ERNSI WORKSHOP 2024

Centro Culturale Don Orione Artigianelli

POSTER SESSIONS – Book of Abstracts

Poster session 1

1. Subspace tracking for online system identification

Authors: Andras Sasfi[a], Alberto Padoan[a], Ivan Markovsky[b], Florian Dorfler[a]
Afiliation: [a]ETH Federal Institute of Technology Zurich, Swiss; [b]CIMNE, Spain
Presenter: Andras Sasfi

Abstract: We propose a method to track slowly time-varying subspaces of $\mathbf{R}^n$ using tools from manifold optimization. The relevance of the setup is illustrated through the problem of online identification of linear time-varying systems in the framework of behavioral systems theory. At each time, a single measurement from the current subspace corrupted by bounded error is available. The subspace estimate is updated online using gradient descent, which corporates a window of the most recent data. We view subspaces as points on the Grassmannian manifold, and herefore, the optimization is performed on the manifold. Under suitable assumptions on the signal-to-noise ratio of the online data, we establish theoretical guarantees for the resulting algorithm. More specifically, we characterize the uncertainty of the estimates by providing an upper bound on their distance to the true subspace. The resulting bound is consistent, and exponential convergence is guaranteed for the special case of time-invariant subspaces and exact data.

2. Weighted Regularized State-Space Neural Networks for Physics-Guided Model Augmentation

Authors: Yuhan Liu, Roland Tóth, Maarten Schoukens
Affiliation: Eindhoven University of Technology, The Netherlands
Presenter: Yuhan Liu

Abstract: Physics-guided neural networks (PGNN) are an effective tool that combines the benefits of data-driven modeling with the interpretability and generalization of underlying physical information. However, for a classical PGNN, the penalization of the physics-guided part is at the output level, which leads to a conservative result as systems with highly similar state-transition functions, can have significantly different time-series outputs. In this work, we introduce a novel model augmentation strategy for nonlinear state-space model identification based on PGNN, using a weighted function regularization (W-PGNN). A new weighted regularization term is added to the cost function to penalize the difference between the state and output function of the baseline physics-based and final identified model. This ensures the estimated model follows the baseline physics model functions in regions where the data has low information content, while placing greater trust in the data when a high informativity is present. The proposed approach can efficiently augment the prior physics-based state-space models based on measurement data.

3. Learning-based model augmentation of physical models

Authors: Jan H. Hoekstra, Chris Verhoek, Roland Tóth, Maarten Schoukens
Affiliation: Eindhoven University of Technology, The Netherlands
Presenter: Jan H. Hoekstra

Abstract: Artificial neural networks (ANN) have proven to be effective in dealing with the identification nonlinear models for highly complex systems. To still make use of prior information available in the form of baseline models, e.g., derived by first-principles (FP) approaches, a variety of methods have been developed that integrate prior knowledge into (ANN-based) identification algorithms. These methods typically achieve faster estimation convergence and better accuracy on unseen data. A promising class of these methods achieve these properties by augmentation of the baseline model. For this purpose, a variety of augmentation structures have been considered in the literature, there is however no unifying theory to these. In this paper, we propose a flexible linear-fractional-representation (LFR) based model augmentation structure. This model structure is able to represent many common model augmentation structures, thus unifying them under one flexible representation form. Furthermore, we introduce an identification algorithm capable of jointly estimating the proposed LFR augmentation-based models. The performance and generalization capabilities of the identification algorithm and the augmentation structure are demonstrated on a hardening mass-spring-damper simulation example and the cascaded tanks benchmark.

4. Non-Parametric Identification Beyond the Nyquist Frequency

Authors: Max van Haren[a], Roy S. Smith[b], Leonid Mirkin[a], Lennart Blanken[a], Tom Oomen[a]
Affiliations: [a]Eindhoven University of Technology, The Netherlands; [b]ETH Federal Institute of Technology Zurich, Swiss
Presenter: Max van Haren

Abstract: Fast-dynamics models are essential for control design, specifically to address intersample behavior. Traditionally, the inputs and outputs of a system are sampled equidistantly at a reduced rate, and consequently identified at the reduced rate. This poster presents non-parametric time and frequency domain approaches to identify the system beyond the Nyquist frequency of the output, if the input is controlled at a higher rate than the output. Examples of such systems include vision-in-the-loop and chemical systems. The methods utilize respectively kernel regularization and local models, resulting in accurate single experiment identification. Both methods demonstrate their effectiveness on an experimental setup.

5. Guaranteeing stability in transfer function identification through unconstrained parametrizations

Authors: Johan Kon, Roland Tóth, Jeroen van de Wijdeven, Marcel Heertjes, Tom Oomen
Affiliation: Eindhoven University of Technology, The Netherlands
Presenter: Johan Kon

Abstract: Given a physical system, it is important that the identified model of this system reflects its true stability properties. Specifically, given a stable system it is desired that the model is also stable. However, even if the underlying system is known to be stable, the identified model can be unstable due to modeling errors, measurement noise and finite-time effects. On this poster, a transfer function model class is presented that is guaranteed to be stable. This is achieved by reparametrizing the set of all stable transfer functions in terms of unconstrained parameters. Thus, it is guaranteed by construction that a stable model is obtained for any choice of parameters. A similar unconstrained parametrization is presented for both passive and gain-bounded transfer functions.

6. Automatic Rank Determination for Bayesian TN Kernel Machines

Authors: Afra Kilic, Kim Batselier
Affiliation: Delft University of Technology, The Netherlands
Presenter: Afra Kilic

Abstract: Tensor decomposition methods have been used to accelerate model learning by constraining the model weights, leading to significant savings in computational complexity and memory. However, traditional approaches rely on parameter tuning to determine the tensor rank or the model complexity, which can be computationally expensive and imprecise. Further, these methods typically do not account for the uncertainty in the data, with those that do being either slow to converge or prone to overfitting. In this research, we introduce a Bayesian Canonical Polyadic decomposition

that automatically and implicitly determines the tensor rank while incorporating data uncertainty. This is achieved by applying a sparsity-inducing hierarchical prior over multiple factor matrices, ensuring that the number of components in the factor matrices is minimized. All the model parameters and hyperparameters are treated as latent variables with corresponding priors. Given the Bayesian approach and the complexity of the interactions between the latent variables, we use variational Bayesian inference to derive a deterministic solution that approximates the posteriors of all model parameters and hyperparameters. The proposed method offers improved computational complexity and precision via the removal of explicit parameter tuning. Further, the use of variational inference, known for faster convergence, allows for more efficient uncertainty quantification than the current methods.

7. Dealing with missing data: A matrix completion-based method for recurrence plots constructed from time series with missing values

Authors: Martijn Boussé, Philippe Dreesen, Pietro Bonizzi, Joël Karel, Ralf Peeters
Affiliation: Maastricht University, The Netherlands
Presenter: Martijn Boussé

Abstract: Incomplete data, i.e., data with missing and/or unknown values, are a common problem in various applications within signal processing, machine learning, and system identification. The data loss can be unintentional, e.g., due to sensor failures, or deliberate, e.g., when measurements are costly or difficult to obtain. In this work, we address this issue for recurrence plots (RPs) generated from time series with missing values by using a matrix completion-based method. RPs are a well-known technique for nonlinear analysis of the behavior of dynamical systems, based on generating a visual plot of the recurrences in the corresponding state-space trajectories, which are crucial for understanding the underlying dynamics of complex systems. Our method leverages the inherent low-rank structure often present in a time-delay embedding of a time series, represented as Hankel matrices, to accurately reconstruct the missing values. By computing a low-rank factorization using only known data points, and then imputing the missing entries based on the low-rank model, we can effectively "complete" the time series, even when data gaps are wide or sampling is irregular. This method is particularly beneficial in scenarios with significant under-sampling or extensive data gaps, as it exploits the redundancy and latent structure in the data. The proposed approach could be used to improve accuracy and reliability of system identification of systems for which only partial information is available about the time series characterizing a system.

8. Using the SVD to compute output difference equation of Polynomial State-Space Models

Authors: Sarthak De, Bart De Moor
Affiliation: KU Leuven, Belgium
Presenter: Sarthak De

Abstract: This poster addresses the challenge of deriving the output equation representation from a polynomial state-space model. Traditionally approached through symbolic computation and algebraic geometric techniques, we propose a new method which leverages tools from numerical linear algebra. We construct a Macaulay matrix using the $n + 1$ output polynomials $y_k, y_{k+1}, \ldots, y_{k+n}$ expressed in terms of the state and model parameters. Finding the output rep- resentation can then be stated as identifying a linear relationship among the rows of the Macaulay in which the state variables are eliminated. Our approach deploys the singular value decomposition (SVD) to both confirm the existence of such linear relations and compute the output representation di- rectly. This method adds flexibility in obtaining output equations with desired characteristics (model order, degree). This presentation will showcase the the- oretical foundation, the numerical algorithm, and the practical implications of using numerical linear algebra for deriving output equations of polynomial state-space models.

9. Memory-dependent abstractions of stochastic dynamical systems

Authors: Adrien Banse[a], Giannis Delimpaltadakis[b], Luca Laurenti[c], Manuel Mazo Jr.[c], Raphael M. Jungers[a]
Affiliation: [a]UC Louvain, Berlgium; [b]Eindhoven University of Technology, The Netherlands; [c]Delft University of Technology, The Netherlands
Presenter: Adrien Banse

Abstract: Recently, because of increasing complexity of systems, approximation methods of stochastic dynamical systems via finite state mathematical objects have been of great interest. In this regard, Markov chains have been used to abstract stochastic systems with a discrete output. Although the states of stochastic systems are described by a Markov stochastic kernel, the Markov property is lost as soon as discrete outputs are studied, thereby introducing an approximation error. In this work, we show that one can mitigate the non-Markovianity of the system by keeping in memory sequences of outputs instead of single out- puts, resulting in larger but better Markov approximations. In particular, we show that one can study these approximations by considering a lifted process, and projecting its transfer operator using a Galerkin method.

10. Extending the ROVA framework to model nonlinear, frequency-translating systems

Authors: Amedeo Varano[a,b], Yves Rolain[a], Dries Peumans[a]
Affiliations: [a]Vrije Universiteit Brussel, Belgium; [b]imec, Leuven, Belgium
Presenter: Amedeo Varano

Abstract: Linear models are often preferred for characterizing systems due to their simplicity. However, real-world systems are typically nonlinear, making nonlinear models more accurate. The ROVA framework is based on the Volterra series, a well-known nonlinear model. ROVA provides a parametric approximation of the truncated Taylor series expansion of the frequency-domain Volterra kernels using least squares. It is linear in its model parameters and avoids the combinatorial explosion of parameters as complexity increases. This framework has previously been validated on measurements of nonlinear, period-preserving systems. In this study, we extend ROVA to handle nonlinear, frequency-translating systems, specifically mixers. Mixers function as up- or downconverters, shifting a low-frequency broadband spectrum around a high-frequency single tone or performing the reverse action. Our simulation results for an upconverter demonstrate that ROVA can accurately predict the output. Compared to current state-of-the-art models, ROVA's advantage lies in its parametric estimation capability, allowing it to effectively describe the nonlinear frequency recombinations in mixers.

11. Disturbance Estimation for Identification of Non-linear Differential-Algebraic Equation Models

Authors: Robert Bereza, Oscar Eriksson, Mohamed R.-H. Abdalmoaty, David Broman, Håkan Hjalmarsson
Affiliation: KTH Royal Institute of Technology, Sweden
Presenter: Robert Bereza

Abstract: Many physical systems, ranging from mechanical to hydraulic or electric systems, can be modeled by systems differential-algebraic equations (DAEs). However, while most real-world systems are affected by process disturbances, modeling such disturbances for DAEs is more challenging than e.g. for ordinary differential equations, especially for non-linear models. As a consequence of this, most parameter estimation methods for non-linear DAEs neglect process disturbances, or consider them only for systems with specific structures. It is well-known that neglecting process disturbances during identification can lead to biased parameter estimates. In prior work we proposed a method for tractable parameter estimation of a general class of non-linear DAEs that allows for incorporating process disturbances, given by the output of stochastic differential equations, into the model. However, there are several challenges and pitfalls related to not only modeling but also estimating the unknown disturbance model from data, and in this work we investigate these pitfalls and propose a way to perform this estimation, both using forward mode and adjoint mode differentiation methods.

12. Bridging Prediction Error Method and Subspace Identification: A Weighted Null Space Fitting Method

Authors: Jiabao He, Håkan Hjalmarsson
Affiliation: KTH Royal Institute of Technology, Sweden
Presenter: Jiabao He

Abstract: Markov parameters play a key role in system identification. There exists many algorithms where these parameters are estimated using least-squares in a first, pre-processing, step, such as SSARX. This contribution introduces a two-step method for identifying Markov parameters of a state-space model, serving as a counterpart to subspace identification methods (SIMs) within the null space of the extended observability matrix. Unlike the first step of SIMs that mainly estimates the range space of the extended observability matrix, our method estimates its null space using multi-step least-squares in the first step. In the second step, we cast an extended state-space model that commonly used in SIMs into an ARMAX model by eliminating state sequences via null space projection, and then estimate Markov parameters from the ARMAX model using weighted least-squares. Regarding statistical properties, our approach is the best linear unbiased estimator of Markov parameters and provides asymptotically efficient estimates of the system's poles. Moreover, it is suitable for both open-loop and closed-loop data. Several applications of our estimates, including the realization of system matrices and prediction of system outputs, are presented as well. Simulation examples are provided to demonstrate the effectiveness and benefits of our method.

13. An Inverse Learning Paradigm for Controller Tuning Rules

Authors: Braghadeesh Lakshminarayanan[a] , Federico Dettú[b] , Cristian R. Rojas[a], Simone Formentin[b]
Affiliations: [a]KTH Royal Institute of Technology, Sweden; [b]Politecnico di Milano, Italy
Presenter: Braghadeesh Lakshminarayanan

Abstract: We present a sim2real, direct data-driven controller tuning approach, where a digital twin is used to generate input-output data and suitable controllers for several possibilities around the nominal values of its parameters. Based on these artificially generated data, neural-network architectures including a state-of-the-art sequence model are then used to learn the controller tuning rule that maps the input-output data onto the controller parameters. In this way, we automate the re-calibration of the controllers by meta-learning the tuning rule directly from data via an inverse supervised learning paradigm, thus practically taking the human out of the loop with a machine learning model. The benefits of this methodology are illustrated via numerical simulations for several choices of neural-network architectures.

14. Transformer architecture – a dynamical system perspective

Authors: Krzysztof Zając, Pawel Wachel
Affiliation: Wroclaw Univ. of Science Technology, Poland
Presenter: Krzysztof Zając

Abstract: Transformer architecture can be applied to many machine learning domains, including natural language processing, machine vision, video/audio processing, and dynamical system identification. However, the inner workings of the architecture are poorly understood, and in many areas, the properties of such models are known only empirically. We attempt to provide some understanding by viewing the transformer as a meta-dynamical system, where the values of the state matrix are dynamically generated for each input element.

15. A Lasso-Based Soft Sensing Method for Sensor Selection and Model Sparsity in Complex Systems

Authors: Le Wang, Ying Wang, Håkan Hjalmarsson
Affiliation: KTH Royal Institute of Technology, Sweden
Presenter: Le Wang

Abstract: In vehicle durability analysis, it is often necessary to estimate certain hardly accessible sensor signals using more easily obtained signals. Soft sensing is a widely used approach for addressing this challenge. However, identifying which sensor signals provide valuable information can be complex, especially since different operating conditions often require different models. In this paper, we propose a Lasso-based method that simultaneously accounts for model fit, parameter sparsity, and model complexity reduction. We further validate the proposed method using field data from a prototype vehicle.

16. A study of Regret Minimization for Static Scalar Nonlinear Systems

Authors: Ying Wang

Affiliation: KTH Royal Institute of Technology, Sweden
Presenter: Ying Wang

Abstract: In recent years, there has been growing interest in regret minimization within the context of adaptive control, particularly for Linear Quadratic Regulators (LQR). This poster seeks to extend these concepts to nonlinear systems. Our investigation starts with static, scalar, and nonlinear systems under idealized conditions, with the primary goal of addressing the conceptual differences and challenges rather than focusing on practical applications. We introduce an efficient input design method and establish its optimal regret rate, which aligns with the results from the linear case. To validate our theoretical findings, we also provide a quadratic numerical example.

17. Adaptive Sampling for Counterfactual Explanations

Authors: Margarita A Guerrero, Cristian R Rojas
Affiliation: KTH Royal Institute of Technology, Sweden
Presenter: Margarita A Guerrero

Abstract: Counterfactual Explanation (CFE) is an approach for interpreting machine learning models that answers the question: ``What would need to be different in the input for the model to produce a different outcome?". In the context of classification tasks, this approach seeks to determine how close a given sample is to the decision boundary of a trained classifier. Unfortunately, many current methods for CFE are not sample-efficient, often requiring large amounts of data to find explanations for complex black-box models. In this paper, we propose a novel and more efficient algorithm for CFE, called Adaptive Sampling for Counterfactual Explanations (ASCE), which is based on Bayesian estimation and stochastic optimization to create a surrogate model using Gaussian Processes for Classification. By employing Monte Carlo sampling and Bayesian optimization, this method prioritizes the most informative points by considering the uncertainty and constraints in the model, requiring fewer evaluations and optimizing the number of points needed to accurately explain the decision boundary in the vicinity of a given input. We empirically compare the ASCE method with four state-of-the-art CFE methods, demonstrating its superior evaluation efficiency while maintaining competitive effectiveness in identifying minimal changes for counterfactual explanations.

18. Data-Driven and Stealthy Deactivation of Safety Filters

Authors: Daniel Arnström, André Teixeira
Affiliation: Uppsala University, Sweden
Presenter: Daniel Arnström

Abstract: Safety filters ensure that only safe control actions are executed. In previous work we proposed a simple and stealthy false-data injection attack for deactivating such safety filters. This attack injects false sensor measurements to bias state estimates to the interior of a safety region, which makes the safety filter accept unsafe control actions. The attack does, however, require the adversary to know the dynamics of the system, the used safety region, and the observer gain. In this work we relax these requirements and show how a similar data-injection attack can be performed when the adversary only observes the input and output of the observer that is used by the safety filter, without any a priori knowledge about the system dynamics, safety region, and observer gain. In particular, the adversary uses the observed data to identify a state-space model that describes the observer dynamics, and then approximates a safety region in the identified embedding.

19. Structured State-Space Models are deep Wiener models

Authors: Fabio Bonassi, Carl Andersson, Per Mattsson, Thomas B. Schön
Affiliation: Uppsala University, Sweden
Presenter: Fabio Bonassi

Abstract: Structured State-space Models (SSMs) have recently emerged as a hot topic in the machine learning community. This interest stems not only from SSMs' state-of-the-art performance in many classification and regression tasks involving long sequences, but also from their remarkable computational efficiency in training and inference.

From the system identification perspective, SSMs are interesting as they represent an effective way to learn deep Wiener models via gradient-based simulation error minimization. With this poster we want to provide a structured, compact, and accessible overview on SSMs for system identification. We dissect the recent developments in SSMs, disentangling the model structure and parameterization from initialization strategy and identification algorithm, while also adopting a jargon more familiar to the system identification community. We aim at stimulating discussion around these architectures, as we believe this community can play a key role in solving some of the open problems affecting SSMs.

20. Machine learning differentiation of Parkinson's disease and normal pressure hydrocephalus using wearable sensors capturing gait impairments

Authors: Stefano Magni[a,b,c], Rene Peter Bremm[a], Konstantinos Verros[d,e] , Xin He[f], Sylvie Lecossois[a], Finn Jelke[a], Andreas Husch[f], Jorge Gonçalves[f,g], Frank Hertel[a]
Affiliations: [a]Centre Hospitalier de Luxembourg, Luxembourg; [b]Department of Medical Informatics, Luxembourg; [c]Laboratoire National de Santé, Luxembourg; [d]Trier University of Applied Sciences, Germany; [e]University of West Attica, Greece; [f]University of Luxembourg, Luxembourg; [g]University of Cambridge, United Kingdom
Presenter: Stefano Magni

Abstract: Gait impairments in patients affected by Parkinson's disease (PD) or normal pressure hydrocephalus (NPH) are typically diagnosed by visual clinical assessment. Despite standardized gait tests and clinicians' expertise, such approaches can be subjective and challenging due to the similarity in symptoms between these two diseases. Wearable sensors and machine learning (ML) can assist clinicians by offering objective and quantitative assessments of gait impairments that can help distinguish between PD and NPH. This study consists of a cohort of 12 PD and 11 NPH patients that performed standardized gait tests. Gait was measured by using wearable sensors embedded in each shoe of each patient and composed of a three-axis gyroscope, a three-axis accelerometer and eight pressure sensors in each insole. The prototype sensors and the computational pipeline to extract gait cycle parameters were beforehand validated and calibrated on 21 healthy subjects, employing an instrumented treadmill. ML approaches were then employed to identify changes in gait cycle parameters between the PD and NPH patients groups. A total of 27 distinct ML classifiers were compared, and linear support vector machines resulted to be the best performers, with a classification accuracy of 0.70 ± 0.28 and area under the ROC curve of 0.74 ± 0.39. Large standard deviations indicate high dependency of the results on which patients' gait data are used for algorithm training, mainly due to the limited cohort size. To increase the robustness of the results, a nested cross validation was employed, with a leave-pair-out scheme in the outer loop and a leave-one-out scheme in the inner loop. In conclusion, combining wearable sensors with ML algorithms trained on gait cycle parameters extracted from those sensors has shown the potential for objective differentiation of gait patterns between PD and NPH patients.

21. A novel recursive total least squares algorithm for online vehicle parameter identification

Authors: Hugo Koide[a,b], Guillaume Mercöre[a], Jeremy Vayssettes[b]
Affiliations: [a]University of Poitiers, France; [b]The Michelin Group, France
Presenter: Hugo Koide

Abstract: Recursive identification of vehicle parameters is of key importance in vehicle safety and control algorithms. This work presents a novel recursive total least squares algorithm which is specifically designed to produce robust online estimations when dealing with sub-optimal vehicle data. The algorithm is further enhanced with a recursive noise covariance estimator to account for heterogeneous noise in the measured data. The proposed algorithm is validated using experimental data from an electric passenger vehicle in urban and rural driving conditions, showcasing the improved accuracy of the algorithm compared to two benchmark algorithms from literature.

22. Nonlinear data-driven predictive control

Authors: Antonio Fazzi, Alessandro Chiuso
Affiliations: Università di Padova, Italy
Presenter: Antonio Fazzi

Abstract: The popularity of data-driven systems representation and related algorithms increased significantly in recent years. The reasons are the less computational effort with respect to the classical model-based strategies and the increasing complexity of the involved systems. While linear time-invariant systems are widely studied in the data-driven framework,

the nonlinear case still needs to be well explored, especially when the available data are affected by noise. This work proposes a stochastic predictive control strategy for nonlinear systems assuming some preliminary knowledge on the structure of nonlinear system dynamics. The starting point is an algorithm to simulate future trajectories of general nonlinear systems starting from a set of noisy data. The control is then computed by a closed-loop strategy by solving a series of least squares problems, where the nonlinear terms are linearized to fit them in a linear system of equations. To conclude, an example illustrates the results.

23. Data-Enabled Policy Optimization for Direct Adaptive Learning of the LQR

Authors: Feiran Zhao[a], Florian Dorfler [a] Alessandro Chiuso[b], Keyou You[c]

Affiliations: [a]ETH Zurich, Switzerland; [b] University of Padova, Italy; [b] Tsinghua University, China

Presenter: Feiran Zhao

Abstract: Direct data-driven design methods for the linear quadratic regulator (LQR) mainly use offline or episodic data batches, and their online adaptation remains unclear. In this paper, we propose a direct adaptive method to learn the LQR from online closed-loop data. First, we propose a new policy parameterization based on the sample covariance to formulate a direct data-driven LQR problem, which is shown to be equivalent to the certainty-equivalence LQR with optimal non-asymptotic guarantees. Second, we design a novel data-enabled policy optimization (DeePO) method to directly update the policy, where the gradient is explicitly computed using only a batch of persistently exciting (PE) data. Third, we establish its global convergence via a projected gradient dominance property. Importantly, we efficiently use DeePO to adaptively learn the LQR by performing only one-step projected gradient descent per sample of the closed-loop system, which also leads to an explicit recursive update of the policy. Under PE inputs and for bounded noise, we show that the average regret of the LQR cost is upper-bounded by two terms signifying a sublinear decrease in time plus a bias scaling inversely with signal-to-noise ratio (SNR), which are independent of the noise statistics. Finally, we perform simulations to validate the theoretical results and demonstrate the computational and sample efficiency of our method.

Poster session 2

1. Measurements and System Identification for the Characterization of Smooth Muscle Cell Dynamics

Authors: Dilan Öztürk[a], Pepijn Saraber[b], Kevin Bielawski[c], Alessandro Giudici[b], Leon Schurgers[b], Koen D. Reesink[b], Maarten Schoukens[a]
Affiliations: [a]Eindhoven University of Technology, The Netherlands; [b]Maastricht University; [c]Optics11 Life, Amsterdam
Presenter: Dilan Öztürk

Abstract: Biological tissue integrity is actively maintained by cells. It is essential to comprehend how cells accomplish this in order to stage tissue diseases. However, addressing the complexity of a cell's system of interrelated mechanisms poses a challenge. This necessitates a well-structured identification framework and an effective integration of measurements. Here we introduce the use of state-of-the-art frequency-domain system identification techniques combined with an indentation measurement platform to analyze the underlying mechanisms from the perspective of control system theory. The ultimate goal is to explore how mechanical and biological factors are related in induced Pluripotent Stem Cell-derived vascular smooth muscle cells. We study on the frequency-domain analysis for the investigation and characterization of cellular dynamics of smooth muscle cells from the measured data. The measurement model in this study exploits the availability of human tissue and samples, enabling fundamental investigations of vascular tissue disease. This approach using human cell lines holds significant potential to decrease the necessity for animal-based safety and efficacy studies. The focus of this study is to investigate the cellular dynamics underlying the myogenic response and to demonstrate the practicability of employing a nano-indentation measurement setup for the broadband frequency-domain characterization of induced Pluripotent Stem Cell-derived vascular smooth muscle cells.

2. Competitive/Collaborative Fusion of Dynamics (CoCoADyn)

Authors: Aurelio Raffa Ugolini[a], Mara Tanelli[a], Valentina Breschi[b]
Affiliations: [a]Politecnico di Milano, Italy; [b]Eindhoven University of Technology, The Netherlands
Presenter: Aurelio Raffa Ugolini

Abstract: In this work, we introduce the Competitive/CollAborative fusion of Dynamic experts (CoCoADyn), a Bayesian approach for the identification of nonlinear dynamical systems with uncertainty quantification. Breaking down a complex learning task into simpler learning problems via local approximations, our approach contemplates the blending of the experts' distributions as well as their mixing, characterizing classical mixtures of experts. This feature allows CoCoADyn to achieve high levels of expressiveness while maintaining a substantial degree of local interpretability. Indeed, compared to approaches based on blending or mixing alone, CoCoADyn better accommodates different scenarios for the intermediate behavior between generating mechanisms, resulting in tighter credible bounds on the response variable. The proposed method is extensively benchmarked against blending- and mixing-only formulations on a suite of synthetic and real examples, demonstrating its efficacy in tackling complex learning problems where uncertainty is a key quantity of interest.

3. Convergence of energy-based learning in linear resistive networks

Authors: Anne-Men Huijzer, Thomas Chaffey, Henk van Waarde, Bart Besseslink
Affiliation: University of Cambridge, United Kingdom
Presenter: Thomas Chaffey

Abstract: Energy-based learning algorithms are alternatives to back-propagation which are well suited to distributed implementations in analog electronic devices. However, a rigorous theory of convergence is lacking. We make a first step in this direction by analysing a particular energy-based learning algorithm, Contrastive Learning, applied to a network of linear adjustable resistors. It is shown that, in this setup, Contrastive Learning is equivalent to projected gradient descent on a convex function, for any step size, giving a guarantee of convergence for the algorithm.

4. Damage detection in nonlinear systems by nonlinearity cancellation via output injection

Authors: Neha Aswal, Adrien Mélot, Laurent Mevel, Qinghua Zhang
Affiliation: Univ. Gustave Eiffel, Inria, Rennes, France
Presenter: Neha Aswal

Abstract: Most civil and mechanical structures exhibit nonlinear stochastic behaviour, which is difficult to model accurately, but necessary for conventional model-based structural health monitoring techniques. Various methods have been developed to estimate nonlinear systems, however they require external force excitation information and are susceptible to sensor noise and modelling inaccuracies. This poster presents a novel approach to detect damage in the structures with localized nonlinearity of some unknown form, irrespective of the damage. It is based on output injection to reject unknown nonlinearities as if they were unknown disturbances. By applying an existing disturbance rejection technique, the need to know or to estimate the nonlinearities is avoided. The method makes use of interacting particle Kalman filter, where the particle filter estimates the health parameters while the Kalman filter simultaneously estimates the states. The efficiency of the proposed method is demonstrated by numerical experiments on a spring-mass-damper oscillator chain with a localized nonlinearity.

5. Streamlining Evaluation and Comparison on Benchmarks in System Identification Research

Authors: Gerben I. Beintema[a], Max D. Champneys[c], Roland Toth[a,b], Timothy J. Rogers[c], Maarten Schoukens[a]
Affiliations: [a]Eindhoven University of Technology, The Netherlands; [b]HUN-REN Institute for Computers Science and Control, Hungary; [c]University of Sheffield, United Kingdom
Presenter: Gerben I. Beintema

Abstract: In developing system identification methods, it is essential to demonstrate the method capabilities by comparing them to established methods on (real-life) benchmark datasets. However, many research papers omit this comparison since it is time-consuming, and often requires creating your own implementation of state-of-the-art algorithms. To streamline the benchmarking process for nonlinear system identification, we have developed and deployed a `nonlinear_benchmark` Python toolbox which automatically downloads, loads, and splits the benchmark data. Furthermore, we provide baseline results with often used models such as linear, NARX, and common neural network models. Lastly, we are developing an online overview and submission portal such that researchers can submit and compare their benchmarking results.

6. On Space-Filling Input Design for Nonlinear Dynamic Model Learning: A Gaussian Process Approach

Authors: Máté Kiss, Yuhan Liu, Maarten Schoukens , Roland Tóth
Affiliation: Eindhoven University of Technology, The Netherlands
Presenter: Máté Kiss

Abstract: The quality of a model resulting from (black-box) system identification is highly dependent on the quality of the data that is used during the identification procedure. Designing experiments for linear time-invariant systems is well understood and mainly focuses on the power spectrum of the input signal. Performing experiment design for nonlinear system identification on the other hand remains an open challenge as informativity of the data depends both on the frequency-domain content and on the time-domain evolution of the input signal. Furthermore, as nonlinear system identification is much more sensitive to modeling and extrapolation errors, having experiments that explore the considered operation range of interest is of high importance. Hence, this paper focuses on designing space-filling experiments i.e., experiments that cover the full operation range of interest, for nonlinear dynamical systems that can be represented in a state-space form using a broad set of input signals. The presented experiment design approach can straightforwardly be extended to a wider range of system classes (e.g., NARMAX). The effectiveness of the proposed approach is illustrated on the experiment design for a nonlinear mass-spring-damper system, using a multisine input signal.

7. Learning Subsystem Dynamics in Nonlinear Systems via Port-Hamiltonian Neural Networks

Authors: G.J.E. van Otterdijk, S. Moradi, S. Weiland, R. Tóth, N.O. Jaensson, M. Schoukens
Affiliation: Eindhoven University of Technology, The Netherlands
Presenter: S. Moradi

Abstract: Port-Hamiltonian neural networks (pHNNs) are emerging as a powerful modeling tool that integrates physical laws with deep learning techniques. However, most existing research has largely concentrated on modeling entire systems, often neglecting the thorough examination of subsystems within dynamic systems. This study presents a novel approach for identifying subsystems using pHNNs to fill this gap. By utilizing the inherent port modeling characteristics of the port-Hamiltonian systems, we have developed an algorithm that partitions port-Hamiltonian systems into distinct subsystems, allowing for more detailed analysis and modeling. To validate our approach, we conducted numerical experiments on nonlinear systems, demonstrating that it effectively captures independent subsystem dynamics.

8. Deep-Learning-Based Model Augmentation of Vehicle Dynamics

Authors: Bendegúz M. Györök[a], Jan H. Hoekstra[b], Tamás Péni[a], Maarten Schoukens[b], Roland Tóth[b]
Affiliations: [a]SZTAKI, Hungary; [b]Eindhoven University of Technology, The Netherlands
Presenter: Bendegúz M. Györök

Abstract: In recent years, accurate dynamic models have become essential for reliable motion control and trajectory planning of autonomous vehicles. While simplified mechanical models based on physical principles can be provided, the performance of these models tends to diminish during aggressive maneuvers. On the contrary, data-driven identification techniques can generate highly accurate models without prior physical insight; however, these black-box models lack physical interpretability, making them difficult to utilize for control and path-planning purposes. Therefore, there exists a need for producing highly accurate, yet physically interpretable models, by augmenting the first-principle dynamics with deep-learning-based techniques. Model augmentation can be accomplished using various structures, such as additive

or multiplicative combinations. We show benefits and drawbacks of these simpler methods and compare them with a general augmentation form based on a linear-fractional representation (LFR). In this structure, latent variables are introduced to describe the unmodeled dynamics, with dimensions determined based on prior physical knowledge. To achieve a more robust representation, the matrices in the LFR structure are also tuned during the optimization, alongside the neural network parameters. The challenge of identifiability arises when tuning the physical parameters simultaneously with the network parameters. To address this, we have implemented novel regularization methods to enhance extrapolation properties. Finally, we compare the presented augmentation methods with state-of-the-art black-box approaches by identifying the dynamics of a small-scale electric vehicle (F1Tenth) in a high-fidelity simulation environment.

9. Tensor Network based Feature Learning Model

Authors: Albert Saiapin, Kim Batselier
Affiliation: Delft University of Technology, The Netherlands
Presenter: Albert Saiapin

Abstract: In the context of kernel machines, complex features (polynomial, Fourier, B-splines) provide a nonlinear extension to linear models by mapping the data to a higher-dimensional space. Depending on an optimization problem formulation (dual or primal) one can encounter scalability problems concerning the number of samples or the dimensionality of the dataset. One way to improve scalability is to exploit the tensor structure present in the features by constraining the model weights to be an under-parametrized tensor network. Another challenge in this context is determining the optimal hyperparameters for the features.The key contribution of this work is a new learnable CP rank-P feature tensor that allows the construction of a more complex feature representation of a model and eliminates the use of cross-validation for hyperparameter tuning. We show that this more generic FL model could be used in several settings depending on one's needs: using L2 regularization on feature parameters one could generate a more complex feature map as a combination of product and additive features; using L1 regularization on feature parameters one could look for the most influential features for the particular problem. The experimental results show that the FL model can be trained faster than an alternative cross-validation procedure having comparable prediction quality on various datasets.

10. Inference of dynamical physical interactions in complex networks with zero knowledge on network topology

Authors: Zuogong Yue[a], Jorge Goncalves[b]
Affiliations: [a]Huazhong University of Science and Technology, China; [b]University of Luxembourg
Presenter: Zuogong Yue

Abstract: Many analysis tools in complex networks have been developed and widely used to understand complicated dynamical behaviours in the biomedicine, economy, environment, etc. However, learning such complex networks from data remains open, among which the task with unknown topology was even questionable on its feasibility. Our work formulates a manageable learning problem on both nonlinear dynamics and network topology in the framework of sparse selection of dictionary functions. Due to the entanglement of nodal dynamics and topology, its inference considers a more general problem, and is solved by proposing a sampling-based algorithm to enforce structured multi-level sparsity. Our approach shows its effectiveness in numerical experiments on several biomedical systems with randomly generated Erdos-Renyi network.

11. The Impact of Nonlinearity Compensation and Noise Reduction Algorithms in Hearing Aids

Authors: Johanna Wilroth, Emina Alickovic, Martin Skoglund, Carine Signoret, Jerker Rönnberg, Martin Enqvist
Affiliation: Linköping University, Sweden
Presenter: Johanna Wilroth

Abstract: Hearing impairment (HI) disrupts social interaction by hindering the ability to follow conversations in noisy environments. While hearing aids (HAs) with noise reduction (NR) partially address this, the "cocktail-party problem" persists, where individuals struggle to attend to specific voices amidst background noise. This study investigated how NR

and an advanced signal processing method for compensating for nonlinearities in EEG signals can improve neural speech processing in HI listeners. Participants wore hearing aids with NR, either activated or deactivated, while focusing on target speech amidst competing masker speech and background noise. The analysis focused on temporal response functions to assess neural tracking of relevant target and masker speech. Results revealed enhanced neural responses (N1 and P2) to target speech, particularly in frontal and central scalp regions, when NR was activated. Additionally, a novel method compensated for nonlinearities in EEG data, leading to improved signal-to-noise ratio (SNR) and potentially revealing more precise neural tracking of relevant speech. This effect was most prominent in the left-frontal scalp region. Importantly, NR activation significantly improved the effectiveness of this method, leading to improved SNR and reduced variance in EEG data and potentially revealing more precise neural tracking of relevant speech. This study provides valuable insights into the neural mechanisms underlying NR benefits and introduces a promising EEG analysis approach sensitive to NR effects, paving the way for potential improvements in HAs.

12. Exploiting the Macaulay Matrix structure for the globally optimal identification of autonomous systems

Authors: Lukas Vanpoucke, Bart De Moor
Affiliation: KU Leuven, Belgium
Presenter: Lukas Vanpoucke

Abstract: Previous work has shown that the stationary points, including the globally optimal parameter values, of the least-squares misfit identification of autonomous systems can be found as the roots of a multiparameter eigenvalue problem, the roots of which can be found using the Block-Macaulay method. This algorithm relies on the construction of a structured Block-Macaulay matrix, the null space of which contains the crucial information about the roots of the problem, which can subsequently be extracted through setting up a multivariate realization problem from this null space. This work proposes a novel approach to directly compute this null space, without building the Block-Macaulay matrix itself. Moreover, the proposed approach is recursive in nature, allowing one to efficiently re-use the previous computations, which leads to improved asymptotic computation times. This turns out to be especially valuable for low-degree systems in many variables, as is illustrated using the least-squares misfit identification problems of autonomous systems.

13. The Cuckoo Problem: Finding the Globally Optimal Critical Value of a Polynomial Optimization Problem using the Macaulay Matrix

Authors: Hans van Rooij, Bart De Moor
Affiliation: KU Leuven, Belgium
Presenter: Hans van Rooij

Abstract: Multivariate polynomial optimization arises in a variety of engineering areas such as system identification, model-order reduction, control theory, and robotics. For a multivariate polynomial objective function, 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 and thus retrieving the optimal solutions that either maximize or minimize a specified cost function. In this poster, we will introduce the Cuckoo Problem, which involves evaluating a specific multivariate polynomial at the shared roots of a set of other multivariate polynomials. By using the Macaulay matrix, the critical values of the multivariate polynomial optimization problem can directly be computed by solving a generalized eigenvalue problem (GEP), without explicitly obtaining the corresponding critical points.

14. Error-in-variables in hybrid system identification

Authors: Wojciech Sopot, Pawel Wachel Wachel
Affiliation: Wroclaw Univ. of Science Technology, Poland
Presenter: Wojciech Sopot

Abstract: We focus on the identification of a class of hybrid systems, specifically, ones that switch between a finite set of linear state space models (i.e., system modes). We propose a novel identification method that utilizes a kernel technique to separate a single mode, further identified by Deming regression. The theoretical properties of the method are analyzed, including its convergence rate, stability, and robustness to variations in input data, ensuring that it can be reliably applied to a wide range of piece-wise smooth systems. The effectiveness of the proposed approach is demonstrated through simulations on benchmark piece- wise smooth systems, highlighting its capability to achieve high accuracy in mode separation and system identification.

15. Modelling Cell Differentiation Trajectories in Single Cell Sequencing Data as an Optimal Transport Problem over Multiple Constrained Marginals

Authors: Magnus Tronstad[a], Johan Karlsson[b] and Joakim Dahlin[a]
Affiliations: [a]Institutet and Karolinska University Hospital, Sweden; [b]KTH Royal Institute of Technology, Sweden
Presenter: Magnus Tronstad

Abstract: A key challenge in biological research is to develop more complete models of cell differentiation: how cells develop from stem cells and specialize to become different mature cell types. Since the advent of single cell RNA-sequencing (scRNA-seq), the cell's state can now be characterized at an unprecedented level of resolution by measuring gene expression levels corresponding to many thousands of genes, with each gene's expression level being represented by a state variable. These measurements are destructive, however, making it impossible to collect longitudinal data through repeat state measurements of the same cell. Instead, one can only obtain a snapshot of the different cell states present in a biological sample at a particular time. A key analytical problem is thus to estimate how the intermediate states in such a snapshot are related to each other, and how they should be ordered, from least mature, to most mature. Previously, an extended optimal transport problem, which optimizes over multiple constrained marginals, has successfully been applied in state estimation and tracking of ensembles of agents. Here, we develop this framework into a model of cell differentiation which uses sequences of optimal transport plans as estimates for cell-cell transition probabilities. This works by connecting initial- and terminal cell states through a series of intermediate optimal transport problem. We use the optimal transport plans to compute a transition probability matrix in a stationary absorbing Markov chain and predict cell fates of intermediate cell states via absorption probabilities. We demonstrate the validity of our modelling approach by inferring terminal differentiation fates of immune cells from early stages of development, and benchmark the performance using publicly available lineage tracing data.

16. A data-driven model-based approach for balancing hydronic heating systems in residential buildings

Authors: Henrik Håkansson, Magnus Önnheim, Mats Jirstrand, Jonas Sjöberg
Affiliation: Chalmers University of Technology, Sweden
Presenter: Henrik Håkansson

Abstract: Radiators with improper flow rates are common in today's hydronic heating systems, which causes undesired temperature variations between thermal zones. Flow rates are set by manually adjustable balancing valves mounted at various locations on the heating system pipes. The conventional procedure for tuning balancing valves is to use settings calculated from a building model based on the construction plan. However, for many zones, those valve settings lead to an unsatisfactory indoor climate, which can be attributed to commonly occurring discrepancies between the construction plan and the actual building. Consequently, this method must be accompanied by manual fine-tuning based on guesswork, which is very time-consuming. In this work, we aim to address these issues with a novel model-based approach involving system identification on operational time series data, including indoor temperature for each thermal zone, central supply temperature, and outdoor temperature. Through an optimal control perspective, we formulate the tuning of valves as an optimization problem informed by identified gray-box models, one for each thermal zone. We demonstrate the method in a case study performed in a residential building in Örebro, Sweden. The results indicate reduced indoor temperature variance after applying valve settings suggested by our method, which is a promising sign of applicability.

17. Data-Driven Stability Analysis of Switched Linear Systems Using Adaptive Sampling

Authors: Alexis Vuille, Raphael M. Jungers

Affiliation: UC Louvain, Berlgium
Presenter: Raphael M. Jungers

Abstract: In the realm of system analysis, data-driven methods have gained a lot of attention in recent years. We introduce a new innovative approach for the data-driven stability analysis of switched linear systems which is adaptive sampling. Our aim is to address limitations of existing approaches, in particular, the fact that these methods suffer from ill-conditioning of the optimal Lyapunov func- tion, which is a direct consequence of the way the data is collected by sampling uniformly the state space. Our adaptive-sampling approach consists in a two-step procedure, in which an optimal sampling distribution is estimated in the first step from data collected with a non-optimal distribution, and then, in the second step, new data points are sampled according to the identified distribution to establish the final probabilistic guarantee for the convergence rate of the system. Numerical experiments show the efficiency of our approach, namely, in terms of the total number of data points needed to guarantee stability of the system with given confidence.

18. Efficient Evaluation of Target Tracking Using Entropic Optimal Transport

Authors: Alfred Wärnsäter, Viktor Nevelius Wernholm
Affiliation: KTH Royal Institute of Technology, Sweden
Presenter: Alfred Wärnsäter

Abstract: Multiple target tracking deals with the task of estimating targets which appear, disappear, and move within a scene, given data from noisy measurements. A wide range of algorithms can be employed to solve this task. To assess the performance of such algorithms, the so-called GOSPA metric for trajectories can be applied. This metric is formulated as an optimization problem, which has proven computationally demanding for large problem instances. In this project, we reformulate this metric to obtain an optimization problem with optimal transport structure. Following a recent breakthrough in computational optimal transport, we introduce entropic regularization into this formulation. For the regularized problem, we present a numerical algorithm for approximating the GOSPA metric for trajectories. Numerical results suggest that the regularization can be made small enough to allow for an adequate approximation of the metric while being less computationally demanding than a conventional linear programming solver in some instances.

19. Using statistical linearization in experiment design for identification of robotic manipulators

Authors: Stefanie A. Zimmermann, Stig Moberg; Svante Gunnarsson, Martin Enqvist
Affiliation: Linköping University, Sweden
Presenter: Stefanie Zimmermann

Abstract: Nonlinear joint stiffness in industrial robots can be determined quickly and accurately through a combination of statistical linearization and optimized robot configurations for data acquisition. The statistical linearization is carried out using the histogram of the measured motor torques. The result of this linearization is used in a criterion that is minimized to determine optimal configurations for data collection. The proposed approach is validated using data from both simulations and experiments with a medium-size industrial robot. In both cases, there is a significant improvement in accuracy compared to both using conventional linearization and collecting data in a larger but random set of configurations.

20. A MIMO Volterra Tensor Network with a Bayesian Approach

Authors: Eva Memmel, Kim Batselier
Affiliation: Delft University of Technology, The Netherlands
Presenter: Eva Memmel

Abstract: This poster presents a novel application of a Bayesian framework for identifying high-order discrete nonlinear multiple-input multiple-output systems. Traditional methods often encounter computational challenges due to the exponential growth of monomials as the order of the Volterra kernel increases. Previous research has demonstrated that the low-rank TN approach effectively addresses this issue by compressing all Volterra kernels simultaneously. The contribution of this work lies in integrating a Bayesian framework, where the elements of all TN-cores are treated as

random variables, allowing for the direct incorporation of prior assumptions into the model. Additionally, adopting a Bayesian perspective provides uncertainty bounds in simulations, accounting for both noise and these prior assumptions.

21. An asymptotic closed-loop analysis of γ-DDPC with terminal constraints

Authors: Valentina Breschi[a], Simone Formentin[b], Alessandro Chiuso[c]
Affiliation: [a]Eindhoven University of Technology, The Netherlands; [b]Politecnico di Milano, Italy; [c]Università di Padova, Italy
Presenter: Valentina Breschi

Abstract: Data-driven predictive control approaches promise to enable the design of constrained control policies directly from data, but they often lack rigorous guarantees. This shortage of formal warranties is particularly true within a stochastic setting, where noise plays a crucial role in shaping the quality and, hence, the properties of the learned control action. In the footsteps of the first work providing formal guarantees for data-driven predictive control, we formally analyze the properties of the so-called gamma-DDPC method by equipping it with terminal constraints, showcasing them on a benchmark example.

22. An in-context learning framework for control

Authors: Riccardo Busetto[a,c], Valentina Breschi[b], Marco Forgione[a], Dario Piga[a], Simone Formentin[c]
Affiliation: [a]IDSIA Dalle Molle Institute for Artificial Intelligence, Swiss; [b]Eindhoven University of Technology, The Netherlands; [c]Politecnico di Milano, Italy
Presenter: Riccardo Busetto

Abstract: Imagine having a system to control, knowing only that it belongs to a certain class of dynamical systems. Wouldn't it be amazing to simply plug in a controller and have it work exactly as you need? With the rise of in-context learning and powerful architectures like Transformers, we can learn a unified model to represent a whole class of dynamical systems, rather then a specific one. Leveraging on this seminal work, we show how this framework is suitable to design a unique contextual controller for an entire class of dynamical systems, instead of just a single instance, paving the way for a major shift in control systems design. Similarly, incontext learning can solve the dual problem of state estimation, designing a contextual state estimator that can abstract from specific instances seen during training and generalize to the whole class. This eliminates the need for complex tuning and achieves superior performance, as validated by benchmark examples. Together, these contributions open new possibilities for adaptive, scalable solutions in control and estimation, significantly simplifying the design process for complex, nonlinear systems.