum-norm interpolating solution in the overparameterized regime (more parameters than data), as long as the maximum disturbance radius is smaller than a threshold. And, conversely, the minimum-norm interpolator is the solution to adversarial training with a given radius. (B) Adversarial training can be equivalent to parameter shrinking methods (ridge regression and Lasso). This happens in the underparameterized region, for an appropriate choice of adversarial radius and zero-mean symmetrically distributed covariates. (C) For l_∞ - adversarial training---as in square-root Lasso---the choice of adversarial radius for optimal bounds does not depend on the additive noise variance. We confirm our theoretical findings with numerical examples.

31. Exploring the critical values of multivariate polynomial optimization problems in system identification applications

***Hans van Rooij**, Bart De Moor*

KU Leuven

In optimization problems, the objective function is often expressed as a multivariate polynomial. The first-order necessary conditions for optimality can be represented as a system of multivariate polynomial equations. By identifying the common roots of these conditions, all critical points of the optimization problem can be determined. It is important to note that multiple critical points may have the same critical value. Interestingly, the set of critical values is always shown to have a Lebesgue measure of zero, as proven by Sard's theorem. In this poster, we show an elegant approach on how to compute the critical values of the objective function, thus finding the global minimum value, without explicitly calculating all the critical points. Once the smallest critical value has been extracted, a linear system can be solved to find its corresponding critical point, avoiding the computation of all other critical points.

The approach presented in this poster tackles this challenge by computing the critical value polynomial (CVP), which resides in the row space of the Macaulay matrix and is a univariate polynomial. The roots of the CVP correspond to the critical values of the objective function. Leveraging the critical value polynomial provides an intriguing way to identify the global optimal solutions in a range of system identification applications involving multivariate polynomial objective functions.

32. Parameterisation of a family of neuralODEs optimally fitting steady-state data

***Fahim Shakib**, Giordano Scarciotti, Alessandro Astolfi*

Imperial College London

This poster presents a parameterisation of families of neural ordinary differential equations (neuralODEs) that fit the steady-state model response to the steady-state system response in the least-squares sense. The family of neuralODEs is cast in the form of recurrent equilibrium networks (NodeRENs), a particularly nonlinear model class that exploits the flexibility of neural networks and exhibits stability and robustness properties. Using the time-domain moment matching technique, one of the main advantages of the proposed approach is that it uses only linear least-squares optimization, for which there is a closed-form expression for the solution of the steady-state fitting problem. This is in contrast to gradient-descent learning approaches which are iterative and do not guarantee convergence to the global optimum. Furthermore, the parameterisation of the family of NodeRENs leaves a subset of parameters free useful for enforcing robustness properties or for fitting also transient data in addition to steady-state data. The proposed parameterisation of the family of NodeRENs can be used in several applications including data-driven modelling and complexity reduction of a complex model.

33. Do we need models for control? A system theoretic study of data-driven policy iteration

Bowen Song*, *Andrea Iannelli

University of Stuttgart

We investigate the role played by the identification of a model in data-driven control of unknown systems. Specifically, we focus on policy iteration (PI), a central algorithm used in several approximate dynamic programming schemes, applied to the linear quadratic regulator problem. We consider two iterative procedures to compute the optimal controller. In indirect policy iteration (IPI), data collected from the system are leveraged to obtain updated model estimates via recursive least squares (RLS). The estimates are subsequently employed for the two standards steps of PI, i.e. approximately computing a value function (policy evaluation)and the associated optimal controller (policy improvement). In direct policy iteration (DPI), on-policy data are employed to directly approximate the value function and the associated controller, with no use of a model. The goal is to analytically study the implications of an indirect and a direct scheme on the required data (sample complexity) and convergence properties of the two algorithms. By viewing the indirect scheme as the feedback loop between two dynamical systems, the PI and RLS algorithms, we investigate the convergence properties of IPI and show that, under noise-free conditions, it is input-to-state stable with respect to the model mismatch introduced by RLS. As for DPI, we propose an extension to a recently proposed scheme to overcome identifiability issues in the noise-free case. Our analysis indicates that, unlike in IPI, it is not possible to provide convergence guarantees for DPI unless a minimum number of data-points is used. Furthermore, IPI does not require on-policy data (i.e. data generated by the controller which is iteratively learned), leading to more flexibility in selecting control signal options and easier to obtain safety guarantees. Introducing the identification of a model therefore offers advantages in sample complexity and robustness over a purely direct (model-free) approach. Finally, we show further insights into these two methods through numerical simulations.

34. Instrumental variables for direct data-driven control

Luuk Spin

Eindhoven University of Technology

Willem's Fundamental Lemma has been a cornerstone result in recent direct data-driven controller design literature. This result allows controller design without an intermediate system identification step. In data-driven predictive control, measured output noise is handled with slack variables in the optimization algorithm. Data-informativity employs noise bounds in a systematic manner for state-input data only. Both control strategies for direct data-driven controller design do not handle noise in a stochastic manner. In order to design (sub)-optimal H_∞ controllers directly from noisy input-output data, in a statically efficient manner, we aim at using Instrumental Variables (IVs). From system identification, it is known that the statically optimal choice for IV is the input and the deterministic part of the output. Instead of using a system identification scheme to iteratively converge to the optimal IV we make use of a behavioral approach to find the optimal IV without in one shot.

35. Control variates for multivariate truncated probability density functions with application in system identification

***Koen Tiels*, Rodrigo A. González, Tom Oomen**

Eindhoven University of Technology

Monte Carlo methods are useful for computing numerical approximations of expected values, especially when these expectations cannot be computed analytically. Nevertheless, these methods depend on random sampling. The accuracy of the numerical approximation depends on the number of samples used and convergence to the true value can be slow. Control variates provide a way to use the samples more efficiently and reduce the variance of the sample mean estimator. This poster considers the computation of control variates for multivariate truncated probability density functions and its application in hyperparameter estimation for regularized impulse response identification of Lebesgue-sampled systems. The use of control variates in this application reduces the computational cost of an expensive step in each iteration of the expectation-maximization (EM) algorithm.

36. Parametric estimation of fractional order impedance models to study battery aging

***Freja Vandeputte*, Noël Hallemans, Nessa Fereshteh Saniee, Widanalage Dhammika Widanage, John Lataire**

Vrije Universiteit Brussel, University of Warwick

Electrochemical impedance spectroscopy (EIS) is a powerful data-driven technique for estimating the impedance of a Li-ion battery from current and voltage measurements. In classical EIS, the battery impedance is estimated nonparametrically, and the nonparametric impedance estimate is then often interpreted by means of an equivalent electrical circuit model (ECM), whose components relate to the physical processes occurring in the battery. However, by using such an ECM, with a Warburg element to model the diffusion, as an underlying fractional order parametric model, the battery impedance can also be estimated parametrically in the frequency domain. While the nonparametric estimate can only be evaluated in the discrete set of excited frequencies, the parametric estimate can be evaluated in every frequency of the frequency band of interest. Moreover, the parametric estimation is not limited to single sine or odd random phase multisine excitation signals, but also works for all other persistently exciting signals, like for example Gaussian white noise excitation signals. Both the nonparametric and parametric estimation methods are applied to battery cycling measurements, to study the effects of battery aging on the equivalent circuit components.

37. Globally optimal misfit identification of multidimensional difference equations

***Lukas Vanpoucke*, Bart De Moor**

KU Leuven

It has been shown before that the globally optimal least-squares misfit identification of single output, autonomous difference equations with constant coefficients can be formulated as a polynomial optimization problem, due to the polynomial nature of these models. The stationary points of such optimization problems comprise the solution set of a system of multivariate polynomials. Moreover, for this identification problem, the resulting system of equations can be written as a particular class of polynomial systems: a so-called multiparameter eigenvalue problem (MEP). Such polynomial systems can be solved using the linear-algebra-based block Macaulay method. This poster extends this methodology to the misfit identification of m-dimensional (mD) autonomous difference equations. A parametrization is first proposed based on a generalization of the Cayley-Hamilton theorem. Additionally, we outline the MEP formulation for the globally optimal identification problem, for which several numerical examples are provided.

38. ROVA, a practical and parsimonious Volterra model

***Amedeo Varano*, Dries Peumans, Yves Rolain**

Vrije Universiteit Brussel, imec

This work details a novel nonlinear data-driven model (ROVA) to describe systems that can be approximated in least squares sense by a Volterra series. The ROVA model estimates the truncated Taylor series expansion of the frequency-domain Volterra kernels in least squares sense. By exploiting the symmetries of these Volterra kernels, a model is obtained that is linear in its model parameters, avoids a combinatorial explosion of model parameters for increasing complexity, and is interpretable.

The performance of the ROVA model is validated on a modulated microwave system: a power amplifier. It is compared against current state-of-the-art memory polynomials. Simulation and experimental validation indicate that ROVA outperforms the memory polynomials with less model parameters and lower modelling error.

39. Using the (Block) Macaulay Matrix in the Chebyshev Polynomial Basis

***Christof Vermeersch*, Bart De Moor**

KU Leuven

At the previous ERNSI Workshop on System Identification, we have demonstrated how to exploit shift-invariant subspaces of (block) Macaulay matrices to solve various applications in systems theory. For example, the shift-invariance of the (right) null space of the Macaulay matrix constructed from the coefficients of a system of multivariate polynomial equations yields the common roots of these polynomials. Similarly, the block Macaulay matrix can be used to solve rectangular multiparameter eigenvalue problems.

While developing these (block) Macaulay matrix algorithms, our focus has been mainly on the standard monomial basis. However, a (matrix) polynomial can also be represented in a different polynomial basis. As a matter of fact, using a different polynomial basis is a well-established practice in some areas of mathematics (e.g., using an orthogonal polynomial basis in approximation theory has some numerical advantages). This has motivated the idea to consider the (block) Macaulay matrix in other polynomial bases, e.g., in the well-known Chebyshev polynomial basis.

In our poster, we will show how to construct the (block) Macaulay matrix for a problem represented in the Chebyshev polynomial basis and how the solutions follow from similar methodology in its (right) null space or column space. Numerical examples in the poster will serve as a motivation and illustration of the adapted (block) Macaulay matrix. Furthermore, we also briefly want to explore the use of other polynomial bases.

40. Demonstrating equivalence between PNLSS and Volterra models for some SISO block-oriented models

***Prabhu Vijayan*, Philippe Dreesen, John Lataire, Mariya Ishteva**

KU Leuven, Vrije Universiteit Brussel, Maastricht University

This work aims to establish a relationship between the Polynomial NonLinear State Space (PNLSS) model and the Volterra model, focusing on three standard block-oriented models: Wiener, Hammerstein and Wiener-Hammerstein. Initially, we generate input/output data for these block-oriented models in PNLSS form, utilizing the known PNLSS parameters, while considering a specified memory length and order of nonlinearity. Subsequently, we estimate the Volterra kernel of the same data using a linear system solver, assuming the availability of model order and memory length information. The symmetric Volterra kernel tensor encompasses various combinations of PNLSS parameters specific to each block-oriented model. We extract the PNLSS parameters and utilize them to regenerate the output signal. Both analytical and numerical approaches are employed to demonstrate an equivalence between the two models. Due to the limited knowledge of the Multiple-Input Multiple-Output (MIMO) block-oriented models, particularly concerning the dimensions of intermediate signals (i.e., signals between the blocks), our investigation is focused solely on Single-Input Single-Output (SISO) systems.

41. Mapping EEG measurements to the brain activation location

***Johanna Wilroth**, Joshua P. Kulasingham, Martin A. Skoglund, Emina Alickovic, Martin Enqvist*

Linköping University

Due to a recent breakthrough demonstrating the predictability of brain responses through electroencephalography (EEG) using Temporal Response Functions (TRFs), research in the field of auditory attention decoding has experienced significant growth. This has particularly impacted the field of modern hearing technology, which envisions using EEG brain responses in a feedback loop to adjust hearing aid settings for detecting and amplifying attended speech. Understanding the brain mechanisms involved in selective attention during speech processing could greatly benefit individuals with hearing impairment. However, the limited spatial resolution of scalp EEG measurements poses challenges in pinpointing the brain activation location. Recent advancements in sparse source-localization methods using MEG responses to speech offer a more direct estimation of linear filters at the brain sources, reducing bias propagation observed in previous two-step approaches. To enhance the development of brain-controlled hearing technology, we have applied these Neuro-Current Response Functions (NCRFs) to EEG data from a hearing-impaired listener in a scenario with multiple speakers. Our preliminary results show promise, and future work will focus on evaluating this method with a larger dataset and exploring novel techniques.

42. Optimal transport for correctional learning

***Rebecka Wingvist**, Inês Lourenco, Francesco Quinzan, Cristian R. Rojas, Bo Wahlberg*

KTH, Oxford University

This poster presents a generalized formulation of correctional learning using optimal transport, which is about how to optimally transport one mass distribution to another.

Correctional learning is a framework developed to enhance the accuracy of parameter estimation processes by means of a teacher-student approach. In this framework, an expert agent, referred to as the teacher, modifies the data used by a learning agent, known as the student, to improve its estimation process. The objective of the teacher is to alter the data such that the student's estimation error is minimized, subject to a fixed intervention budget. Compared to existing formulations of correctional learning, our novel optimal transport approach provides several benefits. It allows for the estimation of more complex characteristics as well as the consideration of multiple intervention policies for the teacher. We evaluate our approach on two theoretical examples, and on a human-robot interaction application in which the teacher's role is to improve the robots performance in an inverse reinforcement learning setting.

43. Measurement embedding for transformer-based system identification

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Transformer as a neural network architecture can achieve state-of-the-art results in many problems, most notably sequence-to-sequence tasks in natural language processing. However, it has not been widely applied in the nonlinear system identification domain, apart from Transformer Physics using Koopman operator. Transformers, when applied to language or images, use the embedding operation, which is a linear up-projection of inputs with additional positional encoding, added directly to the inputs. Our hypothesis is that this operation is one of the keys to the success of the transformer, but there exist no obvious analogues for dynamical systems. Following from the hypothesis, we investigate the operation of converting measurements of signals present in dynamical system to representations useful for transformer architecture.

44. On estimating frequency response functions of a 6-axis robot

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Nonparametric estimates of frequency response functions (FRFs) are often suitable for describing the dynamics of a mechanical system. If treating these estimates as measurement inputs, they can be used for parametric identification of, e.g., a gray-box model. Classical methods for nonparametric FRF estimation of MIMO systems require at least as many experiments as the system has inputs, while local parametric methods do not. We adapted and applied these local methods for estimating FRFs of a 6-axis robotic manipulator, aiming to reduce the experiment time for gray-box identification. The resulting FRFs are compared to classical estimates.

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